ABSTRACT

The aim of this project is to generate an industrially relevant and academically rigorous curriculum which could be deployed to tackle the significant skills gap in composites professionals, vital for delivering on the UK’s National Composite Strategy and allowing the industry to grow to its full potential, forecast by the Composites Leadership Forum to grow by a factor of 5 by 2030. A Masters’ level curriculum of short, industrially focused units has been specified and a small number of trial units developed. Engagement of academics in this novel collaborative curriculum development, utilising each institution’s expertise, has been very good and feedback from industry and participants in pilot units has been positive. Consortium participants are investigating numerous options for developing this further and have begun to put plans in place for the next stage.

Laura Rhian Pickard
Kevin Potter
John Summerscales
Jasper Graham-Jones
Anna Taylor
Sona Rusnakova
Michael Wisnom
HEFCE Composites Curriculum Development Project
ACKNOWLEDGEMENTS

National Composites Centre - key partner
Staff at University of Bristol and University of Plymouth
HEFCE/OfS for funding
Advanced Manufacturing Research Centre
University of Bath
University of Bolton
Cardiff University
Cranfield University
Imperial College London
National Physical Laboratory
University of Nottingham
Queen Mary University of London
University of Sheffield
University of Southampton
Ulster University
University of the West of England
Wrexham Glyndŵr University
Yeovil College University Centre
BMW
FAC Technology
Veale Wasbrough Vizards LLP
Wuhan University of Technology
Department for International Trade
The UK advanced composites industry has the potential to grow very significantly over the next ten years due to new applications in aerospace, automotive, wind energy, construction and oil and gas. However, the current pool of trained and talented composites scientists and engineers is small and needs to be grown very rapidly if the opportunity is to be realised. The urgent need is to be able to retrain existing manufacturing professionals, alongside increasing the number of composites trained graduates coming out of the Universities. This project brings together Bristol and Plymouth universities, both leaders in composites education and training to provide innovative work-based curricula. Over the course of the project academic staff from numerous universities have worked together collaboratively, along with the National Composites Centre and National Physical Laboratory and through discussion with industrial partners; to quantify requirements, identify gaps, and produce a portfolio of flexible topic-based material. Material was trialled at the National Composites Centre and University of the West of England. In the future the curriculum is intended to be made available across a range of sectors and partners to be used for a variety of levels and audiences. Subject to successful bids for funding, we aim to start the process of delivering the volume of skilled workforce needed in composites, alongside demonstrating innovative approaches that could be applied to other emerging technology areas.

This curriculum offers an opportunity to tackle the skills crisis in composites. In order to achieve this, it is recommended that:

- A business case be constructed with a roadmap for success and options for funding through numerous short projects.
- One or more persons, funded as necessary, to take on responsibility for continuation of communication between participating institutions and to drive the next stage.
- Training needs analysis be carried out for the composites sector, including but not limited to the workshops discussed in the 'next steps section'.
- A vehicle for development and delivery of the curriculum be created, with members drawn from the current unofficial consortium and input from an industrial advisory board, with reference to the legal advice enclosed in this report.
- Knowledge capture interviews or similar exercises with experts of retirement age to be carried out and the resulting material used as teaching resources.
- The un-tested and second iteration units produced for this stage to be piloted, with feedback recorded and material modified appropriately.
- Further investigation into other courses which may hold useful lessons for this project, both in other countries and other subject areas, identified herein.
Contents

Introduction ....................................................................................................................................................1

Content of Report .......................................................................................................................................1

Rationale .....................................................................................................................................................1

Project Objectives ...........................................................................................................................................2

Scope of Project ..........................................................................................................................................2

Goals ...........................................................................................................................................................2

Milestones ..................................................................................................................................................2

Demand From Industry ...................................................................................................................................2

Staffing Needs .............................................................................................................................................2

Demand For Training ..................................................................................................................................3

Composites Teaching in the UK ......................................................................................................................5

International Benchmarking ...........................................................................................................................7

  Collaborative course ......................................................................................................................................7
  Courses with Industrial Content ....................................................................................................................8
  Chinese Universities.......................................................................................................................................9

Proposed Composites Curriculum ..................................................................................................................9

  Unit Portfolio ..............................................................................................................................................9
  List of units ...............................................................................................................................................9
  Schematic ..............................................................................................................................................11
  Reviews .....................................................................................................................................................12

Resources developed to date .......................................................................................................................13

  Contextual learning objects .......................................................................................................................13
  Case studies and other resources .............................................................................................................13
  Images, Videos and Physical Objects .........................................................................................................13

Example units ............................................................................................................................................14

  List of example units ...............................................................................................................................14

Report on Trials .............................................................................................................................................15

  Pilot 1- NCC Composites Conversion Course ............................................................................................15
  Pilot 2- UWE CPD Course ..........................................................................................................................15
  Pilot 3- 2 units at NCC ..............................................................................................................................16

Summary of Participant Feedback ..................................................................................................................16

  Demographics .......................................................................................................................................17
Overall rating of the courses .................................................................................................................18
Level of difficulty ...................................................................................................................................18
Key comments on content ....................................................................................................................19
Overview of participant opinions .........................................................................................................19
Delivery of Curriculum ..................................................................................................................................22
Resource requirements for material development ..................................................................................22
Results of example unit development ..................................................................................................22
Models for delivery ...................................................................................................................................24
Assessments, academic qualifications and accreditation ........................................................................25
Assessment ...............................................................................................................................................25
Integrated Learning Package, University of Bolton ..................................................................................26
Industrial Doctorate Centre Assessments, University of Bristol ..............................................................26
Undergraduate Assessments, University of Plymouth ...........................................................................29
Home Laboratory, Queen Mary University of London ..............................................................................29
MSc Composites assessment, University of the West of England ..........................................................29
Continuing Professional Development vs exit qualifications for HEFCE Catalyst multi-site M-level qualification ..............................................................................................................................................29
Technical Accreditation Scheme, Warwick ...........................................................................................30
Degree Apprenticeship ............................................................................................................................31
Accreditation ...........................................................................................................................................32
Making It Happen ........................................................................................................................................32
Next Steps ...............................................................................................................................................32
Legal Advice ...........................................................................................................................................33
Comparable case: Economics Core Curriculum ....................................................................................34
Future Funding ........................................................................................................................................35
Catapult Fellowship? ...............................................................................................................................35
Evaluation of Project ..................................................................................................................................36
Conclusion ...............................................................................................................................................36
Appendices ...............................................................................................................................................37
Appendix 1- Financial Summary ...............................................................................................................37
Appendix 2- Curriculum Mapping Data ....................................................................................................38
Appendix 3- International Benchmarking Data .......................................................................................42
Appendix 4- Sample feedback form .........................................................................................................48
Introduction

Content of Report
This report is a compilation of work carried out during the HEFCE Catalyst funded Composites Curriculum Project. It is intended as a resource for continuation of this work in the next phase. The report describes the problem, the proposed solution and presents relevant data and options for the next stage.

The full dataset of anonymous feedback from the trial units and teaching material developed during this project are available in associated spreadsheet and presentation files.

Rationale
There is a significant skills gap in the UK composites industry. As the industry grows- and a generation of experts reach retirement- this is likely to increase, constraining the potential growth. The Composites Leadership Forum estimated that this industry has the potential to grow by £108n in 10 years, something which cannot be achieved without suitably skilled staff.

Provision of an industrially focused curriculum, at Masters' level, is intended to tackle this problem. Consisting of units which can be delivered according to industry need, engineers whose experience does not include composites; or new graduates without any composites background could attend those units most useful to their business. If possible, an option to add up points towards an academic qualification is considered worthwhile and options for this are discussed. Masters’ level was chosen both because it is easier to develop at the highest level first and follow on with lower level material if needed than vice-versa, and because there are other training schemes under development at lower levels but the gap at Masters’ level remains large.

Experts now reaching retirement present not only a significant loss of experienced persons, but also potentially loss of their accumulated knowledge and wisdom from varied and interesting careers. In addition to training the new generation of composites engineers, the proposed curriculum facilitates knowledge transfer directly from these experts to those attending the courses. At Masters’ level, providing teaching material alone is not sufficient- the benefit which can be obtained from putting the experts in the same room as their students cannot be overstated. The curriculum should facilitate this, ideally starting with the consortium of experts who have contributed to this project.

The skills gap is not unique to the composites industry. The principles of the work presented herein could equally be applied to other areas, which stand to learn from the lessons of this project. In academia multi-institution collaboration on teaching is rare, compared to collaboration in research, but is necessary for this project as no single university holds the expertise necessary to deliver this course alone.

Under this project a curriculum has been specified, with proposed descriptions for each unit, which were reviewed by both academic and industrial experts. Pilot units were delivered to industrial audiences and modified based on their feedback. A record of current composites teaching at Masters’ level in the UK is used to estimate the likely shortfall of staff for the industry without this course and is found to not meet the anticipated industrial demand. Options for future development, including intellectual property (IP), delivery of the course and appropriate awards or qualifications have been discussed and are presented herein.
Project Objectives

Scope of Project
This project seeks to define and carry out a limited pilot of a collaborative curriculum in composites manufacturing. The curriculum, intended as a method to tackle the skills gap in this area, will be at Masters level, with each academic institution contributing unit descriptions in their area of expertise.

The curriculum will be specified with reference to current available teaching in this area and to discussions with representatives of industrial manufacturers of composite parts.

Development of the full curriculum and final delivery structure is not in scope for this project.

Goals
A. Deliver a picture of the current composites teaching being carried out in the UK
B. Compare that picture with international benchmarks.
C. Generate a framework identifying the material that should be included within a composites curriculum.
D. Take a very limited number of the elements of that curriculum, develop delivery material and trial that material at the National Composites Centre.
E. Identify resource requirements to deliver the full set of teaching and associated supporting materials required to deliver the full curriculum.
F. Identify a sustainable structure by which ongoing delivery of the composites curriculum could be achieved and scaled to the industrial demand.

Milestones
1) Curriculum mapping exercise
2) Demand and gap analyses
3) Contextual learning objects, materials and case studies
4) Pilot curriculum at NCC

Demand From Industry

Staffing Needs
An initial estimate of staffing needs was carried out based on an estimate of the future composites market by the Composites Leadership Forum. Based on government figures, it is estimated that 5000 staff are needed for £1Billion turnover.

Of these, 5%-25% are at graduate level. The target of £12Billion turnover in 2030 would therefore require 3000-15000 graduates in work. For this, it is estimated that industry would need to recruit:

- 300-1500 graduates per year
- 60-300 Masters graduates per year
- 30-150 Doctoral graduates per year

A spreadsheet with detailed calculations is included in the appendix and available on request.
This is an approximate figure, which we would like to refine with data from industry.

BMW have provided information on staffing levels needed for the i3 production, shown in the appendix. The i3 project alone needed to recruit 20-35 people with composites expertise at the first stage, of whom 15-25 should have masters’ level or higher qualifications or equivalent experience.

At the second stage, they needed an additional 70+ people of whom 30 would need masters’ level or higher qualifications or equivalent experience.

At the final stage, they needed an additional 40+ people of whom 20 would need masters’ level or higher qualifications or equivalent experience.

Therefore, they required 70 people with masters’ level or higher qualifications or equivalent expertise in addition to normal staff turnover, over 10 years. This is an average of 7 people per year plus normal turnover for a project of this size.

Checking the figures

Turnover was ~5% for engineers in the UK in 2017\(^2\). Assuming similar in Germany, 5% of 70 people is 3 or 4 people, so we estimate (errng on the high side) 11 masters’ level or higher persons needed per year for this product, which achieved 16,052 cars or ~£500M for the first full year of sales in 2014\(^3\).

Using that figure we estimate 22 masters’ level or higher persons per £1bn per year which is in the range of 7.5-37.5 Masters or Doctoral level per £1Bn estimated above.

These would not necessarily all be new graduates- but anyone joining BMW to do this work leaves a vacancy elsewhere.

These figures do not include BMW’s investment in its supply chain.

Automotive projects are generally quicker to market than aerospace. It would be useful to obtain figures from a range of sectors to fill this out further. Those two sectors, at very similar amounts, are the largest in the estimated 2030 market, according to the Composites Leadership Forum’s 2016 UK Composites Strategy.

Demand For Training

In order to provide the staff required, it will be necessary to train them. We expect this requirement to drive demand for this level 7 course and training at other levels. It has however been difficult to obtain a clear signal from industry regarding their view of training needs. Conversations to date suggest that industrialists source training when required- this will only be possible if the course exists at the time when it is needed.

NPL provided the below data from an upcoming report, which indicates that current training availability is considered inadequate.

---

\(^1\) XpertHR Labour turnover rates
\(^2\) [https://www.e-days.co.uk/news/employee-turnover-rates-an-industry-comparison](https://www.e-days.co.uk/news/employee-turnover-rates-an-industry-comparison)[online, 30/08/19]
NPL data

“In a cross-sector deep dive workshop that took place in BEIS (March 8, 2019) we asked 41 industrialists across Aerospace, Automotive, Defence, Marine, Infrastructure and Energy (Oil & Gas) to score the available composites related training between 1 (slightly) and 5 (very). The weighted average scores are shown below

With L7 training targeting graduate engineers and above, it is fair to say that the workshop participants felt that the availability of training is below average (i.e., “3” mid-range) for these levels.

The focus of the workshop was on Regulations, Codes and Standards for polymer composites, however, there were a number of more general questions to capture industry’s views.

We (NPL) will publish a report with all the workshop findings.” (Provided by NPL)

Data from previous work

Pickard’s 2018 thesis includes results of Knowledge Transfer Studies carried out with a variety of organisations in the composites manufacturing sector. Note that these organisations may not be considered a representative sample of the industry as a whole.

- The results show a lack of knowledge transfer between academic groups and almost all participating companies.
- Across all participating organisations, ~60% of participants felt they need to increase their knowledge in order to do their job.
- Current taught courses were considered useful by less than half of participants in large companies and SMEs, but over 60% of participants in academia and a research institution.
- Formal training courses were considered the most useful of a variety of options for knowledge transfer over all organisations.
- Results indicated a preference for interpersonal knowledge transfer.
- Web search was also a popular choice when searching for information.
- Very few participants (<30% in all organisations, <10% in larger companies) agreed that their organisation’s current knowledge management practices work well. This includes training.
Composites Teaching in the UK

A mapping exercise was carried out to identify current (2018/19 academic year) composites courses at level 6 and 7 (Masters). Full details can be seen in the appendix.

- 91 courses at level 6 and above are offered by 31 UK institutions
- 71% of courses identified have compulsory composites modules
- Over half (54%) of courses identified are at MSc and MEng level
- The second most popular occurrence is short courses, which account for 22% of all courses identified.

Student numbers can be used to estimate the possible number of trained people who might be added to the workforce by these courses. It should be noted that for the short courses, an expert estimated that only 5% of students are UK based. While some international students join the UK workforce following their courses, many will instead find jobs elsewhere in the world.

It has not been possible to obtain figures for student numbers on all composites specific courses, but the Higher Education Statistics Agency (HESA) have student numbers by category for previous academic years.

In 2017/18, 68% of all students at UK HE institutions on Engineering and Technology courses were domiciled in the UK. For postgraduate courses in Engineering and Technology, the figure is 42% in both research and taught courses, for undergraduate courses it is 76%4.

In 2016/17, 87% of UK domiciled students leaving a postgraduate course joined the workforce, as did 73% of those leaving an undergraduate course5.

Based on these numbers we can reasonably estimate that for MEng courses (undergraduate), 55% of students are both UK domiciled and join the workforce, and for postgraduate courses 37% of students are both UK domiciled and join the workforce.

Over the 31 identified universities, in 2017/18 there were 59185 persons on undergraduate Engineering and Technology Courses (across 4 years) and 12915 persons on taught postgraduate Engineering and Technology Courses. Approximately 30% of the latter are part time, expected to be on 2 year courses.

Based on the numbers above, we estimate that if they all pass, approximately 4000 taught postgraduates and 8000 undergraduates will join the UK workforce from Engineering/Technology courses from the 31 universities each year. The majority of these will not study composites, and many of the undergraduates will take a BEng rather than an MEng.

---

4 https://www.hesa.ac.uk/data-and-analysis/students/what-study [online, 30/08/19]
5 https://www.hesa.ac.uk/data-and-analysis/publications/destinations-2016-17/introduction [online, 30/08/19]
Using the earlier figure of 22 new Master’s level composite engineers per £1 billion turnover and £12 billion turnover in 2030, we would need 264 persons per year, approximately 2.2% of Engineering/Technology graduates who join the UK workforce from the 31 universities.

At the University of Plymouth, there is 1 person in the final year of an MEng with composites content in the 2018/19 academic year. In the year below, 5 of a total 45 persons studying an undergraduate course with composites content are registered for an MEng. Over all year groups there are 96 students on these courses in total, with 8 registered for the MEng. (data from Plymouth, pers.comm.)

If the 1350 undergraduates enrolled in Plymouth’s engineering and technology courses in 2017/18 is typical, approximately 7% are studying a course with composites content and, averaged over the 4 years, 0.6% are expected to graduate with an MEng with composites content.

According to the HESA 2017-18 data, 1840 undergraduates were enrolled on an Engineering/Technology course at the University of Bristol. In the 2018/19 academic year, the optional 4th year unit Composites Design and Manufacture was studied by 50 undergraduates. (data from University of Bristol, pers.comm.) Assuming ¼ of 1840 graduate each year, approximately 11% are expected to graduate with an MEng including the Composites Design and Manufacture unit.

The HESA data states that 1735 taught postgraduates were enrolled at Cranfield University in 2017-18. In 2018-19, Cranfield University have approximately 90 students taking an M-level unit in composites, of whom approximately 50 are carrying out composites related projects for their thesis. (data from Cranfield, pers.comm.) If 1735 is typical, approximately 5% of Cranfield taught postgraduates are taking an M-level unit in Composites and approximately 3% of Cranfield taught postgraduates show sufficient interest in composites to focus on this for their thesis.

As universities may differ significantly, it is not clear how widely applicable these numbers are. Using the Plymouth and Bristol figures as upper and lower bounds for undergraduates, and the Cranfield figure for postgraduates, these numbers suggest that approximately 48-880 MEng and 200 taught postgraduates with at least a single M-level module of Composites training join the UK workforce each year.

**At the lower bound, this would not meet demand even if all these people chose to pursue a career in Composites Engineering.**

Even at the upper bound, this would only meet demand if approximately 1/4 of graduates with at least 1 M-level unit of Composites education chose to pursue a career in Composites Manufacturing.

Over the period 2012/13 to 2016/17, approximately 30% of Engineering/Technology graduates from undergraduate degrees joined the Manufacturing sector as a whole. 59% are recorded as working in “Professional” jobs. A Composites Manufacturing Engineer would fit both of these categories. It is highly unlikely that all of these people are working with Composites.

Finally, it should be noted that a single module at M-level can only cover a limited amount of information, delivering new Composites Engineers who will still need training in the areas most useful to their jobs.

International Benchmarking

Master’s level courses in composites or with a clear composites component from a range of countries are summarised here for comparison to the proposed curriculum. A spreadsheet with full details is included as an appendix, with links to each course. It should be noted that the value of 1 credit is not the same in each country, so the total credits should be referred to when assessing how much of the course is composites related. For European countries, 1 European Credit Transfer System (ECTS) credit is considered approximately equivalent to 2 UK credits or 25-30 hours of study.

These were identified using the findamasters.com website and the resources complied by the University of Plymouth. It should be noted that this is not an exhaustive list, but represents that which is readily accessible to (mostly) English speaking internet users.

This includes 4 courses in France, 3 linked courses at a USA university, 2 in each of Belgium, Germany and Sweden, 1 in each of Australia, Canada, Denmark, Saudi Arabia and Turkey. In addition, one course is collaboratively taught across five universities in four countries (Belgium, Finland, France and Germany).

Of these 19 courses, 8 include compulsory material related to composites and 12 have either compulsory or optional content including at least some composites manufacturing content. The majority are full time, campus based courses, but the USA options are available entirely online. The Saudi Arabian course has a part time option. One of the German courses is designed to be carried out by employed people and taught in blocks, while one of the French courses includes an option to carry out part of the work as paid employment in industry. In addition to these two, seven others offer optional internships.

Collaborative course

The MSc in Advanced Materials for Innovation and Sustainability (Chemistry) is offered by five universities in collaboration: University of Liège, Belgium; Aalto University, Finland; University of Bordeaux, France; Grenoble INP, France; T.U. Darmstadt, Germany. The two years must each be taken at different universities, with the second year being a specialisation. The Composites specialisation is taught at the University of Bordeaux. The degree is jointly awarded by the two universities chosen by each student. The options are limited by the student’s preference for the second year specialisation— for example, to attend the second year at the University of Bordeaux, the students must study for their first year at either Grenoble INP, Aalto University or TU Darmstadt. The Master’s thesis is jointly supervised by the ‘home’ and ‘host’ institutions.

This course also has industrial partners: ArcelorMittal, Luxembourg; Arkema, France; CEA, France; Fraunhofer, Germany; IMEC, Belgium. Students have the option in year 1 to undertake an internship, attend a summer camp working on industry case studies or work on a business model project. In year 2 students can carry out practical work on industrial projects or a business model project.

https://www.u-bordeaux.com/Education/Study-offer/Masters-in-English/Chemistry/Advanced-Materials-for-Innovation-and-Sustainability-AMIS [online, 30/08/19]
Courses with Industrial Content

A majority of the courses offer an optional internship in industry, which may be used as a research project for the Master’s thesis, and some include industrial case studies in the university based programme.

The course Éco-conception des Polymères et Composites (Eco-design of Polymers and Composites)\(^8\) at the Université Bretagne Sud, France, has an option with more industrial content. The second year of the MSc can be spent based mostly in industry. The student spends the first semester alternating between the university and industry, with two weeks at each, and the second semester based entirely in industry. This is a paid job, which may lead to employment after the course concludes, and the work is used towards the student’s project. This option is open to students under the age of 26 and employees or jobseekers over that age who meet certain conditions.

The Textile Engineering\(^9\) course at RWTH Aachen is based at the Institute for Textile Technology (ITA) and has a more industrial focus than most. The course has two pathways, ‘research’ and ‘coursework’, with the latter including topics such as factory planning and production metrology. The students have access to specialised equipment at the ITA. Their research projects are either publicly funded or R&D for industry.

**Professional Development Masters**

The Verbundwerkstoffe (Composites) MSc\(^10\) at PFH Stade Hansecampus, Germany, is intended for persons employed in industry, to carry out a Master’s degree through professional development. In this respect it is planned similarly to our proposed composites curriculum. PFH is a private university.

The students study on campus at the university for blocks of 7-17 day courses, plus some weekend courses. Those who are based at the noted ‘partner institutions’ of Airbus, DLR and Fraunhofer, located near the campus, may find this convenient, but access does not appear to be restricted to employees of these organisations. The part time qualification requires 60 ECTS (~120 UK credits), though an option for a full time course of 90 ECTS (~180 UK credits) is also mentioned - this may be the English variant as it appears to involve more study time. Whether these result in different final qualifications is not clear. Students must carry out their taught units over 2 semesters only, with a third semester for the research project and thesis.

The course is taught in both English and German. The German variant can be studied with significantly fewer days away from work than the English, as more courses are taught at weekends. The German course comprises of one two week block, one single week block and five weekend courses (~31 days). The English course comprises of four 16 day blocks and a single weekend course (~66 days). A business module is taught via distance learning and ‘blended learning’ is also mentioned.

The course is delivered by “Professors with practical experience” and designed to be carried out while working full time. As such, this model is worth further investigation.

---

\(^8\) [https://www.ecoconceptionpolymerescomposites.com/] [online, 30/08/19]

\(^9\) [https://www.academy.rwth-aachen.de/en/education-formats/msc-degree-programmes/textile-engineering] [online, 30/08/19]

\(^10\) [https://www.pfh-university.com/studies/technology/composites-master.html] [online, 30/08/19]
Chinese Universities
In addition to the above, Wuhan University of Technology have kindly supplied a list of 46 Chinese universities who teach composites specific courses, along with details of some of these courses (in Chinese). An expert who teaches Chinese to English translation at the University of Bristol has indicated an interest in working with these documents to produce a summary of which topics are taught where, particularly at a level equivalent to a UK MSc, MEng or MRes, and any industrially applicable teaching methods such as design/build/test projects or placements carried out in industry. Any future project may wish to consider this.

Proposed Composites Curriculum
The proposed curriculum, constructed by experts from a variety of UK institutions, is intended to be both industrially relevant and academically rigorous.

The intention is that the developed curriculum could be delivered by subject matter experts in response to industrial demand; organisations can choose the units most relevant to their business and utilise them as new recruit training or Continuous Professional Development. There may also be an option for individuals to build up credits towards an academic qualification.

Unit Portfolio
There are 5 core units which serve as an introduction to advanced composites. The 54 specialised units, directly relevant to design and manufacture of composite products in industry, are split into 9 blocks of 6, by topic. Each unit involves 2 days of teaching and an optional assignment, worth 2 credit points at Masters level.

An organisation can choose either a full course structure or individual units to fit their requirements.

List of units
Core (5 units)
- Introduction
- Composite Constituents
- Manufacturing of composite products
- Product design
- Properties of composites

Materials (6 units)
- Polymeric matrices
- Polymer melt viscosity and chemorheology, cure and degradation
- Fibres and moulding compounds
- Characterisation techniques
- Dry fabrics and prepregs
- Characteristics of fabric reinforcements- drape, conformability, permeability etc
Product Design A (6 units)
- The design cycle and requirements capture
- Costing in a design environment
- Drawing practices and lay-up rules
- Design for manufacture
- Acceptance criteria, rework, concessions- designing out defects
- Standards and Certification

Product Design B (6 units)
- Micromechanics
- Laminate design and analysis
- Stress analysis - classical
- Stress analysis – Finite Element Analysis
- Joints – bonded, bolted, 3D structures
- Damage tolerance

Manufacturing Processes A (6 units)
- Reinforcement manipulation and preforming
- Contact moulding: hand lamination and spray
- Prepreg processes: vacuum bag
- Prepreg and SMC processes/compression moulding
- Resin transfer moulding
- Resin infusion processes

Manufacturing Processes B (6 units)
- AFP and ATL
- Rapid prototyping and additive manufacture
- Filament winding and pultrusion
- Thermoplastic matrix processes
- Process automation
- Processes for Ceramic Matrix Composites and Metal Matrix Composites

Manufacturing Operations A (6 units)
- Production costing
- Process design
- Process modelling
- Process monitoring, Quality Assurance and Quality Control
- Process planning
- Tooling design and manufacture

Manufacturing Operations B (6 units)
- Joining and assembly
- Factory design and layout
- Lean, Six Sigma and similar methods
Tolerancing, variability and defects
Machining composites
Surface finishing and painting

Performance A (6 units)
- Mechanical properties and testing - anisotropic elasticity
- Mechanical properties and testing - static strength, failure modes and failure criteria
- Mechanical properties and testing - dynamic and fatigue, crashworthiness
- Durability: weathering, moisture diffusion, osmosis and blistering and galvanic corrosion
- Non-structural properties - erosion, wear, electrical and thermal properties
- Fire and post-fire performance of composites

Performance B (6 units)
- NDE, condition monitoring, structural health monitoring and in-service inspection
- Multifunctional composites
- In service damage and repair
- Recycling and reuse
- Sustainable composites
- The broad perspective on composites.

Schematic
The course structure is shown in the diagram below.
**Example Combinations**

For organisations requiring a full course, this can be tailored by choice of blocks or units. Examples of a Product Design led combination (left) and a Manufacturing led combination (right) are shown below.

---

**Reviews**

The unit descriptions and overall curriculum were reviewed by both academic experts and, on behalf of industry, the National Composites Centre.

It was noted that learning outcomes should be checked for consistency and all should be at M-level. Some units may require prerequisites. This should not be a specific course, but necessary knowledge--for example, if the student needs to be familiar with differential equations this should be mentioned. It was not considered a problem if a small number of units require a mathematical background as no individual will need to complete all the units, but they should be kept broadly accessible where possible. It may be reasonable to provide some pre-course reading if students are likely to need reminding of mathematics that they have not seen since their school days.

Some unit descriptions were commented on in more detail by academic reviewers, to ensure all required content is covered.
Resources developed to date

Contextual learning objects

Case studies and other resources
A series of web elements have been prepared which can be loaded into webpages elsewhere using the iframe capability in HTML

- The **Composites Courses**\(^{11}\) web element provides links to appropriate training and education for composites in the context of Schools, Apprenticeship, Colleges and Universities, and further links for careers, continuing professional development, professional accreditation and ultimately professional recognition.

- The new **Case Studies**\(^{12}\) web element brings together links for over 100 individual webpages describing applications of composite materials, categorised under Aerospace, Architecture, building, civil and structural engineering, Automotive, Bridges and walkways, Chemical plant, Defence, Delivery solutions, Design, materials and miscellaneous, Furniture and fittings, Machinery, Manufacturing processes, Marine and watersports, Modelling, Renewable energy, Railways, Sports

- The new **Composites Resources**\(^{13}\) web element provides links to Books/chapters (as free downloads), Best Practice Guides, Conference series archives, Coventive Explains series, JS' virtual books, Kindle books at £10 and other on-line resources.

- The new **Videos**\(^{14}\) web element provides links for a selection of videos which might help understanding of the respective concepts.

- Further, a pre-existing resource identifying **Review Papers**\(^{15}\) relevant to composites design and manufacture has been continuously updated.

Images, Videos and Physical Objects

The University of Bristol have compiled a catalogue of images and videos which can be used in this curriculum. Many of the images are photographs of physical objects currently held at the University of Bristol which demonstrate important aspects of composites manufacturing.

**Videos of lectures**
The majority of lectures delivered as part of the third pilot- *Tolerancing, Variability and Defects* and *Production Costing* - were recorded, with permission from attendees. Clips from some of these lectures have been included in the second version of the slides, using the lecturer’s anecdotes to illustrate points.

\(^{11}\) [https://www.fose1.plymouth.ac.uk/sme/composites/courses.php](https://www.fose1.plymouth.ac.uk/sme/composites/courses.php) [online, 30/08/19]

\(^{12}\) [https://www.fose1.plymouth.ac.uk/sme/composites/case_studies.php](https://www.fose1.plymouth.ac.uk/sme/composites/case_studies.php) [online, 30/08/19]

\(^{13}\) [https://www.fose1.plymouth.ac.uk/sme/composites/resources.php](https://www.fose1.plymouth.ac.uk/sme/composites/resources.php) [online, 30/08/19]

\(^{14}\) [https://www.fose1.plymouth.ac.uk/sme/mats347/videos.php](https://www.fose1.plymouth.ac.uk/sme/mats347/videos.php) [online, 30/08/19]

\(^{15}\) [https://www.fose1.plymouth.ac.uk/sme/mats347/ReviewPapers.htm](https://www.fose1.plymouth.ac.uk/sme/mats347/ReviewPapers.htm) [online, 30/08/19]
Knowledge Capture Interview

A Knowledge Capture interview was carried out with Professor Kevin Potter, an expert who retired during the course of the project. Prompts based on questions from current and former IDC students- who carry out their research projects in industry were used as starting points, from which Professor Potter talked about his experiences, interesting anecdotes and his opinions regarding composites manufacturing. Following the principles of knowledge capture during exit interviews, Professor Potter was encouraged to talk through his thought process, use examples, compare different options and give a clear final message. It is recommended that the interview be transcribed, and split into short clips based on topic, which can be used in lectures or other teaching resources as with the videos above. It would also be worth producing a full length video of the interview, edited for pauses and the interviewer’s questions, for those who are interested to watch.

These resources are available on request.

Example units

Draft versions of core unit material were developed for the first pilot. Approximately half of core unit 1 was then refined and re-developed for the second pilot. Two full example units were developed in full, save for the assignment, for the third pilot. All of these were carried out by Professor Kevin Potter at the University of Bristol.

In addition, Dr Nuri Ersoy of the University of the West of England and Dr Stefanos Giannis of the National Physical Laboratory each developed a single example unit.

The time required to develop each of the four full example units was recorded by each unit director. This is used to refine estimates of the resource requirements for developing the full curriculum. The four units each cover significantly different topics and types of teaching- for example, some require hands-on exercises while others use computer based exercises- and were developed in three different institutions, so taken together these are considered to provide a reasonable estimate of likely resource requirements for the whole curriculum.

List of example units

Unit 2-6 Standards and Certification
This was developed by Dr Stefanos Giannis and colleagues at the National Physical Laboratory.

Unit 6-1 Production Costing
This was developed by Professor Kevin Potter and Dr Carwyn Ward at the University of Bristol and was delivered to a trial class at the National Composites Centre. A second version of the slides and class exercise was created in response to feedback from the trial.

Unit 7-4 Tolerancing, Variability and Defects
This was developed by Professor Kevin Potter and Dr Michael Elkington (practical component) at the University of Bristol and was delivered to a trial class at the National Composites Centre. A second version of the slides was created in response to feedback from the trial.

Unit 8-1 Mechanical Properties and Testing – Anisotropic Elasticity
This was developed by Dr Nuri Ersoy at the University of the West of England.
Three pilots were carried out using draft course material. Pilot 1 and Pilot 2 used material from the core units, while pilot 3 was a full-scale trial of two units from the main curriculum.

Pilot 1- NCC Composites Conversion Course

The NCC Composites Conversion Course is intended for persons experienced in working with other materials. Advanced composites require a very different approach to, say, metals, through the whole design, manufacture and test process.

The pilot for the NCC course was delivered in April 2018. This included material from initial drafts of the five core units of this Composites Curriculum. No formal feedback was gathered, but informal responses were very positive, supporting the decisions made regarding the content of the core units.

Pilot 2- UWE CPD Course

In February 2019, Professor Kevin Potter delivered a condensed version of approximately half the material in core unit 1, Introduction to Composites, as part of a Continuing Professional Development Course at the University of the West of England. *An Introduction to the History and Manufacture of Composite Materials* was a 1 day course. 3 hours of lectures were supplemented by handling physical samples of composite parts, test coupons and materials as well as a question and answer session.

The 10 attendees, including the UWE academic who arranged the course, completed an anonymous feedback questionnaire. Utilising a mixture of quantitative ratings and space for opinions to be expressed, this questionnaire was intended to identify both problem areas and those aspects which worked well. The questionnaire also included demographic questions regarding the number of years’ experience the respondent has in science/engineering in general and composites in particular, and the nature of their job. No personal details were collected.

Only one attendee declared prior experience working with composites. In science/engineering in general experience ranged from a student with no industrial experience to 17 years. 8 of the attendees had 5 years or more of experience in science/engineering, of whom 3 declared over 12 years’ experience.

The feedback was largely positive, with 8/10 rating their enjoyment of the course positively and 2 neutral. The majority (8/10) considered the course interesting and expected to refer back to their notes in future, despite the fact that few thought the topics relevant to their work.

Areas for improvement were also identified- most participants felt there was too much content for the time available and slides were considered overly verbose.

9/10 attendees thought the content made sense, the lecturer was easy to understand and considered the industrial examples included in the slides and handling composite parts beneficial. Half the students chose one of those two aspects as their favourite part of the course. No-one rated the course too easy, with the majority placing the level at ‘perfect’. 4/10 considered it difficult, though none excessively so.

6/10 participants were interested in learning more about advanced composites, likewise 6/10 were interested in the concept of adding up points from such a course towards an academic qualification. However only 3/10 thought an optional assignment would be useful to consolidate the learning.
Pilot 3- 2 units at NCC

Two units from the main curriculum were delivered in full at the National Composites Centre in late March and early April of 2019. Each unit was taught by Professor Kevin Potter, with contributions from colleagues, over two days, following development of the material specifically for this purpose.

This final pilot served as the most realistic trial of this curriculum to date. Participants were staff members from NCC and manufacturers of advanced composite components in the aerospace industry. The only aspect not included was the optional assessment, as we are unable at this time to offer credit points towards an academic qualification.

As the units were delivered free of charge and were advertised only to NCC member companies at short notice, the level of interest and companies represented cannot be considered representative of the general case. The majority of participants were from larger companies. Participants were asked to fill out a feedback form similar to that used for Pilot 2.

Unit 7-4 Tolerancing, Variability and Defects, from the Manufacturing Operations B block, was trialled in March 2019. All lectures and classroom exercises were delivered by Professor Kevin Potter and the practical session was led by Dr Michael Elkington. 14 of the 16 attendees filled out the questionnaire, all but one of whom currently work with advanced composites. Experience in composites ranged from none to 8 years, with the majority having 1-5 years’ experience. All attendees had 2 or more years’ experience in science/engineering in general, up to a maximum of 18 years, with most in an 8-12 year band.

Unit 6-1 Production Costing, from the Manufacturing Operations A block, was trialled in April 2019. The first day of lectures and classroom exercises was delivered by Professor Kevin Potter, the second day-including the ‘Virtual Composites Company Spreadsheet’ was delivered by Dr Carwyn Ward. 6 of the 8 attendees filled out the questionnaire. 4 declared that they currently work with advanced composites. Two people recorded over 15 years’ experience with advanced composites and over 24 years in science/engineering in general.

Summary of Participant Feedback

No participants worked exclusively hands-on, with most spending some time in computer based work.
Over all three courses where data was collected, there was a large range of years’ experience in science and engineering among participants.

The majority of participants had relatively little experience with composites, none at all, or did not say.
Overall rating of the courses

No ratings of less than 6/10 were received. 4 participants did not answer this question. Of the total 30 questionnaires, no participants stated that they did not enjoy the course. 4 gave a neutral rating, 20 said ‘yes’ they enjoyed it (including all 6 from Production Costing) and 6 selected ‘amazing’.

Level of difficulty

Using the same colour scheme as above- the majority of participants rated the level of difficulty as ‘perfect’ by placing a mark on the above scale. None went outside the ‘easy-difficult’ range. None of the students on the introductory course considered it easy, and no-one found the production costing course difficult.
Key comments on content

The free text questions regarding students’ favourite and least favourite parts of the courses, topics they would like to know more about and suggestions for improvement elicited a range of responses, which are all available in the spreadsheet. As the three courses are different these are difficult to compare, but some general points can be made:

- No negative responses to “Did you enjoy the course?”
- The practical exercises and industrial examples were popular
  - “The practical section of laying up prepreg was very useful. This made it clear how difficult it is to avoid defects with some geometry”
- There is demand for worked examples and case studies
  - “More group problem solving to discuss real life issues as these help the understanding of the presented material” “Can do with more examples!!”
- We need to make the level of the course and any expected prior knowledge clearer
- There was demand to add material which fits in other units- when the full curriculum is available it will be possible to refer students to the relevant units.

Some more relevant quotes:

- “Make easier to understand slides, less text, more figures and graphic examples”
  - This was a very popular point. The most common complaint was that the slides were too verbose. This is one of the main issues being tackled in creating version 2 of the Production Costing and Tolerancing, Variability and Defects teaching material.
- “It’s easier to learn when you have time i.e. not working”
  - The course is useful, but completing assignments might be difficult for students whose employers cannot afford to lose them. This is particularly relevant for students from SMEs, who are less likely to have other employees who can cover for the student.
- “Kevin’s industrial expertise is invaluable. If the presenter just followed the slides it could be boring. Kevin’s anecdotes & tips/gems are key to this”
  - This quote, and other comments along these lines, demonstrate the value of having an expert carrying out the teaching- someone who can answer questions and come up with relevant examples from their working career. This suggests that a train-the-trainer model may not be appropriate for courses at this level.

Overview of participant opinions

Participants were asked to rate their level of agreement with a set of statements on a Likert scale, from -2 (disagree) to +2 (agree). The graphic overleaf shows those who indicated agreement, at +1 or +2, with the statements, coloured by their years of experience in science/engineering.
An optional assignment would help to consolidate what I have learned. I would be interested in adding up points from courses like this towards an academic qualification.
<table>
<thead>
<tr>
<th>Statement</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>Blank</th>
</tr>
</thead>
<tbody>
<tr>
<td>The course was interesting</td>
<td>2</td>
<td>12</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The content made sense</td>
<td>2</td>
<td>17</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The topics we covered are applicable to my work</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>The industrial examples were a valuable inclusion</td>
<td>1</td>
<td>8</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The practical aspect was beneficial (Seeing and holding composite parts</td>
<td>6</td>
<td>3</td>
<td>20</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I have more questions now than before attending the course</td>
<td>3</td>
<td>5</td>
<td>12</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>The lecturer was easy to understand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The slides are well laid out</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>13</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I had sufficient opportunity to ask questions</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>There was too much content for the time available</td>
<td>3</td>
<td>11</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>I would like to learn more about advanced composites/other topics in</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>composites manufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>My company would benefit from (more) training in advanced composites</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>8</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>An optional assignment would help to consolidate what I have learned</td>
<td>2</td>
<td>3</td>
<td>7</td>
<td>13</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>I would be interested in adding up points from courses like this</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>
The highlighted points indicate demand for an academic qualification from 2/3 of participants and show that over half of participants see an assignment as valuable for consolidation of learning.

All but one participant (who was neutral) agree that the industrial examples are useful, demonstrating that such examples should be included in all units. It should also be noted that there were no negative responses to the statements ‘The course was interesting’, ‘The content made sense’ and ‘The lecturer was easy to understand’.

Most participants thought they would refer back to their notes. Providing good quality material is important here, particularly if the text on the slides is reduced, as students may not have time to write sufficient notes themselves. For this reason, the lecture slides being modified for ease of viewing will be accompanied with a written document based on the original text, so that the detail is not lost.

Most participants expressed an interest in learning more and felt that their companies would benefit from training in advanced composites.

Delivery of Curriculum

Resource requirements for material development
Prior to the trial units, the following estimate was used:

At 30 minutes to create a slide, 30-40 slides per hour of lecturing, it takes approx. 125 person-hours for 7 hours of lecturing. This is 2.5 to 3 days of work for an hour’s lecture.

The 125 person-hours is doubled to allow for class exercises, practical activities, assignments and other non-lecture items, giving approximately 250 person-hours per unit, or ~ 35 person-days to make a unit, assuming the person starts with no previously prepared material available.

This results in approximately 2000 person-days for the whole curriculum, or ~10 person-years of work time.

Estimates from other sources vary, with NPL suggesting 25 hours’ preparation for 1 hour in the classroom, so 300 person-hours per unit, ~43 person-days. By contrast, UWE estimated that a single expert could prepare a unit of material in 12 days, broken into 6 days for slides, practical and a mini assessment and 6 days for creating illustrations for the slides. It is possible that this expert had material from elsewhere which could be used.

Results of example unit development

Tolerancing, Variability and Defects
Professor Kevin Potter reported that the Tolerancing, Variability and Defects unit took 60 hours of development, based on modifying existing materials rather than starting from nothing. The resulting slides were then modified, by more junior persons with composites knowledge, to produce a more visually attractive and easier to read set of slides plus a reference document containing all the additional text. This took 48 hours. In addition, Dr Michael Elkington developed the plan and guidance for the practical session. The total development time for this unit is estimated as 120 hours, and it should be noted that this did not start from nothing.
Production Costing
1 day (“half”) of the Production Costing unit took Professor Potter 30 hours, with the second day developed by Dr Carwyn Ward. Again, this was based on modifying material which was already available. The slides were likewise modified following the trial unit and a worked example for the Virtual Composites Company spreadsheet was produced. For this unit the modification work took 86 hours. The total development time for this unit is estimated as 150 hours.

Mechanical Properties and Testing: Anisotropic Elasticity
Dr Nuri Ersoy delivered a set of slides and suggested assessment following the 12 days of work. At 6 hours per day this is 82 hours. There are significantly fewer slides than in the above two lecture packs, though it is likely that more time will be spent on laboratory sessions for this unit. This material would optimally have an accompanying text and/or recording of an expert delivering the material for later reference. Based on feedback from the pilots, inclusion of industrial examples would be beneficial.

The assessment refers to practical testing which would be carried out either by the students or a suitably trained demonstrator as part of the 2-day course. For this topic a practical component is vital. The assessment will involve interpretation of the results. The suggested assessment allows combination with other units (e.g. producing panels in one unit to cut into test coupons for another), which could help students to appreciate the bigger picture but may not always be practical- for example, not all students will take the same units and they may not always be geographically or chronologically convenient. The assessment can also be standalone.

Standards and Certification
NPL developed the Standards and Certification unit following a different model. Three experts developed the technical material, which was then passed to their internal training team for conversion into slides.

This unit includes three exercises, all of which involve planning trials based on the principles presented in the lessons. Practical testing and data analysis are included in some of the exercises. In principle, following the example of Mechanical Properties and Testing: Anisotropic Elasticity, these exercises could form the basis of an assessment. The exercises require use of relevant standards. The standards are not included in the material provided, due to IP restrictions, but students on this unit will reasonably require access to standards in order to learn how to read and apply them.

Summary

<table>
<thead>
<tr>
<th>Unit</th>
<th>Institution</th>
<th>Time</th>
<th>Cost</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerancing, Variability and</td>
<td>Bristol</td>
<td>120</td>
<td>£3252</td>
<td>245 slides, 6 handouts, practical session</td>
</tr>
<tr>
<td>Defects</td>
<td>(internal)</td>
<td>hours</td>
<td>(estimate)</td>
<td>guide</td>
</tr>
<tr>
<td>Production Costing</td>
<td>Bristol</td>
<td>150</td>
<td>£3974</td>
<td>255 slides, 7 handouts, worked example for</td>
</tr>
<tr>
<td></td>
<td>(internal)</td>
<td>hours</td>
<td>(estimate)</td>
<td>calculation spreadsheet</td>
</tr>
<tr>
<td>Mechanical Properties and Testing: Anisotropic Elasticity</td>
<td>UWE</td>
<td>82</td>
<td>£7678</td>
<td>135 slides + new diagrams, practical guide/assessment</td>
</tr>
<tr>
<td>Standards and Certification</td>
<td>NPL</td>
<td></td>
<td>£42250+VAT</td>
<td>309 slides, 3 exercise guides, calculation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>spreadsheet + instructions</td>
</tr>
</tbody>
</table>
The units developed by academics at the University of Bristol and University of the West of England all took significantly less time than the initial estimate, but in each of these cases the academic had access to material prepared for other courses to modify, reference or use as a starting point. The Virtual Composites Company spreadsheet used in Production Costing is an existing teaching aid.

The time taken for producing the initial teaching material is similar for three units, being ~60-70 hours for the two Bristol units and 82 hours for the UWE unit. As the UWE unit required production of new graphics and illustrations it is to be expected that this should take longer. The greater cost of the UWE unit is likely to be due to the difference between in-house work at Bristol and external work for hire from UWE. Bristol costs were estimated from the internal costs applied to the project.

The post-pilot modifications to the Bristol units added significantly to the time- though less to the cost as these were carried out by more junior staff. The slides are visually improved, making them easier to follow, and the addition of handouts for later reference by the students will be valuable. It should be noted that the handouts produced for Production Costing were formatted as standalone documents and edited/rewritten for readability, whereas those produced for Tolerancing, Variability and Defects were largely copied verbatim from the original slide set. Production Costing also included addition of a worked example, something demanded in student feedback.

It should be expected that any course will need some modification following pilot delivery, and addition of handouts or other supplementary material would be valuable for all units.

The Standards and Certification unit was notably more expensive, but developed following a very different method. The total time taken is not yet known, but given the number of people working on the project and the likelihood of not having previously written material this can be expected to have taken significantly more person-hours.

It should be noted that quantity does not equal quality- for example a course with more lab work is expected to require fewer lecture slides.

Future development will require a set of ‘known good’ teaching material to act as a model, and/or more detailed guidelines. The very different outputs of the example units demonstrate this need. As a first task, any follow on project should decide on what a ‘good’ unit requires.

Models for delivery
Feedback from the pilot units demonstrates the value of learning from an expert. It is proposed that the units be delivered in response to demand, with experts travelling to a location convenient for the students. Options for the location depend on the unit- Production Costing could reasonably be taught anywhere with a suitable meeting room, whereas Fire and Post-fire Performance can realistically only be taught at the University of Bolton due to their unique facilities. Most units will be accessible at a range of sites, with the National Composites Centre in the south, and Advanced Manufacturing Research Centre in the North, being good locations for accessing equipment in many cases.

It is of course possible to create videos for off-site teaching, but these are no substitute for hands-on experience and engagement with experts face-to-face. For the students to gain as much as possible from these units, it is recommended that the practical aspects should be considered vital. Both the feedback
from the trial units and a wealth of literature on the value of learning by doing (I can add references here if necessary) attest to this.

A train-the-trainer model was discussed, but it was considered inappropriate for material at this level, and unlikely to deliver comparable results to teaching carried out by an expert. A network of experts, willing to travel, is in itself beneficial to improving knowledge transfer in composites manufacturing, particularly between academia and industry. Results presented in Pickard’s 2018 thesis demonstrate that for the companies who took part in the presented knowledge transfer study (mostly SMEs) staff did not report any learning from persons in academia or a research institution. The same work shows a clear preference for interpersonal learning, supporting the assertion that opportunity to converse with and question an expert in person is something worth having.

Part of the rationale behind this project was to capture knowledge from those soon to retire. An excellent example is Professor Kevin Potter, co-lead on this project with wide industrial experience and teacher of the pilot units, who has now retired. His anecdotes were considered a highlight of the taught units. With his permission, video clips of him telling some of the most amusing and enlightening stories will be embedded into the slides so that future students can benefit. In general, it would be worth recording these units- and perhaps interviews with experts- for this purpose.

Videos, lectures slides and supplementary material can however be made available for later reference online. Most participants in the trial units thought they would refer back to notes and handouts, so making this material available for reference is clearly of value and would be helpful to anyone choosing to attempt assessments. An alternative would be an online resource which could reflect technical developments after the delegate attendance. As the courses are likely to be delivered on a paid-for basis, it may be advisable to keep this in a secure area and provide a login to participants. Options such as time-limited logins and companies paying for access to the material should be discussed when the future IP model is decided.

Assessments, academic qualifications and accreditation

Assessment
The role of assessment is dependent on context. Within an established degree programme, assessment is an essential prerequisite of the formal qualification. However, in the context of Continuing Professional Development (CPD), many delegates to short courses may not appreciate the value of assessment and certification for consolidation of their learning and formal recognition of achievement, rather than simply attendance. Further, where the CPD is in a commercial/industrial context, the institution funding the training may simply want an enhanced skill set on the shop floor now without enabling time for formal assessment.

If a formal qualification at Master’s level is to be offered, there is unlikely to be time to carry out full assessments during the unit delivery- and as an optional element, this would not be a good use of time. Participants choosing to pursue the qualification would therefore carry out the assessment remotely over a set period of time, ideally in and linked to their employer business.

Current assessment methods may be suitable for use here, or able to be modified.
Integrated Learning Package, University of Bolton

One model that has been suggested is the Integrated Learning Package, developed by the University of Bolton for remote assessments. This is a three part assessment which may have different deadlines for each part and can be carried out remotely. The assignment includes a list of references. The lecturer is expected to offer help via email, phone and post during the period of assessment. The assignments are typically limited to 4000 words.

Part 1, typically 20 marks out of a total 100, contains short answer questions and/or simple problem-solving exercises, intended to develop comprehension of the material. This should be relatively easy for the student and act as a confidence booster.

Part 2, typically 30 marks out of a total 100, consists of in-depth problems with structured questions, intended to develop problem solving skills, and/or a comprehension exercise from a published scientific work.

Part 3, typically 50 marks out of a total 100, is a case study where the student must work independently to propose a solution to a novel problem. This may be an essay question and/or a laboratory study.

For the unit 8-6 Fire and Post-Fire Performance of composites, Professor Kandola suggested a slightly altered version of the ILP could be used as follows: “The ILP consists of two components in which Part 1 examines the candidate’s basic understanding of the concept, principles and awareness of the module, Part 2 probes and investigate selected classes of answers which are designed to reflect deep understanding of the subject.”

Industrial Doctorate Centre Assessments, University of Bristol

Written and computational assignments

The majority of units are assessed using written assignments. These are mostly in-depth questions requiring the student to demonstrate understanding and independent thinking. They may be structured with sub questions or not, and often require reference to external sources of knowledge. Some references are given, but students are also expected to conduct independent literature based research.

Written assignments may include industry focused tasks such as producing risk assessments or manufacturing instruction sheets. They may also involve writing up, interpreting and discussing practical work carried out during the unit.

Students may be required to carry out computer based tasks such as simulations and report on these, the simulation files may also be submitted as part or all of the material to be assessed. This requires the students to have access to software licenses and appropriate computing resources. For the IDC, laptops and limited licenses are supplied to students.

Presentations and videos

Some units are partially assessed by presentations delivered in person or by videos submitted by the student. It is possible that presentations could also be delivered over an online conferencing system, but this requires the student and assessor to be available at the same time. Student produced videos negate this problem but does not allow the assessor an opportunity to question the student on their presented work. Student feedback suggests alternatives to written assignments are welcome.
The Laminate Analysis unit is assessed by an online test in Blackboard. The lecturer creates a large number of possible questions, which are placed into pools. The system then draws questions from each pool to create a test according to a plan specified by the lecturer (e.g., 2 questions from pool 1, 3 questions from pool 2). Mathematical questions can be varied according to simple formulae, where the lecturer sets a range of values for each variable. This ensures that two students taking the test simultaneously cannot work together, as they each receive different questions. Questions can include photos (Flickr), videos (YouTube) and presentations (SlideShare).

Given orthotropic elastic modulus, $G_{12} = [G]$ kN/mm² for a UD composite, estimate the corresponding percentage failure strain values for the ply strength $G_{12} = [S]$ N/mm², adding 10% to your estimate if you would expect an underestimate due to the assumption of linearity.

16 Screenshots from online test included with the kind permission of Dr Ian Farrow
The students take the test at the same time, remotely, though there is an option to delete marks and allow a student a second try if technical problems such as internet connection failure affect their result. The nature of the test system means a second try is highly unlikely to be the same as the first.

The first part of the test is short questions, which can be automatically marked. Types of question include inputting numerical answers, multiple choice, selecting true or false statements, fill in the blank, matching pairs of statements or ordering lists.

The second part of the test is a set of questions on a case study. The students are able to read information pertaining to the case study prior to the test. Here the students are expected to carry out calculations, draw sketches etc by hand. They then write a summary of their method and any numerical answers in the online test. It is also possible to photograph their handwritten notes for uploading. This part of the test cannot be marked automatically.

The students are given a trial version of the test, with a limited number of questions, so that they can familiarise themselves with the interface. If there are sufficient questions in each pool, they are unlikely to encounter repeat questions in the assessment.

It is possible to restrict the time available, and to allow extra time for students who require this.

Student feedback has been largely positive, though some felt the test too long for the time available. The group (6 persons) were evenly split as to whether they preferred a test like this or a written assessment. Technical comments included difficulty in inputting equations, which can be solved by uploading photographs of handwritten work, and a request to be allowed to move back and forth between questions rather than completing them in order. Blackboard help pages suggest that this is possible, but using this setting means the test cannot be resumed if the student is accidentally disconnected or presses the back button in their browser.
Undergraduate Assessments, University of Plymouth
The University of Plymouth assesses undergraduates through both examinations and coursework.

The examination for Composites Design and Manufacture lasts three hours and consists of 6-8 equal value questions, from which the student may select 4. Each question is split into numerous sub-questions, some of which test memory of key facts while higher mark items require discussion and/or calculation, allowing the student to demonstrate their understanding.

The coursework for the same unit involves practical group work followed by an individual report.

The Composites Engineering coursework is an extended design, build and test project. Each student creates a specification and theoretical design and manufacturing plan. The group then agree the design, manufacturing and testing programme, before carrying this out, which may include numerous prototypes. Reports are then written individually.

Home Laboratory, Queen Mary University of London
QMUL’s Home Laboratory is a piece of experimental coursework which can be carried out in the home without specialised equipment. The example provided involves creation of ice composites using easily available fibres and a home freezer. These ice composites are assessed and compared to unreinforced ice through mechanical testing. The student is expected to design and construct apparatus for quantifiable tests using items found around the home, encouraging inventive problem solving and practical skills, then to write up the result in the manner of a scientific paper, with consideration of relevant theory.

MSc Composites assessment, University of the West of England
This coursework is split into two tasks. The first requires the student to construct a spreadsheet for various laminate analysis calculations. This spreadsheet is submitted for marking as the task 1 deliverable and used in task 2.

The second task is a design exercise, requiring independent reading and application of theoretical concepts. The student is expected to use the aforementioned spreadsheet and Abaqus in the design process and should submit a report and the Abaqus files.

The coursework can be carried out remotely provided the student has access to the required software on a computer capable of running it.

Continuing Professional Development vs exit qualifications for HEFCE Catalyst multi-site M-level qualification
There is a desperate need for composites Training Needs Analysis (TNA) to quantify industrial demand and hence indicate numbers of students/delegates likely to participate in the training. The industry driver is to enhance the skill set on shop floor, often as a short-term solution. Similarly design office workers may need understanding of limitations set by design and manufacture. In that context any individual modules may address the immediate needs of the employer without commitment to a full formal
qualification. A certificate of attendance may be adequate for the employer, although some acknowledgment of competence may be preferred.

The employee with a commitment to career progression may be interested in more formal recognition of the Continuing Professional Development, especially when working towards Incorporated/Chartered Engineer/Environmentalist/Scientist status. Existing CPD courses—mostly not at Masters level—may be recognised for these schemes.

Where CPD is delivered by an academic institution, accumulation of credits may result in Post-Graduate Certificate (PGCert ~ 60 credits), Post-Graduate Diploma (120 credits) or Masters (180 credits). Masters is often split 120:60 (MSc: Master of Science) or 70:110 (MRes: Master of Research) with the ratio indicating the credit split for taught modules:dissertation. The latter, with taught modules combined with a workplace-based dissertation, may be an attractive model for industrial delegates.

For personnel in small- or medium-sized enterprises (SME), there will be a significant challenge in completing a formal academic qualification on the timescales required by the academic institution. 30 two-day units is of the order of 25% full-time equivalent (FTE) of the working year which could be a significant reduction in manpower for such a company, even spread over a two-year part-time study, and especially where that individual is the only person in the company with specific technical expertise.

It is implicit in the collaborative model under consideration here that modules may be delivered in more than one institution, especially for specialist modules hosted by institutions with unique facilities, e.g. fire at Bolton. This raises the Spectre of a student having a collection of credits from different institutions. The classic models for inter-institution collaboration were Credit Accumulation and Transfer Scheme (CATS) or Integrated Graduate Development Scheme (IGDS, formerly funded by EPSRC as a vehicle to provide modular part-time education/training for graduates in industry but the scheme closed about 15 years ago).

It may be necessary for the awarding institution to consider either of Accreditation of Prior Certificated Learning (APCL) for credits gained elsewhere, or Accreditation of Prior Experiential Learning (APEL) for appropriate experience, respectively for a student to gain an exit qualification. Many universities recognise European Credit Transfer System (ECTS) credits for courses involving study abroad, where 1 ECTS credit is considered equal to 2 UK credits.

Technical Accreditation Scheme, Warwick
WMG at Warwick hosts the Jaguar Land Rover Lifelong Learning Academy. This is intended to tackle a skills gap in the automotive industry, with a focus on hybrid vehicles, embedded and electronic systems.

Jaguar Land Rover worked with WMG and nine other universities to deliver M-level training modules for engineers, which can result in an MSc. The Technical Accreditation Scheme uses experts to deliver five day units based on campus, using practical and classroom exercises alongside other teaching styles, with discussion encouraged.

17 https://warwick.ac.uk/newsandevents/pressreleases/jaguar_land_rover_launches_lifelong_learning_academy_with_wmg_as_partner/
18 http://wrap.warwick.ac.uk/67863/
Some taught elements were delivered by experts from industry. It was stated that their relative lack of teaching experience limited the effectiveness of some teaching, but their experience was very valuable and students gave favourable responses when asked. Where a course is taught by a person from a particular company, to students from that company, it can become too specific to their business processes.

The assessment required students to find and talk to technical experts within their company. This facilitates development of a knowledge network and is worth considering when developing assessments for the composites curriculum. While the assessment was stated to be compulsory, submission rates varied considerably between modules. It was found that many students did not appreciate the value of the assessment in consolidating their learning, hence those who were not interested in an academic qualification considered it unnecessary.

This scheme was later expanded to include other employers through the Advanced Skills Accreditation Scheme, which follows a similar model of individual units to that suggested for the composites curriculum. Each unit is individually accredited, and these credits can be added up towards a postgraduate qualification.

Modules are valued at 10 or 15 CATS (Credit Accumulation and Transfer Scheme) points, with 1 point equal to 10 hours of study, and each module has a compulsory assessment. The student registers for individual modules at the appropriate host universities. A Chosen University, which must provide a minimum of 50% of the total CATS points, can recognise modules from the other universities through the CATS scheme and award an appropriate qualification. However, we have been informed that the CATS scheme is no longer available.

**Degree Apprenticeship**

A level 7 degree apprenticeship or ‘mastership’ may be a suitable option for some students, though the units should remain open to those who wish to study through a different route. Degree apprenticeships combine on the job learning with study, often through day release or block release. The apprentice must spend at least 20% of their time studying. The degree apprenticeship funding might cover a Post-Graduate Diploma; the student would have the option of taking an extra 60 credits for an MSc, perhaps through a dissertation based on their employment.

It may be possible to create a new standard for Composites Manufacture, or to add modules to the existing Postgraduate Engineer degree apprenticeship standard. This standard suggests a typical apprenticeship should last 24-30 months. The University of the West of England (UWE) currently offer this apprenticeship.

---


20 [https://www.instituteforapprenticeships.org/apprenticeship-standards/post-graduate-engineer/](https://www.instituteforapprenticeships.org/apprenticeship-standards/post-graduate-engineer/)

21 [https://www1.uwe.ac.uk/business/degreeapprenticeships/currentdegreeapprenticeships/postgraduateengineer.aspx](https://www1.uwe.ac.uk/business/degreeapprenticeships/currentdegreeapprenticeships/postgraduateengineer.aspx)
Degree apprenticeships are cheaper for SMEs (5% of the cost) but the majority of students on UWE’s existing Postgraduate Engineer degree apprenticeship are from larger companies. The aforementioned issue with loss of a worker’s time for SMEs may be an issue.

Accreditation

The Institute of Materials, Minerals and Mining (IOM3), as the Professional Engineering Institution hosting the British Composites Society (BCS), provides accreditation for a list of degree programmes including BEng/MEng, MSc or EngD. Accreditation is a lengthy process, involving a team of professional engineers visiting the institution hosting the course to assess the content and quality of that provision. A graduate of the accredited institution will then have a clear route to professional status, including Chartered Engineer (Engineering Council), Chartered Environmentalist (Society for the Environment) or Chartered Scientist (Science Council).

The aspiration in developing a network of UK universities collaborating to permit accredited continuing professional development in composites across a number of well-found institutions raises the spectre of a student having a collection of credits from different institutions. Our understanding is that, unfortunately, the former Credit Accumulation and Transfer Scheme (CATS) scheme is no longer available as a functional option. University of Plymouth AD T&L Science and Engineering advised “Academic credit can only be awarded by one institution at a time, so it looks like you will need to set-up some kind of arrangement where a group of universities formally agree to recognise one another’s credits as leading to an award made by one of them (as awards can’t be made by the group, just by the institution that the student enrols with)”. There may be scope for one or more institutions to operationalise such a scheme, recognising credits from other institutions by Accreditation of Prior Certificated Learning (APCL), and/or maybe Accreditation of Prior Experiential Learning (APEL).

An alternative model might be the Integrated Graduate Development Scheme (IGDS). This scheme was formerly funded by the UK Engineering and Physical Sciences Research Council (EPSRC) as a vehicle to provide modular part-time education/training for graduates employed in industry. The delegates (students) gained industrially orientated and market-driven postgraduate training whilst remaining in full-time employment. There were about fifty IGDS programmes available covering all sectors of industry, but the scheme seems to have ended approximately 15 years ago.

Making It Happen

Next Steps

The group have discussed various options for continuing the work, including an NPL-NCC led proposal:

“The UK Composites Curriculum project was an important first step in an overall program aimed at closing the skills gap in the Advanced Composites industry. With a predicted growth in the use and application of advanced composites, there is an urgent need to address well documented industrial skills shortages.

Funded by HEFCE, the Phase 1 project scope was to identify what materials should be included in the curriculum and to produce a framework for a masters program. This required a review of composites

22 https://www.iom3.org/academic-accreditation-list
teaching as is currently being delivered in the UK, supported by international benchmarking. The Phase 1 project also sought to identify industrial and academic demand, to substantiate and validate skills requirements.

A phase 2 programme is now proposed, to continue development when Phase 1 completes in August 2019. The phase 2 programme aims to create, plan and ultimately deliver training content based upon the 59 unit descriptions developed during Phase 1. In addition, the market intelligence gained from phase 1, namely industrial and academic demand and international benchmarking, is an important pointer to the success of phase 2 work. This would be used to prioritise material development, addressing the immediate needs and maximising impact for the benefit of UK industry.

Prior to any further work, a Phase 2 programme team will need to be created, inclusive of curriculum development partners, a Steering Group and a core Project Team. NCC and NPL, having complimentary composites technical capabilities and experience in developing and delivering accredited training courses, expressed an interest to and initiated work for formulating a Phase 2 Programme.

The Phase 2 programme will develop Phase 1 deliverables into a full business proposal, outlining the key steps to the successful delivery. It will address the phased development of curriculum content over a 3-year period, completing in September 2022. It will coordinate the creation of these materials by consortia members commensurate with their abilities. It will also consider the commercial elements of development such as distribution of funding between consortia partners, challenges surrounding intellectual property and an appropriate mechanism of delivery to the industrial base.” (Provided by NCC and NPL)

In addition to this, workshops to obtain a clearer demand signal from industry, following on from the initial work presented in this report, are planned for the autumn of 2019. Funding is available for two such workshops. This can be carried out in parallel with the NPL-NCC plan. It is likely that additional work may be needed in order to clarify the demand signal, which can be considered as part of phase 2. It is regrettably notable that obtaining a clear, quantitative demand for long term training needs is a difficult prospect across the wider engineering sector.

The most immediate next step is to create a business case for the future. Following on from this, the next phase will require collaboration agreements, which will likely be based on the legal advice commissioned as part of this project and may involve formation of a joint body. Constructing a framework for development and delivery of the units; including the legal requirements; which is acceptable to all parties, will require a small project team.

NCC and NPL have expressed interest in working on this and may be able to fund some staff time. The Universities of Bristol and Plymouth wish to remain involved but at the close of this project will no longer be able to employ staff for this purpose unless other funding is obtained.

Legal Advice
A detailed legal advice note has been received from Veale Wasbrough Vizards LLP. They narrow down the options for structuring the future project to two:

1) Contractual Collaboration, with a specified Lead Member. A Consortium Agreement would define the legal rights and responsibilities of the Members. As the Consortium is not a legal body, any agreements, ownership of IP or applications for funding would have to be made by one or more Members on behalf of
the Consortium. It is recommended that a Lead Member, preferably the organisation responsible for the
day to day running of the project, be chosen who would be responsible for this.

2) Joint Venture forming a Limited Liability Company. The LLC would be owned and controlled by the
Members, with day to day running overseen by a board of directors. The LLC may or may not have
charitable status, VWV recommend that unless the LLC is expected to make significant profits- which
would be tax free on charitable activities, the greater flexibility afforded by not having charitable status is
preferable.

In either case it is recommended that foreground IP- e.g. teaching material developed for this curriculum-
should sit with one party, either the Lead Member or LLC, either by assignment or an irrevocable
exclusive license. If an exclusive basis is not considered appropriate, it is recommended that other use of
the material be restricted, with permitted use- such as academic and research purposes- set out in the
Consortium Agreement.

The advice note details a number of points which should be considered before any decisions are made.

Comparable case: Economics Core Curriculum

This\textsuperscript{23} is a collaborative curriculum with contributions by a number of different organisations. Unlike the
proposed Composites Curriculum, the Economics courses are used in early undergraduate courses and
schools as well as a postgraduate course for students from diverse backgrounds. Material is provided
online rather than delivered in person by subject matter specialists.

Despite the differences between this and the proposed Composites Curriculum, there are numerous
similar challenges. It may be possible to learn from their experiences.

Governance: A registered charity (England and Wales) for the public benefit, overseen by Trustees who
manage the business and guide the strategic planning. Day to day running is carried out by a Charity
Secretary and operations are carried out by the Production Team. Some work is carried out by
volunteers and interns. If a Limited Liability Company is set up to deliver the Composites Curriculum it
may be registered as a charity, but does not have to be.

Copyright: CORE’s material is open access and available under Creative Commons Attribution-
NonCommercial-NoDerivs license, meaning it can be freely distributed worldwide for non-commercial
purposes provided the source is credited, but the material may not be changed in any way or used
commercially. This is an option for the Composites Curriculum if all participating organisations agree.
This license keeps control over the material, so it cannot legally be modified and presented under the
source’s branding and prevents others from legally profiting by it. However, it is available worldwide,
which may be an issue if the consortium or a funding body wish to restrict the material to the UK. It
should be noted that reading teaching material alone is not considered a substitute for learning from an
expert in person, as discussed above, so if the materials were to be distributed there would still be a
great deal of value in attending the units. It appears from the website that the material is licensed by the
charity rather than separately by contributors, as in the model suggested by VWV.

Funding: Grant funded from a variety of sources, at least some of which are specific to provision of open
access learning material. Choosing to use Creative Commons may allow the Composites Curriculum to

\textsuperscript{23} \url{https://www.core-econ.org/}
apply for such funding, but it is not known whether or not delivery of courses in person, for which a fee must be charged in order to cover costs, would be permitted.

Teaching collaboration: Material is provided by subject matter experts from numerous institutions. This includes a jointly authored textbook, available as an ebook. All authors and institutions providing material must agree to do so under the above Creative Commons license.

Online reference materials: An ebook, lecture slides, videos, quizzes, a glossary of terms and interactive spreadsheets are available to students online, along with references for facts stated in the ebook. There are YouTube links to narrated lectures.

Assessments: As the material is provided for use by universities and schools, assessments are carried out separately by each institution. This negates any issue of transferring credits but may be more difficult for the Composites Curriculum as the assessments will need to be set and marked by subject matter experts, most likely those who produce and deliver the course materials.

Branding: All material is provided under the CORE brand rather than that of the contributing institution. The Composites Curriculum project may wish to consider a similar approach, for consistency and to ensure no individual institution’s brand is subject to risk by being associated with material beyond their control.

**Future Funding**

Creation of a business case which can be used to apply for future funding has been discussed with the National Composites Centre. It is considered likely that a clear vision of the future and a detailed roadmap will be needed, with an option for numerous small projects, separately funded, to contribute to the long-term plan.

Two workshops to investigate industrial demand are funded under a separate project, the results will be beneficial to both that project and this.

The University of Plymouth have applied for a Knowledge Transfer Partnership with a composites SME which follows on from this work and develops it further. “To develop and embed a new business process to intrinsically capture and document internal knowledge and experience, to enable training and knowledge transfer to support business growth within the composite manufacturing sector.” The application is for funding of £180k for 24 months.

Issues encountered in the composites industry may be reflected in the wider digital engineering sector. It is therefore possible that work on this project could be used as a pilot for a new approach which may benefit a larger range of businesses.

**Catapult Fellowship?**

One option explored is the possibility of an individual fellowship under HVMC. An initial proposal, shown in the appendices, was submitted to HVMC. The proposed Fellow would be an academic, funded to drive this project forward as their full-time job, including sourcing funding for a collaborative next stage. They would be able to work alongside the NCC-NPL team or any alternative group.
Evaluation of Project

This project has lasted longer than originally planned, largely due to staffing difficulties in the early stages. It has however delivered everything in the original business case and more, with the addition of example units, multiple pilots, shared resources and detailed feedback.

The project is grateful to HEFCE Catalyst for the initial funding. However, as this unique funding opportunity is no longer available, it is difficult to define a clear plan for continuation of the work. The need is well-defined, the suggested curriculum a good starting point- but to make it a reality both funding and a core team are needed to ensure the good work so far does not go to waste.

Engagement with academics has been broadly good, with representatives of a small number of universities present at all meetings and many others in contact via email or attending one meeting only. Unit descriptions have been written by a variety of people, but overall the bulk have been contributed by the two co-leads, Professor John Summerscales and Professor Kevin Potter. Increasing levels of contribution, and critical appraisal, from other institutions would be welcome.

Engagement with industry has been more difficult. Only one company has provided staffing figures which could be used to improve our estimate of future requirements and there have been very few responses to requests for comment. Through NCC, attendance at the third pilot units were good, with Tolerancing, Variability and Defects over-subscribed. NCC has acted as a representative of industry through most of the project and conducted reviews of the unit descriptions on this basis.

Conclusion

This project has delivered on its aims and provides a good basis for future development of industrially focused teaching at Masters level in the composites industry. The proposed curriculum covers a wide range of topics, intended to be taught by experts in the field to industrial participants as short, 2-day courses in response to demand.

Any future work requires funding. it is recommended that continuation should start by constructing a joint body and IP agreement that all institutions are happy to sign up to, followed by a plan for delivery of the units and funding their development.
## Appendix 1- Financial Summary

HEFCE Composites Curriculum Development Project, Provisional Budget Summary August 2019

<table>
<thead>
<tr>
<th>Income</th>
<th>HEFCE Catalyst</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Salaries</td>
<td>Actual to date</td>
<td>In process</td>
<td>Total</td>
</tr>
<tr>
<td>Academic</td>
<td>£ 20,614.82</td>
<td>£ 12,672.26</td>
<td>£ 33,287.08</td>
</tr>
<tr>
<td>Hourly paid teachers</td>
<td>£ 4,940.40</td>
<td>-</td>
<td>£ 4,940.40</td>
</tr>
<tr>
<td>Professional/Admin</td>
<td>£ 4,963.33</td>
<td>-</td>
<td>£ 4,963.33</td>
</tr>
<tr>
<td>Temporary staff service</td>
<td>£ 20,392.74</td>
<td>£ 3,746.41</td>
<td>£ 24,139.15</td>
</tr>
<tr>
<td>Sub-total</td>
<td>£ 50,911.29</td>
<td>£ 16,418.67</td>
<td>£ 67,329.96</td>
</tr>
<tr>
<td>Non salary</td>
<td>Actual to date</td>
<td>In process</td>
<td>Total</td>
</tr>
<tr>
<td>Travel and Subsistence</td>
<td>£ 217.00</td>
<td>-</td>
<td>£ 217.00</td>
</tr>
<tr>
<td>Casual staff costs</td>
<td>£ 25,917.41</td>
<td>£ 834.02</td>
<td>£ 26,751.43</td>
</tr>
<tr>
<td>Equipment/Consumables</td>
<td>£ 1,836.73</td>
<td>-</td>
<td>£ 1,836.73</td>
</tr>
<tr>
<td>Catering &amp; other food</td>
<td>£ 566.19</td>
<td>-</td>
<td>£ 566.19</td>
</tr>
<tr>
<td>Room hire costs</td>
<td>£ 2,689.00</td>
<td>-</td>
<td>£ 2,689.00</td>
</tr>
<tr>
<td>UWE Unit Development</td>
<td>£ 7,678.00</td>
<td>-</td>
<td>£ 7,678.00</td>
</tr>
<tr>
<td>NPL Unit Development</td>
<td>-</td>
<td>£ 50,700.00</td>
<td>£ 50,700.00</td>
</tr>
<tr>
<td>Copyright legal advice</td>
<td>-</td>
<td>£ 4,200.00</td>
<td>£ 4,200.00</td>
</tr>
<tr>
<td>NCC material review and hosting of pilot units</td>
<td>-</td>
<td>£ 15,330.00</td>
<td>£ 15,330.00</td>
</tr>
<tr>
<td>Sub-total</td>
<td>£ 38,904.33</td>
<td>£ 71,064.02</td>
<td>£ 109,968.35</td>
</tr>
<tr>
<td>Plymouth costs</td>
<td>Actual to date</td>
<td>In process</td>
<td>Total</td>
</tr>
<tr>
<td>Travel</td>
<td>£ 5,000.00</td>
<td>-</td>
<td>£ 5,000.00</td>
</tr>
<tr>
<td>Staff</td>
<td>£ 11,394.00</td>
<td>-</td>
<td>£ 11,394.00</td>
</tr>
<tr>
<td>Estates</td>
<td>£ 1,731.00</td>
<td>-</td>
<td>£ 1,731.00</td>
</tr>
<tr>
<td>Indirect costs</td>
<td>£ 6,875.00</td>
<td>-</td>
<td>£ 6,875.00</td>
</tr>
<tr>
<td>Sub-total</td>
<td>£ 25,000.00</td>
<td>-</td>
<td>£ 25,000.00</td>
</tr>
<tr>
<td>Total spending</td>
<td></td>
<td></td>
<td>£ 202,298.31</td>
</tr>
</tbody>
</table>

**Shortfall + ** -£ 2,298.31

* shortfall covered by Institution’s contribution

Please note that staff costs are paid in arrears, so the final payment will be made in September.

Timesheets have been approved. A final summary can be provided once all pay and invoices clear.
## Appendix 2- Curriculum Mapping Data

<table>
<thead>
<tr>
<th>Institution</th>
<th>Course Type</th>
<th>Course name</th>
<th>Composites compulsory or optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bath</td>
<td>MEng</td>
<td>Aerospace Engineering</td>
<td>Optional</td>
</tr>
<tr>
<td>Bath</td>
<td>MEng</td>
<td>Integrated Design Engineering</td>
<td>Optional</td>
</tr>
<tr>
<td>Bath</td>
<td>MEng</td>
<td>Mechanical Engineering</td>
<td>Optional</td>
</tr>
<tr>
<td>Bath</td>
<td>MEng</td>
<td>Mechanical with Automotive Engineering</td>
<td>Optional</td>
</tr>
<tr>
<td>Birmingham</td>
<td>MSc</td>
<td>Materials Science &amp; Engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Birmingham</td>
<td>MRes</td>
<td>Science &amp; Engineering of Materials</td>
<td>Mixed</td>
</tr>
<tr>
<td>Birmingham</td>
<td>MEng</td>
<td>Aerospace Engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Birmingham</td>
<td>MEng</td>
<td>Materials Science and engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Bolton</td>
<td>MSc</td>
<td>Advanced Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Bristol</td>
<td>PhD</td>
<td>Advanced Composites</td>
<td>Mixed</td>
</tr>
<tr>
<td>Bristol</td>
<td>EngD</td>
<td>Composites Manufacture</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Bristol</td>
<td>MEng</td>
<td>Aerospace Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cambridge</td>
<td>MASt</td>
<td>Materials Science</td>
<td></td>
</tr>
<tr>
<td>Cranfield</td>
<td>MSc</td>
<td>Advanced Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>MSc</td>
<td>Aerospace Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>MSc</td>
<td>Aerospace Manufacturing</td>
<td>Optional</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Modelling, Simulation and Monitoring of Composites Cure</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Composite Material Structures</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Introduction to Composite Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Functional Composites Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Composites Integration Repair and Joining</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>High Performance Composite Structures and Components - Materials, Design and Manufacturing Techniques</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Materials Selection</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course (Online)</td>
<td>Principles of Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>MSc/PG Diploma/PG Certificate</td>
<td>Aerospace Materials/Aircraft Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Toughening of Polymer Resins</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Sustainable Composites Manufacturing and Industrial Applications</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Introduction to Aircraft Stress Analysis</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Cranfield</td>
<td>Short Course</td>
<td>Nanomaterials and advanced composites</td>
<td>Compulsory</td>
</tr>
<tr>
<td>University</td>
<td>Degree</td>
<td>Major</td>
<td>Type</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------</td>
<td>--------------------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Edinburgh</td>
<td>MEng</td>
<td>Mechanical Engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Edinburgh Napier</td>
<td>MEng</td>
<td>Mechanical Engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Exeter</td>
<td>BEng</td>
<td>Materials Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Exeter</td>
<td>MSc</td>
<td>Materials Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Glasgow</td>
<td>MEng</td>
<td>Aeronautical Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Glyndwr</td>
<td>MSc/PG Diploma</td>
<td>Composite Material Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Glyndwr</td>
<td>BEng</td>
<td>Composite Design</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Hertfordshire</td>
<td>Short Course</td>
<td>Composite Repair</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Imperial</td>
<td>MSc</td>
<td>The Science, Technology and Engineering Application of Advanced Composites</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Kingston University</td>
<td>BEng/MEng</td>
<td>Aerospace Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Kingston University</td>
<td>BEng/MEng</td>
<td>Mechanical Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Kingston University</td>
<td>MEng/MSc</td>
<td>Mechanical Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Kingston University</td>
<td>MSc</td>
<td>Advanced Industrial and Manufacturing Systems</td>
<td>Optional</td>
</tr>
<tr>
<td>Kingston University</td>
<td>MSc</td>
<td>Aerospace Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Kingston University</td>
<td>BEng</td>
<td>Aircraft Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Liverpool</td>
<td>MSc</td>
<td>Advanced Aerospace Engineering</td>
<td>Optional</td>
</tr>
<tr>
<td>Liverpool</td>
<td>MEng/BEng</td>
<td>Mechanical Engineering</td>
<td>Optional</td>
</tr>
<tr>
<td>Liverpool</td>
<td>Meng/BEng</td>
<td>Aerospace Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Loughborough</td>
<td>PG Cert/Diploma/MSc</td>
<td>Materials Science and Technology</td>
<td>Mixed</td>
</tr>
<tr>
<td>Loughborough</td>
<td>Diploma/MSc/PG certificate</td>
<td>Polymer Science and Technology</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Manchester</td>
<td>MSc</td>
<td>Textile Technology (Technical Textiles)</td>
<td>Optional</td>
</tr>
<tr>
<td>Manchester</td>
<td>MSc</td>
<td>Polymer Materials Science and Engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Manchester</td>
<td>MSc</td>
<td>Advanced Engineering Materials</td>
<td>Mixed</td>
</tr>
<tr>
<td>Manchester</td>
<td>MEng</td>
<td>Materials Science and Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Newcastle</td>
<td>MEng</td>
<td>Civil and Structural Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Newcastle</td>
<td>MEng</td>
<td>Mechanical Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Nottingham</td>
<td>MSc</td>
<td>Additive Manufacturing and 3D Printing</td>
<td>Mixed</td>
</tr>
<tr>
<td>Nottingham</td>
<td>MSc</td>
<td>Advanced Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Nottingham</td>
<td>MSc</td>
<td>Mechanical Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>University</td>
<td>Degree</td>
<td>Course Description</td>
<td>Requirement</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>---------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Oxford Brookes</td>
<td>MSc</td>
<td>Motorsport Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Oxford Brookes</td>
<td>MSc</td>
<td>Mechanical Engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Oxford</td>
<td>MEng</td>
<td>Materials Science</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Plymouth</td>
<td>BEng/MEng</td>
<td>Mechanical Engineering with Composites</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Portsmouth</td>
<td>MSc</td>
<td>Mechanical Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>QMUL</td>
<td>MEng</td>
<td>Materials Science and Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>QMUL</td>
<td>MEng</td>
<td>Aerospace Engineering</td>
<td>Mixed</td>
</tr>
<tr>
<td>Sheffield</td>
<td>MSc/MRes</td>
<td>Aerodynamics and Aerostructures</td>
<td>Optional</td>
</tr>
<tr>
<td>Sheffield</td>
<td>MSc</td>
<td>Advanced Manufacturing Technologies</td>
<td>Optional</td>
</tr>
<tr>
<td>Sheffield</td>
<td>MSc/MEng</td>
<td>Polymers and Polymer Composite Science and Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Sheffield</td>
<td>MSc/MEng</td>
<td>Aerospace Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Solent</td>
<td>BEng</td>
<td>Ship Science/Yacht and Small Craft</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Southampton</td>
<td>MEng/ MSc</td>
<td>Yacht and Small Craft</td>
<td>Optional</td>
</tr>
<tr>
<td>Strathclyde</td>
<td>MSc</td>
<td>Advanced Mechanical Engineering with Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Surrey</td>
<td>MSc</td>
<td>Advanced Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Surrey</td>
<td>Short Course</td>
<td>Composite Materials Technology: Design, Technology and Performance</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Surrey</td>
<td>Short Course</td>
<td>Characterisation of Advanced Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Surrey</td>
<td>Short Course</td>
<td>Polymers: Science, Engineering and Applications</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Surrey</td>
<td>Short Course</td>
<td>Materials Under Stress: An Introduction to Fracture Mechanics and Fatigue</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Surrey</td>
<td>Short Course</td>
<td>The Science and Technology of Adhesive Bonding</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Surrey</td>
<td>Short Course</td>
<td>Introduction to Composite Materials</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Ulster</td>
<td>MSc</td>
<td>Advanced Composites and Polymers</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Ulster</td>
<td>PG diploma</td>
<td>Advanced Composites and Polymers</td>
<td>Compulsory</td>
</tr>
<tr>
<td>UWE</td>
<td>Short Course</td>
<td>Advanced Manufacturing</td>
<td>Compulsory</td>
</tr>
<tr>
<td>UWE</td>
<td>MEng</td>
<td>Mechanical Engineering/Automotive Engineering/Aerospace Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>UWE</td>
<td>Short Course</td>
<td>Aircraft Structural Design and Stress Analysis</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Warwick</td>
<td>MSc</td>
<td>Analytical and Polymer Science</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Warwick</td>
<td>MEng</td>
<td>Automotive Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Warwick</td>
<td>MEng</td>
<td>Mechanical Engineering</td>
<td>Compulsory</td>
</tr>
<tr>
<td>Institution</td>
<td>Eng/tech undergrads</td>
<td>Eng/tech taught postgrads</td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------</td>
<td>---------------------------</td>
<td></td>
</tr>
<tr>
<td>Bath</td>
<td>2715</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Birmingham</td>
<td>2175</td>
<td>630</td>
<td></td>
</tr>
<tr>
<td>Bolton</td>
<td>610</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Bristol</td>
<td>1840</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Cambridge</td>
<td>1460</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Cranfield</td>
<td>0</td>
<td>1735</td>
<td></td>
</tr>
<tr>
<td>Edinburgh</td>
<td>1565</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>Edinburgh Napier</td>
<td>915</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Exeter</td>
<td>910</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Glasgow</td>
<td>1625</td>
<td>295</td>
<td></td>
</tr>
<tr>
<td>Glyndŵr</td>
<td>700</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Hertfordshire</td>
<td>1385</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Imperial</td>
<td>3585</td>
<td>1035</td>
<td></td>
</tr>
<tr>
<td>Kingston</td>
<td>1740</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>Liverpool</td>
<td>1940</td>
<td>155</td>
<td></td>
</tr>
<tr>
<td>Loughborough</td>
<td>3455</td>
<td>640</td>
<td></td>
</tr>
<tr>
<td>Manchester</td>
<td>3675</td>
<td>1245</td>
<td></td>
</tr>
<tr>
<td>Newcastle</td>
<td>2040</td>
<td>785</td>
<td></td>
</tr>
<tr>
<td>Nottingham</td>
<td>2835</td>
<td>310</td>
<td></td>
</tr>
<tr>
<td>Oxford Brookes</td>
<td>685</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Oxford</td>
<td>645</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Plymouth</td>
<td>1350</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Portsmouth</td>
<td>2170</td>
<td>425</td>
<td></td>
</tr>
<tr>
<td>QMUL</td>
<td>1230</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Sheffield</td>
<td>4165</td>
<td>710</td>
<td></td>
</tr>
<tr>
<td>Solent</td>
<td>1120</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Southampton</td>
<td>2450</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>Strathclyde</td>
<td>3715</td>
<td>630</td>
<td></td>
</tr>
<tr>
<td>Surrey</td>
<td>1855</td>
<td>445</td>
<td></td>
</tr>
<tr>
<td>Ulster</td>
<td>1245</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Ulster</td>
<td>1245</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>UWE</td>
<td>1850</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Warwick</td>
<td>1535</td>
<td>1240</td>
<td></td>
</tr>
</tbody>
</table>

**sum**                  | 59185               | 12915                     |
**per year**             | 14796.25            | 10977.75                  |
**joining workforce**    | 8137.9375           | 4061.7675                 |

4 years total            |                     | 30% are part time
Appendix 3- International Benchmarking Data

<table>
<thead>
<tr>
<th>Course</th>
<th>Type</th>
<th>Uni</th>
<th>Country</th>
<th>Compulsory</th>
<th>Manufacturing topic(s)?</th>
<th>Industry project?</th>
<th>Other industry?</th>
<th>Type</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master of Engineering</td>
<td>M.Eng</td>
<td>Australian National University</td>
<td>Australia</td>
<td>No</td>
<td>Optional</td>
<td>No</td>
<td>No</td>
<td>Full time</td>
<td>1 yr</td>
</tr>
<tr>
<td>Materials Engineering</td>
<td>MSc</td>
<td>KU Leuven</td>
<td>Belgium</td>
<td>No</td>
<td>Optional</td>
<td>Optional</td>
<td>No</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Chemical and Materials Engineering</td>
<td>MSc</td>
<td>Vrije Universiteit Brussel</td>
<td>Belgium</td>
<td>No</td>
<td>Optional</td>
<td>Optional</td>
<td>Company visits</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Advanced Materials Manufacturing</td>
<td>MEL</td>
<td>University of British Columbia</td>
<td>Canada</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Full time</td>
<td>1 yr</td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>MSc</td>
<td>Aarhus University</td>
<td>Denmark</td>
<td>No</td>
<td>No</td>
<td>Optional</td>
<td>No</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Advanced Composite Engineering and Science</td>
<td>M-ENG</td>
<td>Centrale Nantes</td>
<td>France</td>
<td>Yes</td>
<td>Yes</td>
<td>Optional</td>
<td>No</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Advanced Materials</td>
<td>MSc</td>
<td>University of Bordeaux</td>
<td>France</td>
<td>No</td>
<td>No</td>
<td>Optional</td>
<td>No</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Advanced Materials for Innovation and Sustainability</td>
<td>MSc</td>
<td>Bordeaux/ Grenoble/ Aalto/ Darmstadt/ Liège</td>
<td>France/ Finland/ Belgium/ Germany</td>
<td>No</td>
<td>No</td>
<td>Optional</td>
<td>Industrial partners</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Aerospace Engineering</td>
<td>MSc</td>
<td>École Centrale de Lyon</td>
<td>France</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Eco-conception des Polymères et Composites</td>
<td>MSc</td>
<td>Université Bretagne Sud</td>
<td>France</td>
<td>Yes</td>
<td>Yes</td>
<td>Optional</td>
<td>Option to work second year</td>
<td>Full time OR split with industry</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Textile Engineering</td>
<td>MSc</td>
<td>RWTH Aachen University</td>
<td>Germany</td>
<td>Yes</td>
<td>Yes</td>
<td>Optional</td>
<td>Based at ITA</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Verbundwerkstoffe</td>
<td>MSc</td>
<td>PFH Stade Hansecampus</td>
<td>Germany</td>
<td>Yes</td>
<td>Yes</td>
<td>While working</td>
<td>Collaborator s nearby</td>
<td>Short blocks plus thesis</td>
<td>1.5 yrs</td>
</tr>
<tr>
<td>Chemical Engineering Programme</td>
<td>M.S.</td>
<td>King Abdullah University of Science and Technology</td>
<td>Saudi Arabia</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Full time or part time</td>
<td>1.5 yrs</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------</td>
<td>------------------------------------------------</td>
<td>-------------</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Composite Materials</td>
<td>MSc</td>
<td>Luleå University of Technology</td>
<td>Sweden</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Connected to needs of partner companies</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Materials Engineering</td>
<td>MSc</td>
<td>Chalmers University</td>
<td>Sweden</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Links with a list of companies</td>
<td>Full time</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Materials Science and Engineering</td>
<td>MSc</td>
<td>Koç University</td>
<td>Turkey</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Full time</td>
<td>?</td>
</tr>
<tr>
<td>Composites Manufacturing and Engineering</td>
<td>Grad Cert</td>
<td>University of Delaware</td>
<td>USA</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Designed for industry</td>
<td>Online</td>
<td>?</td>
</tr>
<tr>
<td>Composite Materials</td>
<td>Grad Cert</td>
<td>University of Delaware</td>
<td>USA</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Designed for industry</td>
<td>Online</td>
<td>?</td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>MSc</td>
<td>University of Delaware</td>
<td>USA</td>
<td>No</td>
<td>Optional</td>
<td>No</td>
<td>Access above courses</td>
<td>Full time or Online</td>
<td>1.5-2 yrs</td>
</tr>
<tr>
<td>Course</td>
<td>Notes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Master of Engineering</td>
<td>Composite materials optional 6 unit (of 48) course including design exercise, research project, practical manufacturing techniques.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Engineering</td>
<td>Polymers and Composites is a 'career oriented' 12 credit option of a total 120 credits. 4 courses: Composites Manufacturing, Mechanics of Heterogenous Materials, Polymer Processing, Design and Applications of Polymers and Composites- including a group case study to &quot;(re)engineer a polymer or a composite component&quot; assessed by report.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical and Materials Engineering</td>
<td>Two profiles: process technology and materials. Composites are mentioned in the materials profile. There is an option to receive credit points for an internship (6 -10 ECTS). Little composites content.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Materials Manufacturing</td>
<td>Combination of engineering and business courses, 1 course on advanced composite materials compulsory, also an optional composite materials course and more general courses which will include some composites. Learning through case studies, group projects, experiments and demonstrations.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>Mentions many industrial examples. Fracture Mechanics (10ECTS) and Mechanics of Composite Materials (SECTS) are one of the 'specialised study' options (not compulsory). Some of the electives, e.g. wind energy systems, are likely to involve composites too. There is an option to carry out a project in collaboration with a company or research group.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Composite Engineering and Science</td>
<td>Includes 1 semester (30 credits of 120 total) of almost all composites courses- constituents and processes, characterization, processing modelling, structures, manufacturing system organization and multi-physics modelling for processes. Also a project and language. Thesis may be done through industrial internship.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Materials</td>
<td>Chemistry focused. Optional module on innovative and composite materials (6 credits of total 120). 6 month training period in academic or industrial laboratories.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Materials for Innovation and Sustainability</td>
<td>Chemistry department. Double degree by two universities- an example of co-operation on teaching, with one year at each. Internships and industrial projects available. Has industrial partners. Composites and ceramics an optional year 2 speciality, taught in Bordeaux. Practical work and a project.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerospace Engineering</td>
<td>Option for Dynamic and Sustainability of Composite Materials. One optional module focuses on the design process for an aircraft or a rocket engine. The final research project is 6 months. General manufacturing (e.g. Lean) is covered but not composites specific options, though it may be included under 'process-product-performances'.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Éco-conception des Polymères et Composites</td>
<td>Second year of the course has an option for alternating between the university and industry, 2 weeks in each, with second semester entirely in the company. Appears to be open to employees as well as students. The student has a salary for their work and it gives access to a job. First year study includes some manufacturing technologies. If the 'alternating' option is not taken there is still an option for an internship.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Program</td>
<td>Description</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textile Engineering</td>
<td>Student chooses to either follow the 'coursework' route, focused on practical and applied engineering in industry, or 'research', for specialising in an R&amp;D field. Very composites focused. Optional courses include industrial items such as factory planning and production metrology for the coursework route. Located at Aachen’s Institute for Textile Technology.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verbundwerkstoffe</td>
<td>Targeted at students with professional experience, who want to gain a qualification through professional development. 60 ECTS part time or 90 ECTS full time over three semesters. Units are taught in blocks over 7-17 days and weekend courses for the first two semesters. The third semester is for the thesis. Advertises 'up to date content provided by professors with practical experience. Collaborative partners (Airbus, DLR, Fraunhofer) near campus. Management content included. Composites and industry focus.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical Engineering Programme</td>
<td>Chemical engineering focus, unit on physical chemistry of macromolecules includes composites. May go on to a PhD, industry sponsored students can study part time.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Materials</td>
<td>120 credits. Composite materials, multifunctional polymer composites: advanced processing and manufacturing, biocomposites and composites: design and numerical methods are compulsory, a total of 30 credits. Some optional courses are likely to include significant composites content. Linked to companies SICOMP and ABB who are recruiting.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Engineering</td>
<td>120 credits. States that courses are &quot;closely linked to the industry&quot;. Run by academic staff from across different departments. Composite and Nanocomposite materials is an optional course. States that they cooperate with large and small companies, listing Volvo, Volvo cars, GKN Aerospace, SAAB, SKF, SCA, Sandvik, SWEREA and ARCAM.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Science and Engineering</td>
<td>Multicomponent polymeric systems is an optional course including composites. Polymer composites are also included in other courses such as surface and interface properties of materials, thermomechanical properties of materials and introduction to polymer science. 30 credits or 21 plus a thesis are needed.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composites Manufacturing and Engineering</td>
<td>Online course, all composites. Exercises using software are included, but no lab sessions. These courses are also available to those doing an MSc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Materials</td>
<td>Designed for engineering/science professionals who are new to composites. States it is all online, but some of the courses seem very practical in nature and would need lab work.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>30 credits. Can be done entirely online. Composites options from the above courses are available, but not compulsory. Thesis is optional.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Course</td>
<td>Link</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Engineering</td>
<td><a href="https://onderwijsaanbod.kuleuven.be/opleidingen/e/CQ_50545818.htm#activetab=diploma_omschrijving">https://onderwijsaanbod.kuleuven.be/opleidingen/e/CQ_50545818.htm#activetab=diploma_omschrijving</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Materials Manufacturing</td>
<td><a href="https://www.grad.ubc.ca/prospective-students/graduate-degree-programs/master-of-engineering-leadership-advanced-materials-manufacturing">https://www.grad.ubc.ca/prospective-students/graduate-degree-programs/master-of-engineering-leadership-advanced-materials-manufacturing</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Materials</td>
<td><a href="https://www.u-bordeaux.com/Education/Study-offer/Masters-in-English/Chemistry/Advanced-Materials">https://www.u-bordeaux.com/Education/Study-offer/Masters-in-English/Chemistry/Advanced-Materials</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Éco-conception des Polymères et Composites</td>
<td><a href="https://www.ecoconceptionpolymerescomposites.com/">https://www.ecoconceptionpolymerescomposites.com/</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical Engineering Programme</td>
<td><a href="https://pse.kaust.edu.sa/study/academic-programs/chemical-engineering/Pages/academics-information.aspx">https://pse.kaust.edu.sa/study/academic-programs/chemical-engineering/Pages/academics-information.aspx</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Materials</td>
<td><a href="https://www.itu.se/edu/program/TMKOA/TMKOA-Kompositmaterial-master-1.83577?l=en">https://www.itu.se/edu/program/TMKOA/TMKOA-Kompositmaterial-master-1.83577?l=en</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composites Manufacturing and Engineering</td>
<td><a href="http://me.udel.edu/academics/graduate/graduate-certificate-in-composites-manufacturing-engineering/">http://me.udel.edu/academics/graduate/graduate-certificate-in-composites-manufacturing-engineering/</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Materials</td>
<td><a href="https://me.udel.edu/academics/graduate/graduate-certificate-in-composite-materials/">https://me.udel.edu/academics/graduate/graduate-certificate-in-composite-materials/</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td><a href="http://me.udel.edu/academics/graduate/">http://me.udel.edu/academics/graduate/</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 4- Sample feedback form

HEFCE Composites Curriculum Development Project

Trial unit feedback questionnaire

This questionnaire is anonymous and participation is entirely voluntary. Answers to these questions will be used to improve the trial teaching material. Data will be entered onto a spreadsheet on a University of Bristol computer and the paper questionnaires will be shredded so that no record of your handwriting is kept. Anonymous data may be shared with other institutions to develop and improve composites courses in the UK.

You are not obliged to answer every question. Please continue on another piece of paper if you wish to write more. All feedback gratefully received, please give your honest opinion. Swearing is permitted.

1) Please mark your level of agreement with the following statements:

<table>
<thead>
<tr>
<th>Statement</th>
<th>Disagree ------ Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disagree ------- Agree</td>
<td></td>
</tr>
<tr>
<td>The course was interesting</td>
<td>-2</td>
</tr>
<tr>
<td>The content made sense</td>
<td>-1</td>
</tr>
<tr>
<td>The topics we covered are applicable to my work</td>
<td>0</td>
</tr>
<tr>
<td>The industrial examples were a valuable inclusion</td>
<td>1</td>
</tr>
<tr>
<td>Seeing and holding composite parts and moulds was beneficial</td>
<td>2</td>
</tr>
<tr>
<td>I have more questions now than before attending the course</td>
<td>-2</td>
</tr>
<tr>
<td>The lecturer was easy to understand</td>
<td>-1</td>
</tr>
<tr>
<td>The slides are well laid out</td>
<td>0</td>
</tr>
<tr>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td>1</td>
</tr>
<tr>
<td>I had sufficient opportunity to ask questions</td>
<td>2</td>
</tr>
<tr>
<td>There was too much content for the time available</td>
<td>-2</td>
</tr>
<tr>
<td>I would like to learn more about advanced composites</td>
<td>-1</td>
</tr>
<tr>
<td>My company would benefit from training in advanced composites</td>
<td>0</td>
</tr>
<tr>
<td>An optional assignment would help to consolidate what I have learned</td>
<td>1</td>
</tr>
<tr>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td>2</td>
</tr>
</tbody>
</table>

2) Did you enjoy An Introduction to the History and Manufacture of Composite Materials? Circle an answer.

Yes Meh Amazing!! Rubbish

No

3) Was the level of the content right for you? Please mark on the scale below where it fits.

Knew it all before Easy Perfect Difficult Over my head

P.T.O. →
4) Tell us about your favourite part of the course

5) Tell us about your least favourite (or the most boring) bit

6) Is there a particular topic or theme you would like to know more about?

7) What do you think we need to improve and why? Can you suggest how to do this?

8) Overall, how would you rate this course out of ten? /10

Your current job (for our reference only)
Please do not name your employer

9) Does your current job involve advanced composites (polymer resin + fibre reinforcement)? Y/N
10) Please mark where on the diagram your job fits →
11) Approximately how many years of experience do you have working with advanced composites?
12) Approximately how many years of experience do you have in engineering and science overall?

Thank you for your time
Appendix 5- Full data from unit feedback forms

Feedback from HEFCE Unit trials

Results of questionnaires handed out at the UWE and NCC 2019 pilots. The questionnaires are copied here for reference. Charts may be filtered by course to compare the trial units.

Results are arranged by question. The first set of worksheets displays the results graphically (scrolling required) the second includes all the data. Demographic data, from the 'current job' section, is displayed alongside the question 8 charts and can be used to filter the tables and charts.

Abbreviations:
Compjob? = does your current job involve advanced composites?
Yrscomp = number of years experience with advanced composites
Yrseng = number of years experience in science/engineering

Job type? As marked on Venn diagram
Computer, Hands-on or Meetings
Mixtures C&H, M&C, H&M
Mix = mix of all three

Question 1: Agreement with the statements on a scale -2 to +2
Displayed as a coloured table
Graph showing 'agreement' (+1 or +2) with each coloured by Yrseng

Question 2: Enjoyment of the unit
Simple chart showing number of people choosing each option

Question 3: Level of the content
Simple chart coloured by Yrseng, answers categorised at data entry stage
Markers overlaid on scale showing position of all answers

Question 4: Favourite parts of the course
Simple chart showing favourite parts, paraphrased (see data worksheet)
Some people gave multiple answers, all are included

Question 5: Least favourite parts of the course
Simple chart showing least favourite parts, paraphrased (see data worksheet)
Some people gave multiple answers, all are included
Question 6: Topics they would like to know more about
Simple chart, topics categorised (see data worksheet)
Some people gave multiple answers, all are included

Question 7: Suggestions for improvement
Simple chart, paraphrased (see data worksheet)
Some people gave multiple answers, all are included

Question 8: Rating out of 10
Simple chart
Demographics shown as pie charts for job type and yrseng
<table>
<thead>
<tr>
<th>Person</th>
<th>Compjob?</th>
<th>Job type</th>
<th>Yrs comp</th>
<th>Yrs eng</th>
<th>Course</th>
<th>Statement</th>
<th>Agree?</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The course was interesting</td>
<td>2</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The content made sense</td>
<td>0</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The topics we covered are applicable to my work</td>
<td>0</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The industrial examples were a valuable inclusion</td>
<td>1</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
<td>2</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I have more questions now than before attending the course</td>
<td>0</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The lecturer was easy to understand</td>
<td>2</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The slides are well laid out</td>
<td>1</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td>2</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I had sufficient opportunity to ask questions</td>
<td>2</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>There was too much content for the time available</td>
<td>-1</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td>-1</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>My company would benefit from (more) training in advanced composites</td>
<td>1</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>An optional assignment would help to consolidate what I have learned</td>
<td>0</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td>0</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Manufacture of Composite Materials</td>
<td>The course was interesting</td>
<td>2</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Manufacture of Composite Materials</td>
<td>The content made sense</td>
<td>2</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Manufacture of Composite Materials</td>
<td>The topics we covered are applicable to my work</td>
<td>2</td>
</tr>
</tbody>
</table>
An Introduction to the History and Manufacture of Composite Materials

The industrial examples were a valuable inclusion.

The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet).

I have more questions now than before attending the course.

The lecturer was easy to understand.

The slides are well laid out.

I am likely to refer back to the handouts and/or my notes from today.

I had sufficient opportunity to ask questions.

There was too much content for the time available.

I would like to learn more about advanced composites/other topics in composite manufacturing.

My company would benefit from (more) training in advanced composites.

An optional assignment would help to consolidate what I have learned.

I would be interested in adding up points from courses like this towards an academic qualification.

The course was interesting.

The content made sense.

The topics we covered are applicable to my work.

The industrial examples were a valuable inclusion.

The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet).

I have more questions now than before attending the course.

The lecturer was easy to understand.

The slides are well laid out.

I am likely to refer back to the handouts and/or my notes from today.
<table>
<thead>
<tr>
<th>UWE3</th>
<th>Student</th>
<th>Blank</th>
<th>Blank</th>
<th>Blank</th>
<th>An Introduction to the History and Manufacture of Composite Materials</th>
<th>I had sufficient opportunity to ask questions</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>There was too much content for the time available</td>
<td>1</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td>2</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>My company would benefit from (more) training in advanced composites</td>
<td>0</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>An optional assignment would help to consolidate what I have learned</td>
<td>2</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td>2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>Manufacture of Composite Materials</td>
<td>The course was interesting</td>
<td>1</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The content made sense</td>
<td>1</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The topics we covered are applicable to my work</td>
<td>-2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The industrial examples were a valuable inclusion</td>
<td>0</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
<td>0</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I have more questions now than before attending the course</td>
<td>0</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The lecturer was easy to understand</td>
<td>2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The slides are well laid out</td>
<td>2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td>2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I had sufficient opportunity to ask questions</td>
<td>2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>There was too much content for the time available</td>
<td>2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td>2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>My company would benefit from (more) training in advanced composites</td>
<td>-2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>An optional assignment would help to consolidate what I have learned</td>
<td>-2</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td>1</td>
</tr>
</tbody>
</table>
An Introduction to the History and Manufacture of Composite Materials

The course was interesting

The content made sense

The topics we covered are applicable to my work

The industrial examples were a valuable inclusion

The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)

I have more questions now than before attending the course

The lecturer was easy to understand

The slides are well laid out

I am likely to refer back to the handouts and/or my notes from today

I had sufficient opportunity to ask questions

There was too much content for the time available

I would like to learn more about advanced composites/other topics in composites manufacturing

My company would benefit from (more) training in advanced composites

An optional assignment would help to consolidate what I have learned

I would be interested in adding up points from courses like this towards an academic qualification
<table>
<thead>
<tr>
<th>Course Code</th>
<th>Grade</th>
<th>Student Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The lecturer was easy to understand 2</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The slides are well laid out 1</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I am likely to refer back to the handouts and/or my notes from today -1</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I had sufficient opportunity to ask questions 2</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>There was too much content for the time available 0</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing -2</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>My company would benefit from (more) training in advanced composites 1</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>An optional assignment would help to consolidate what I have learned -1</td>
</tr>
<tr>
<td>UWE6 N Mix 0 8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification -1</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The course was interesting 1</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The content made sense 2</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The topics we covered are applicable to my work 1</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The industrial examples were a valuable inclusion 2</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet) 2</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I have more questions now than before attending the course 0</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The lecturer was easy to understand 1</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>The slides are well laid out 1</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I am likely to refer back to the handouts and/or my notes from today 2</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I had sufficient opportunity to ask questions 2</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>There was too much content for the time available -1</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing 1</td>
</tr>
<tr>
<td>Course Code</td>
<td>Grade</td>
<td>Comment</td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
<td>---------</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>-1</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>0</td>
<td>An optional assignment would help to consolidate what I have learned</td>
</tr>
<tr>
<td>UWE7 N Mix 1.5 17</td>
<td>1</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>The content made sense</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>0</td>
<td>The topics we covered are applicable to my work</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>The industrial examples were a valuable inclusion</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>I have more questions now than before attending the course</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>The lecturer was easy to understand</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>The slides are well laid out</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>I had sufficient opportunity to ask questions</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>There was too much content for the time available</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>0</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>1</td>
<td>An optional assignment would help to consolidate what I have learned</td>
</tr>
<tr>
<td>UWE8 N M&amp;C 0 14</td>
<td>2</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
</tr>
<tr>
<td>UWE9 N M&amp;C 0 7</td>
<td>2</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>UWE9 N M&amp;C 0 7</td>
<td>1</td>
<td>The content made sense</td>
</tr>
<tr>
<td>UWE9 N M&amp;C 0 7</td>
<td>-1</td>
<td>The topics we covered are applicable to my work</td>
</tr>
<tr>
<td>Course</td>
<td>Tutor</td>
<td>Notes</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C 0</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
</tr>
<tr>
<td>Code</td>
<td>Type</td>
<td>Module</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix 0 5 An Introduction to the History and Manufacture of Composite Materials</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix 0 5 An Introduction to the History and Manufacture of Composite Materials</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix 0 5 An Introduction to the History and Manufacture of Composite Materials</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix 0 5 An Introduction to the History and Manufacture of Composite Materials</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix 0 5 An Introduction to the History and Manufacture of Composite Materials</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix 0 5 Manufacture of Composite Materials</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer 5 12 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer 5 8 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer 5 8 Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer 5 8 Tolerancing, Variability and Defects</td>
</tr>
</tbody>
</table>
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | The industrial examples were a valuable inclusion | 2  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet) | 2  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | I have more questions now than before attending the course | -1  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | The lecturer was easy to understand | 2  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | The slides are well laid out | 1  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | I am likely to refer back to the handouts and/or my notes from today | 1  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | I had sufficient opportunity to ask questions | 1  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | There was too much content for the time available | -2  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | I would like to learn more about advanced composites/other topics in composites manufacturing | 1  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | My company would benefit from (more) training in advanced composites | 2  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | An optional assignment would help to consolidate what I have learned | -1  
| TVD2 | Y | Computer | 5 | 8 | Tolerancing, Variability and Defects | I would be interested in adding up points from courses like this towards an academic qualification | 0  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | The course was interesting | 1  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | The content made sense | 1  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | The topics we covered are applicable to my work | 2  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | The industrial examples were a valuable inclusion | 2  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet) | 2  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | I have more questions now than before attending the course | -1  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | The lecturer was easy to understand | 2  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | The slides are well laid out | 0  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | I am likely to refer back to the handouts and/or my notes from today | 1  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | I had sufficient opportunity to ask questions | 2  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | There was too much content for the time available | -1  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | I would like to learn more about advanced composites/other topics in composites manufacturing | 2  
| TVD3 | Y | Computer | Blank | 2 | Tolerancing, Variability and Defects | My company would benefit from (more) training in advanced composites | 1  

Page 60
<table>
<thead>
<tr>
<th>TVD3</th>
<th>Y</th>
<th>Computer Blank</th>
<th>2</th>
<th>Tolerancing, Variability and Defects</th>
<th>An optional assignment would help to consolidate what I have learned</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td></td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>The course was interesting</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>The content made sense</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>The topics we covered are applicable to my work</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>The industrial examples were a valuable inclusion</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>I have more questions now than before attending the course</td>
<td>1</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>The lecturer was easy to understand</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>The slides are well laid out</td>
<td>1</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>I had sufficient opportunity to ask questions</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>There was too much content for the time available</td>
<td>-1</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>My company would benefit from (more) training in advanced composites</td>
<td>2</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>An optional assignment would help to consolidate what I have learned</td>
<td>0</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td>1</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>The topics we covered are applicable to my work</td>
<td>2</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>The industrial examples were a valuable inclusion</td>
<td>2</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
<td>2</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>I have more questions now than before attending the course</td>
<td>0</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>The lecturer was easy to understand</td>
<td>1</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>The slides are well laid out</td>
<td>0</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>I had sufficient opportunity to ask questions</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>There was too much content for the time available</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>An optional assignment would help to consolidate what I have learned</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The content made sense</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The topics we covered are applicable to my work</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The industrial examples were a valuable inclusion</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>I have more questions now than before attending the course</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The lecturer was easy to understand</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The slides are well laid out</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>I had sufficient opportunity to ask questions</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>There was too much content for the time available</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>An optional assignment would help to consolidate what I have learned</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>The content made sense</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>The topics we covered are applicable to my work</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>The industrial examples were a valuable inclusion</td>
</tr>
<tr>
<td>-----</td>
<td>----</td>
<td>-----</td>
<td>---</td>
<td>----</td>
<td>-------------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>I have more questions now than before attending the course</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>The lecturer was easy to understand</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>The slides are well laid out</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>I had sufficient opportunity to ask questions</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>There was too much content for the time available</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>An optional assignment would help to consolidate what I have learned</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The content made sense</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The topics we covered are applicable to my work</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The industrial examples were a valuable inclusion</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>I have more questions now than before attending the course</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The lecturer was easy to understand</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The slides are well laid out</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>I had sufficient opportunity to ask questions</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>There was too much content for the time available</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>Course Code</td>
<td>Year</td>
<td>Faculty</td>
<td>Year Level</td>
<td>Title</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>------</td>
<td>---------</td>
<td>------------</td>
<td>-------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1 9</td>
<td>Tolerancing, Variability and Defects</td>
<td>An optional assignment would help to consolidate what I have learned. I would be interested in adding up points from courses like this towards an academic qualification.</td>
<td></td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1 9</td>
<td>Tolerancing, Variability and Defects</td>
<td>The course was interesting. The content made sense.</td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3 12</td>
<td>Tolerancing, Variability and Defects</td>
<td>The topics we covered are applicable to my work. The industrial examples were a valuable inclusion.</td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3 12</td>
<td>Tolerancing, Variability and Defects</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet). I have more questions now than before attending the course.</td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3 12</td>
<td>Tolerancing, Variability and Defects</td>
<td>The lecturer was easy to understand. The slides are well laid out.</td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3 12</td>
<td>Tolerancing, Variability and Defects</td>
<td>I am likely to refer back to the handouts and/or my notes from today. I had sufficient opportunity to ask questions.</td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3 12</td>
<td>Tolerancing, Variability and Defects</td>
<td>There was too much content for the time available. I would like to learn more about advanced composites/other topics in composites manufacturing.</td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3 12</td>
<td>Tolerancing, Variability and Defects</td>
<td>My company would benefit from (more) training in advanced composites. An optional assignment would help to consolidate what I have learned. I would be interested in adding up points from courses like this towards an academic qualification.</td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5 4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The course was interesting. The topics we covered are applicable to my work. The industrial examples were a valuable inclusion.</td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5 4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet). I have more questions now than before attending the course.</td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5 4</td>
<td>Tolerancing, Variability and Defects</td>
<td>The lecturer was easy to understand. The slides are well laid out.</td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td>Type</td>
<td>Grade</td>
<td>Comment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>I had sufficient opportunity to ask questions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>There was too much content for the time available</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>My company would benefit from (more) training in advanced composites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>An optional assignment would help to consolidate what I have learned</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I had sufficient opportunity to ask questions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>There was too much content for the time available</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>My company would benefit from (more) training in advanced composites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>An optional assignment would help to consolidate what I have learned</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The course was interesting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The content made sense</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The topics we covered are applicable to my work</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The industrial examples were a valuable inclusion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I have more questions now than before attending the course</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The lecturer was easy to understand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The slides are well laid out</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I had sufficient opportunity to ask questions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>There was too much content for the time available</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>My company would benefit from (more) training in advanced composites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>An optional assignment would help to consolidate what I have learned</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I had sufficient opportunity to ask questions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>There was too much content for the time available</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The course was interesting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The content made sense</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2 Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The topics we covered are applicable to my work</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The course was interesting
The content made sense
The topics we covered are applicable to my work
<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Score</th>
<th>Rating</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>Code</td>
<td>Name</td>
<td>Mark</td>
<td>Type</td>
<td>Tolerancing, Variability and Defects</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>TVD14</td>
<td>Y</td>
<td>M&amp;C</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Company</td>
<td>Department</td>
<td>Year</td>
<td>Course</td>
<td>Comments</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>------</td>
<td>--------</td>
<td>----------</td>
</tr>
<tr>
<td>PC4</td>
<td>Computer</td>
<td>8</td>
<td>Production Costing</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
</tr>
<tr>
<td>PC4</td>
<td>Computer</td>
<td>8</td>
<td>Production Costing</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>PC4</td>
<td>Computer</td>
<td>8</td>
<td>Production Costing</td>
<td>An optional assignment would help to consolidate what I have learned</td>
</tr>
<tr>
<td>PC4</td>
<td>Computer</td>
<td>8</td>
<td>Production Costing</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>The content made sense</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>The topics we covered are applicable to my work</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>The industrial examples were a valuable inclusion</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>I have more questions now than before attending the course</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>The lecturer was easy to understand</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>The slides are well laid out</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>I had sufficient opportunity to ask questions</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>There was too much content for the time available</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>I would like to learn more about advanced composites/other topics in composites manufacturing</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>My company would benefit from (more) training in advanced composites</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>An optional assignment would help to consolidate what I have learned</td>
</tr>
<tr>
<td>PC5</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>I would be interested in adding up points from courses like this towards an academic qualification</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>The course was interesting</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>The content made sense</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>The topics we covered are applicable to my work</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>The industrial examples were a valuable inclusion</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>The practical aspect was beneficial (Seeing and holding composite parts and moulds/Hand layup exercise/Virtual Composites Company spreadsheet)</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>I have more questions now than before attending the course</td>
</tr>
</tbody>
</table>
The lecturer was easy to understand 2
The slides are well laid out 2
I am likely to refer back to the handouts and/or my notes from today 1
I had sufficient opportunity to ask questions 1
There was too much content for the time available -1
I would like to learn more about advanced composites/other topics in composites manufacturing 1
My company would benefit from (more) training in advanced composites 1
An optional assignment would help to consolidate what I have learned 1
I would be interested in adding up points from courses like this towards an academic qualification 1

There was too much content for the time available
The topics we covered are applicable to my work
The slides are well laid out
The lecturer was easy to understand
The industrial examples were a valuable inclusion
The course was interesting
The content made sense
My company would benefit from (more) training in advanced composites
I would like to learn more about advanced composites/other topics in...
I would be interested in adding up points from courses like this towards an...
I have more questions now than before attending the course
I had sufficient opportunity to ask questions
I am likely to refer back to the handouts and/or my notes from today
An optional assignment would help to consolidate what I have learned
The practical aspect was beneficial (Seeing and holding composite parts and...
<table>
<thead>
<tr>
<th>Suggestion</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>There was too much content for the time available</td>
<td>12</td>
</tr>
<tr>
<td>The topics we covered are applicable to my work</td>
<td>20</td>
</tr>
<tr>
<td>The slides are well laid out</td>
<td>15</td>
</tr>
<tr>
<td>The lecturer was easy to understand</td>
<td>25</td>
</tr>
<tr>
<td>The industrial examples were a valuable inclusion</td>
<td>20</td>
</tr>
<tr>
<td>The course was interesting</td>
<td>25</td>
</tr>
<tr>
<td>The content made sense</td>
<td>25</td>
</tr>
<tr>
<td>My company would benefit from (more) training in advanced composites</td>
<td>20</td>
</tr>
<tr>
<td>I would like to learn more about advanced composites/other topics in composites...</td>
<td>20</td>
</tr>
<tr>
<td>I would be interested in adding up points from courses like this towards an academic...</td>
<td>25</td>
</tr>
<tr>
<td>I have more questions now than before attending the course</td>
<td>15</td>
</tr>
<tr>
<td>I had sufficient opportunity to ask questions</td>
<td>20</td>
</tr>
<tr>
<td>I am likely to refer back to the handouts and/or my notes from today</td>
<td>15</td>
</tr>
<tr>
<td>An optional assignment would help to consolidate what I have learned</td>
<td>20</td>
</tr>
<tr>
<td>The practical aspect was beneficial (Seeing and holding composite parts and...)</td>
<td>20</td>
</tr>
</tbody>
</table>
### Question 2

<table>
<thead>
<tr>
<th>Person</th>
<th>Compjob?</th>
<th>Job type</th>
<th>Yrs comp</th>
<th>Yrs eng</th>
<th>Course</th>
<th>Enjoyment</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Amazing!!</td>
<td>2</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Amazing!!</td>
<td>2</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>UWE5</td>
<td>Y</td>
<td>Mix</td>
<td>Blank</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Meh</td>
<td>0</td>
</tr>
<tr>
<td>UWE6</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Meh</td>
<td>0</td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>UWE8</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>14</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Amazing!!</td>
<td>2</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>7</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>5</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Amazing!!</td>
<td>2</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Amazing!!</td>
<td>2</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>10</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Amazing!!</td>
<td>2</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
<td>Tolerancing, Variability and Defects</td>
<td>Meh</td>
<td>0</td>
</tr>
<tr>
<td>TVD14</td>
<td>Y</td>
<td>M&amp;C</td>
<td>2</td>
<td>7</td>
<td>Tolerancing, Variability and Defects</td>
<td>Meh</td>
<td>0</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
<td>Production Costing</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>-----</td>
<td>---</td>
<td>-----</td>
<td>----</td>
<td>----</td>
<td>---------------------</td>
<td>-----</td>
<td>---</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>Too many</td>
<td>Production Costing</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
<td>Production Costing</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
<td>Production Costing</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>PC5</td>
<td>Y</td>
<td>M&amp;C</td>
<td>15</td>
<td>24</td>
<td>Production Costing</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>Blank</td>
<td>Production Costing</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>Person</td>
<td>Compjob?</td>
<td>Job type</td>
<td>Yrs comp</td>
<td>Yrs eng</td>
<td>Course</td>
<td>Was the level correct?</td>
<td>Y axis</td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>---------</td>
<td>----------------------------------------------------</td>
<td>------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Bit difficult</td>
<td>1.1</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>UWE5</td>
<td>Y</td>
<td>Mix</td>
<td>Blank</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Bit difficult</td>
<td>1.5</td>
</tr>
<tr>
<td>UWE6</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Bit difficult</td>
<td>0.9</td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>UWE8</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>14</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>7</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Difficult</td>
<td>2</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>5</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Bit easy</td>
<td>-0.9</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>10</td>
<td>Tolerancing, Variability and Defects</td>
<td>Difficult</td>
<td>2</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Perfect</td>
<td>0</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Bit easy</td>
<td>-0.5</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>Bit easy</td>
<td>-0.7</td>
</tr>
<tr>
<td>Code</td>
<td>Letter</td>
<td>Category</td>
<td>Value</td>
<td>Tolerancing, Variability and Defects</td>
<td>Grade</td>
<td>Difficulty</td>
<td>Years</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>----------</td>
<td>-------</td>
<td>--------------------------------------</td>
<td>-------</td>
<td>------------</td>
<td>-------</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>Perfect</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>Tolerancing, Variability and Defects</td>
<td>Perfect</td>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td>Difficult</td>
<td>2</td>
<td>-0.1</td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Perfect</td>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>Tolerancing, Variability and Defects</td>
<td>Perfect</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>Tolerancing, Variability and Defects</td>
<td>Difficult</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>TVD14</td>
<td>Y</td>
<td>M&amp;C</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Easy</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>Production Costing</td>
<td>Perfect</td>
<td>0</td>
<td>-0.6</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>Production Costing</td>
<td>Perfect</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>Production Costing</td>
<td>Easy</td>
<td>-2</td>
<td>0.1</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>Production Costing</td>
<td>Easy</td>
<td>-2</td>
<td>-0.1</td>
</tr>
<tr>
<td>PC5</td>
<td>Y</td>
<td>M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>Bit easy</td>
<td>-1.3</td>
<td>0</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>Production Costing</td>
<td>Perfect</td>
<td>0</td>
<td>-0.7</td>
</tr>
<tr>
<td>Person</td>
<td>Job type</td>
<td>Yrs comp</td>
<td>Yrs eng</td>
<td>Course</td>
<td>Favourite part(s) of course</td>
<td>Category</td>
<td>Full quote</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>----------</td>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>----------------------------</td>
<td>-------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>History</td>
<td>Lecture section</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Handling composite parts</td>
<td>Practical</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Blank/None</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Industrial examples</td>
<td>Examples/case study</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Handling composite parts</td>
<td>Practical</td>
</tr>
<tr>
<td>UWE5</td>
<td>Y</td>
<td>Mix</td>
<td>Blank</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Blank/None</td>
</tr>
<tr>
<td>UWE6</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Blank/None</td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Different manufacturing techniques</td>
<td>Lecture section</td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Industrial examples</td>
<td>Examples/case study</td>
</tr>
<tr>
<td>UWE8</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>14</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Resin Transfer Moulding</td>
<td>Lecture section</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>7</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Automation</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Compute r</td>
<td>5</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>-----------</td>
<td>---</td>
<td>----</td>
<td>--------------------------------------</td>
<td>--------------------</td>
<td>----------</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Compute r</td>
<td>5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Compute r</td>
<td>5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Effects of defects</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Blank</td>
<td>2</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>10</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Defect root cause investigation</td>
<td>Examples/case study</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Industrial examples</td>
<td>Examples/case study</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Defect taxonomy</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Effects of defects</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>Defects</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>Defect taxonomy</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>Knowledgeable lecturer</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Effects of defects</td>
<td>Lecture section</td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Compute r</td>
<td>0.5</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Defect taxonomy</td>
<td>Lecture section</td>
</tr>
<tr>
<td>Code</td>
<td>Name</td>
<td>Mix</td>
<td>Tolerance, Variability and Defects</td>
<td>Defect root cause investigation</td>
<td>Examples/case study</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>-----</td>
<td>-----------------------------------</td>
<td>--------------------------------</td>
<td>-------------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8 12 Tolerancing, Variability and Defects</td>
<td>Defect root cause investigation</td>
<td>Examples/case study</td>
<td>The discussion using examples of pieces containing defects.</td>
<td></td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C Computer</td>
<td>0.333 2 Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
<td>Enjoyed the hand layup. Gave us an appreciation of how difficult it was.</td>
<td></td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0 18 Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
<td>Hand layup exercise</td>
<td></td>
</tr>
<tr>
<td>TVD14</td>
<td>Y</td>
<td>M&amp;C</td>
<td>2 7 Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
<td>The practical section of laying up prepreg was very useful. This made it clear how difficult it is to avoid defects with some geometry</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Mix</th>
<th>Production Costing</th>
<th>Overall understanding</th>
<th>Tips</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20 30 Production Costing</td>
<td>Overall understanding</td>
<td>Blank/None</td>
<td>Getting a better understanding of costing overall it is easier to learn when you have time to concentrate ie not working</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>Too many Production Costing</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank 10 Production Costing</td>
<td>Design for manufacture</td>
<td>Lecture section</td>
<td>DFMA</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Compute r</td>
<td>8 8 Production Costing</td>
<td>Industrial examples</td>
<td>Examples/case study</td>
<td>Industrial examples</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Compute r</td>
<td>8 8 Production Costing</td>
<td>Design for X</td>
<td>Lecture section</td>
<td>How DFX was applied</td>
</tr>
<tr>
<td>PC5</td>
<td>Y</td>
<td>M&amp;C</td>
<td>15 24 Production Costing</td>
<td>Statistics</td>
<td>Lecture section</td>
<td>Some interesting &amp; previously unknown stats.</td>
</tr>
<tr>
<td>PC5</td>
<td>Y</td>
<td>M&amp;C</td>
<td>15 24 Production Costing</td>
<td>Tips</td>
<td>Lecture section</td>
<td>A few tips not currently adopted.</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>M&amp;C</td>
<td>Blank Blank Production Costing</td>
<td>Good slides Knowledgeable lecturer</td>
<td>Slides Knowledgeable lecturer</td>
<td>Good slides</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>M&amp;C</td>
<td>Blank Blank Production Costing</td>
<td>Good slides Knowledgeable lecturer</td>
<td>Slides Knowledgeable lecturer</td>
<td>Good slides</td>
</tr>
</tbody>
</table>
### Question 5

<table>
<thead>
<tr>
<th>Person</th>
<th>Comp job?</th>
<th>Job type</th>
<th>Yrs comp</th>
<th>Yrs eng</th>
<th>Course</th>
<th>Least favourite part(s) of course</th>
<th>Category</th>
<th>Full quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Too much content</td>
<td>Too much content</td>
<td>A lot of info to fit into a day</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>UWE3</td>
<td>Blank</td>
<td>Meetings</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Too much content</td>
<td>Too much content</td>
<td>Understanding all the concepts, it was quite a lot to take in</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Process comparison</td>
<td>Lecture section</td>
<td>Process comparison</td>
</tr>
<tr>
<td>UWE5</td>
<td>Y</td>
<td>Mix</td>
<td>Blank</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Too much content</td>
<td>Too much content</td>
<td>Too much content for the timescale</td>
</tr>
<tr>
<td>UWE6</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Too much content</td>
<td>Too much content</td>
<td>Don't have much experience with composite so a lot of information to take in.</td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Lecture section</td>
<td></td>
</tr>
<tr>
<td>UWE8</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>14</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>7</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>5</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>All good</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Repair and concessions</td>
<td>Lecture section</td>
<td>Repair and concessions</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Repair and concessions</td>
<td>Lecture section</td>
<td>Concessions section as this was the part that I was already most familiar with</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Slides too verbose</td>
<td>Too much content</td>
<td>Large amount of words on the slides and a long time to be listening to a lot of information</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Too much content</td>
<td>Too much content</td>
<td></td>
</tr>
<tr>
<td>TVD</td>
<td>Y/M&amp;C</td>
<td>1/2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Prior knowledge assumed</td>
<td>Slides too verbose</td>
<td>Prior knowledge assumed</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>-----</td>
<td>--------------------------------------</td>
<td>------------------------</td>
<td>---------------------</td>
<td>------------------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y/M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>Prior knowledge assumed</td>
<td>Slides too verbose</td>
<td>Prior knowledge assumed</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y/M&amp;C</td>
<td>1.5</td>
<td>Tolerancing, Variability and Defects</td>
<td>Effects of defects</td>
<td>Effects of defects</td>
<td>Effects of defects</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD6</td>
<td>Y/M&amp;C</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD7</td>
<td>Mix</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Engineering drawing</td>
<td>Engineering drawing</td>
<td>Engineering drawing</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y/M&amp;C</td>
<td>1</td>
<td>Tolerancing, Variability and Defects</td>
<td>Slides too verbose</td>
<td>Slides too verbose</td>
<td>Slides too verbose</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD9</td>
<td>Y/M&amp;C</td>
<td>3</td>
<td>Tolerancing, Variability and Defects</td>
<td>Prior knowledge assumed</td>
<td>Slides too verbose</td>
<td>Prior knowledge assumed</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD10</td>
<td>Y/Comp</td>
<td>0.5</td>
<td>Tolerancing, Variability and Defects</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD11</td>
<td>Y/Mix</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Hand layup exercise</td>
<td>Practical</td>
<td>Some of the lay-up practical exercise was too long and not required</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y/M&amp;C</td>
<td>0.3333</td>
<td>Tolerancing, Variability and Defects</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD13</td>
<td>N/Comp</td>
<td>0</td>
<td>Tolerancing, Variability and Defects</td>
<td>Too much content</td>
<td>Too much content</td>
<td>Lots of powerpoint slides</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>TVD14</td>
<td>Y/M&amp;C</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Too much content</td>
<td>Too much content</td>
<td>Presentations seemed to go on for a while and could have benefitted from something to break them up more. Videos, more practical etc</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>PC1</td>
<td>Y/Mix</td>
<td>20</td>
<td>Production Costing</td>
<td>Too much content</td>
<td>Too much content</td>
<td>There was a lot to take in. Not sure if will ever have to cost a whole factory but who knows!</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>PC2</td>
<td>N/Comp</td>
<td>0</td>
<td>Production Costing</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>PC3</td>
<td>Y/M&amp;C</td>
<td>Blank</td>
<td>Production Costing</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Blank/None</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>PC4</td>
<td>Y/Comp</td>
<td>8</td>
<td>Production Costing</td>
<td>More examples needed</td>
<td>More examples needed</td>
<td>Can do with more examples!!</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>PC5</td>
<td>Y/M&amp;C</td>
<td>15</td>
<td>Production Costing</td>
<td>Design for manufacture</td>
<td>Lecture section</td>
<td>DFM...</td>
<td>Too much content</td>
<td>Too much content</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Production Costing</td>
<td>Virtual composites company spreadsheet</td>
<td>Practical</td>
<td>Spreadsheet was a bit dry! Could simplify and create quick cost analysis from scratch on spreadsheet</td>
<td></td>
</tr>
<tr>
<td>Person</td>
<td>Compj</td>
<td>Job type</td>
<td>Yrs comp</td>
<td>Yrs eng</td>
<td>Course</td>
<td>Topics(s) they would like to know more about</td>
<td>Category</td>
<td>Full quote</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>----------</td>
<td>----------</td>
<td>---------</td>
<td>------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------</td>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Manufacturing aircraft</td>
<td>Manufacturing</td>
<td>Manufacturing aircraft</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Aeroplanes</td>
<td>Composite product(s)</td>
<td>aeroplanes</td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>History</td>
<td>History</td>
<td>history</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank</td>
<td>Blank/None</td>
<td>Everything. I am going to go over the material to understand things more.</td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Everything</td>
<td>Everything</td>
<td>Everything</td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Resin infusion</td>
<td>Manufacturing</td>
<td>Resin infusion</td>
</tr>
<tr>
<td>UWE5</td>
<td>Y</td>
<td>Mix</td>
<td>Blank</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>None</td>
<td>Blank/None</td>
<td>N/A</td>
</tr>
<tr>
<td>UWE6</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank</td>
<td>Blank/None</td>
<td>N/A</td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Mass production</td>
<td>Manufacturing</td>
<td>Mass production -</td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Future trends and possibilities</td>
<td>Future</td>
<td>future trends/possibilities</td>
</tr>
<tr>
<td>UWE8</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>14</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Resin Transfer Moulding</td>
<td>Manufacturing</td>
<td>RTM</td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>7</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Non-aerospace/automotive applications</td>
<td>Composite product(s)</td>
<td>Applications outside aerospace/automotive industries</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>5</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Mould design</td>
<td>Manufacturing</td>
<td>Mold design</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Accounting for defects in requirements</td>
<td>Part requirements</td>
<td>How defects can be taken into account in the</td>
</tr>
<tr>
<td>TVD</td>
<td>Code</td>
<td>Unit</td>
<td>Page</td>
<td>Tolerancing, Variability and Defects</td>
<td>Description</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>-------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>12</td>
<td>Stress analysis of defects</td>
<td>Defect stress analysis from a stress point of view</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>8</td>
<td>Investigating defect root cause</td>
<td>Defect root cause investigation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>8</td>
<td>Defect correction</td>
<td>Defect correction and corrections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Blank</td>
<td>2</td>
<td>2</td>
<td>Materials other than prepreg</td>
<td>Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Blank</td>
<td>2</td>
<td>2</td>
<td>Manufacturing</td>
<td>Manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>10</td>
<td>Manufacturing</td>
<td>General manufacturing processes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Defects in assemblies/joints</td>
<td>Defects in specific area/item</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Defects/variability in CFRP tools</td>
<td>Defects &amp; variability in CFRP tools</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Experimental data on effects of defects</td>
<td>Effects of defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Inspections and working procedures</td>
<td>Managing manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Blank</td>
<td>Blank/None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>12</td>
<td>Materials variability and specifications, OOA</td>
<td>Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5</td>
<td>4</td>
<td>Testing</td>
<td>Testing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

More types of material - mostly pre-preg covered in this course. More on manufacturing of composites.

Materials other than prepreg. Materials and manufacturing processes.

Defects in assemblies/joints if possible. Further experimental data on effect of each defect. + clearer.

Inspections and working procedures. Managing manufacturing procedures.

With respect to materials variability & materials specifications. Content was mainly with respect to autoclave tech. How does out of autoclave tech differ? Or is it very similar?
<table>
<thead>
<tr>
<th>TVD11</th>
<th>Y</th>
<th>Mix</th>
<th>8</th>
<th>12</th>
<th>Tolerancing, Variability and Defects</th>
<th>Defect knock down on mechanical properties</th>
<th>Effects of defects</th>
<th>Linking defects to knock down in mechanical properties.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Non-destructive testing</td>
<td>Testing</td>
<td>New NDT developments</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Blank</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
<td>Tolerancing, Variability and Defects</td>
<td>Blank</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>TVD14</td>
<td>Y</td>
<td>M&amp;C</td>
<td>2</td>
<td>7</td>
<td>Tolerancing, Variability and Defects</td>
<td>Blank</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
<td>Production Costing</td>
<td>Costs of more processes</td>
<td>Manufacturing</td>
<td></td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>Too many</td>
<td>Production Costing</td>
<td>Composite materials</td>
<td>Materials</td>
<td>Composite materials &amp; application</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
<td>Production Costing</td>
<td>Blank</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
<td>Production Costing</td>
<td>Non-destructive testing</td>
<td>Testing</td>
<td>NDT</td>
</tr>
<tr>
<td>PC5</td>
<td>Y</td>
<td>M&amp;C</td>
<td>15</td>
<td>24</td>
<td>Production Costing</td>
<td>Blank</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>Blank</td>
<td>Production Costing</td>
<td>Open source cost modelling tools</td>
<td>Software tools</td>
<td>Open source costing model tools?</td>
</tr>
</tbody>
</table>
Categories of topics participants would like to know more about. Note that some chose more than one topic.
### Question 7

<table>
<thead>
<tr>
<th>Person</th>
<th>Comp job?</th>
<th>Job type</th>
<th>Yrs comp</th>
<th>Yrs eng</th>
<th>Course</th>
<th>Suggestions for improvement</th>
<th>Full quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td>None</td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>UWE3</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>More time- too much content. Spreading the talk over a longer period of time to give more time to understand and ask questions</td>
<td></td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Trip to NCC</td>
<td>Could be based around a trip to NCC?</td>
</tr>
<tr>
<td>UWE5</td>
<td>Y</td>
<td>Mix</td>
<td>Blank</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Breakdown content and split out over longer period of time</td>
<td></td>
</tr>
<tr>
<td>UWE6</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>UWE8</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>14</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank/None</td>
<td></td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>7</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Improve/reduce slides- less text, more graphics</td>
<td>Make easier to understand slides, less text, more figures and graphic examples- less information on slides</td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>5</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Improve/reduce slides- less text, more graphics</td>
<td>Lots of words on slides- not all used</td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>More practical</td>
<td>Add more practical and ??? Examples</td>
</tr>
<tr>
<td>------</td>
<td>---</td>
<td>----------</td>
<td>----</td>
<td>----</td>
<td>-------------------------------------</td>
<td>---------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>More group case studies/industrial examples</td>
<td>More group problem solving to discuss real life issues as these help the understanding of the presented material</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Improve/reduce slides- less text, more graphics</td>
<td>More images of defects in slides to break up words</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>More group case studies/industrial examples</td>
<td>+ more case studies.</td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Make level of course clearer</td>
<td>Unclear on level pitched at. Presumed some prior knowledge.</td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>10</td>
<td>Tolerancing, Variability and Defects</td>
<td>More group case studies/industrial examples</td>
<td>More engagement through the slides. “table exercises” would probably help</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>More group case studies/industrial examples</td>
<td>The more exercises the better,</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Improve/reduce slides- less text, more graphics</td>
<td>a few more pictures/diagrams too. Kevin’s industrial expertise is invaluable. If the presenter just followed the slides it could be boring. Kevin’s anecdotes &amp; tips/gems are key to this</td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>Keep Kevin’s stories</td>
<td></td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Add material related to another unit NDT</td>
<td>Add in information on how to detect + measure defects (NDT, microscopy, CT, metrology techniques) -&gt; Advantages + limitations. Do this through slides + practical exercise (NCC would probably be able to support exercise).</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>More group case studies/industrial examples</td>
<td>More practical examples</td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>Improve/reduce slides- less text, more graphics</td>
<td>less slides</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>Add material related to another unit Stress analysis (classical)</td>
<td>Calculations, tolerance stacks, hand calcs on stress from defects. Perhaps add some worked numerical examples of problems we may see that we can apply in our industry roles.</td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>More group case studies/industrial examples</td>
<td></td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>Improve/reduce slides- less text, more graphics</td>
<td>From Q5</td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>Add material related to another unit</td>
<td>Characteristics of fabric reinforcement, Polymer melt viscosity and chemorheology</td>
</tr>
<tr>
<td>------</td>
<td>---</td>
<td>-----</td>
<td>---</td>
<td>-----</td>
<td>----------------------------------</td>
<td>--------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>Improve/reduce slides- less text, more graphics</td>
<td>Less text on slides</td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>More group case studies/industrial examples</td>
<td>More discussion on design drawings. Maybe starting with basics. Some examples of good ones. Not just jumping straight to the terribles one.</td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.333</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>Blank/None</td>
<td>Break up the powerpoint slides with other things.. Maybe more practical work or videos or more student interaction</td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
<td>Tolerancing, Variability and Defects</td>
<td>More practical</td>
<td>The course seemed to be mainly based on autoclave and aerospace. This, although not too much of an issue, was not made clear.</td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
<td>Production Costing</td>
<td>More group case studies/industrial examples</td>
<td>We could have gone through a worked example with the cost tool- but will have a go!</td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>Too many</td>
<td>Production Costing</td>
<td>More practical</td>
<td>Some composite hard exhibits</td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
<td>Production Costing</td>
<td>Blank/None</td>
<td>Clear course objectives &amp; evaluate</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
<td>Production Costing</td>
<td>Make content of course clearer</td>
<td>From Q5</td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
<td>Production Costing</td>
<td>More group case studies/industrial examples</td>
<td>From Q5</td>
</tr>
<tr>
<td>PCS</td>
<td>Y</td>
<td>M&amp;C</td>
<td>15</td>
<td>24</td>
<td>Production Costing</td>
<td>Add detail in a specific area</td>
<td>Probably more emphasis on RC &amp; NRC split, impacts of processing on tooling &amp; NRCs</td>
</tr>
<tr>
<td>-----</td>
<td>---</td>
<td>-----</td>
<td>----</td>
<td>----</td>
<td>-------------------</td>
<td>-----------------------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>Blank</td>
<td>Production Costing</td>
<td>More group case studies/industrial examples</td>
<td>From Q5</td>
</tr>
<tr>
<td>Person</td>
<td>Compjob?</td>
<td>Job type</td>
<td>Yrs comp</td>
<td>Yrs eng</td>
<td>Course</td>
<td>Rating out of 10</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>---------</td>
<td>----------------------------------------------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>UWE1</td>
<td>N</td>
<td>Blank</td>
<td>0</td>
<td>6</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank</td>
<td></td>
</tr>
<tr>
<td>UWE2</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>UWE3</td>
<td>Student</td>
<td>Blank</td>
<td>Blank</td>
<td>Blank</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>UWE4</td>
<td>N</td>
<td>Meetings</td>
<td>Blank</td>
<td>13</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>UWE5</td>
<td>Y</td>
<td>Mix</td>
<td>Blank</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank</td>
<td></td>
</tr>
<tr>
<td>UWE6</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>8</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>UWE7</td>
<td>N</td>
<td>Mix</td>
<td>1.5</td>
<td>17</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>UWE8</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>14</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>Blank</td>
<td></td>
</tr>
<tr>
<td>UWE9</td>
<td>N</td>
<td>M&amp;C</td>
<td>0</td>
<td>7</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>UWE10</td>
<td>N</td>
<td>Mix</td>
<td>0</td>
<td>5</td>
<td>An Introduction to the History and Manufacture of Composite Materials</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>TVD1</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TVD2</td>
<td>Y</td>
<td>Computer</td>
<td>5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TVD3</td>
<td>Y</td>
<td>Computer</td>
<td>Blank</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>TVD4</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>10</td>
<td>Tolerancing, Variability and Defects</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TVD5</td>
<td>Y</td>
<td>Mix</td>
<td>1.5</td>
<td>8</td>
<td>Tolerancing, Variability and Defects</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TVD6</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>TVD7</td>
<td>Y</td>
<td>Mix</td>
<td>4</td>
<td>11</td>
<td>Tolerancing, Variability and Defects</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TVD8</td>
<td>Y</td>
<td>M&amp;C</td>
<td>1</td>
<td>9</td>
<td>Tolerancing, Variability and Defects</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>TVD9</td>
<td>Y</td>
<td>M&amp;C</td>
<td>3</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>TVD10</td>
<td>Y</td>
<td>Computer</td>
<td>0.5</td>
<td>4</td>
<td>Tolerancing, Variability and Defects</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TVD11</td>
<td>Y</td>
<td>Mix</td>
<td>8</td>
<td>12</td>
<td>Tolerancing, Variability and Defects</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TVD12</td>
<td>Y</td>
<td>M&amp;C</td>
<td>0.3333</td>
<td>2</td>
<td>Tolerancing, Variability and Defects</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>TVD13</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>18</td>
<td>Tolerancing, Variability and Defects</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td>Y/N</td>
<td>M&amp;C</td>
<td>Rating</td>
<td>Remarks</td>
<td>Category</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-----</td>
<td>------</td>
<td>--------</td>
<td>--------------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD14</td>
<td>Y</td>
<td>M&amp;C</td>
<td>2</td>
<td>7</td>
<td>Tolerancing, Variability and Defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>Y</td>
<td>Mix</td>
<td>20</td>
<td>30</td>
<td>Production Costing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC2</td>
<td>N</td>
<td>Computer</td>
<td>0</td>
<td>Too many</td>
<td>Production Costing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC3</td>
<td>Y</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>10</td>
<td>Production Costing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC4</td>
<td>Y</td>
<td>Computer</td>
<td>8</td>
<td>8</td>
<td>Production Costing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC5</td>
<td>Y</td>
<td>M&amp;C</td>
<td>15</td>
<td>24</td>
<td>Production Costing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC6</td>
<td>Blank</td>
<td>M&amp;C</td>
<td>Blank</td>
<td>Blank</td>
<td>Production Costing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 6- Original HEFCE bid

**Catalyst Fund: Closing the skills gap and supporting the Industrial Strategy through curriculum development**

**HEFCE business case template**

<table>
<thead>
<tr>
<th>Project information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lead institution</strong></td>
</tr>
<tr>
<td><strong>Project title</strong></td>
</tr>
<tr>
<td><strong>Project start date</strong></td>
</tr>
<tr>
<td><strong>Project end date</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contact person for the proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Title and full name</strong></td>
</tr>
<tr>
<td><strong>Position</strong></td>
</tr>
<tr>
<td><strong>Address for correspondence</strong></td>
</tr>
<tr>
<td><strong>Phone</strong></td>
</tr>
<tr>
<td><strong>Email</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Partners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Other institutions involved</strong></td>
</tr>
<tr>
<td><strong>Other key partners and investors</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Funding and investment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Catalyst Fund request</strong></td>
</tr>
<tr>
<td><strong>Total funding from other sources</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Breakdown of funding from other sources</th>
<th>1.0 FTE Staff resource</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Revenue</strong></td>
<td>£300,000</td>
</tr>
<tr>
<td><strong>Capital</strong></td>
<td>£</td>
</tr>
<tr>
<td><strong>Total project cost</strong></td>
<td>£300,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compliance with state aid and other relevant legislation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In your opinion, are state aid issues applicable to this project?</strong></td>
</tr>
</tbody>
</table>
Project description

The project will collaborate with the industrial partners of the National Composites Centre (a High Value Manufacturing Catapult hosted by the University of Bristol), to fund the curriculum design and development of innovative master’s level work-based learning in composites design and manufacturing. Using the capability and infrastructure of the National Composites Centre as the underpinning technology knowledge base, such curriculum will be tailored to demonstrated industrial need and co-designed with industry to be primarily accessible to second cycle learners from a range of composite disciplines. This well-structured and comprehensive portfolio of learning material will catalyse the creation of a sustainable training activity to up and re-skill existing and future workforce, and will potentially have significant impact in closing the skills gap. Professional accreditation of non-credit bearing courses will be sought from the Institute of Materials, Minerals and Mining (IOM3) and the Institution of Mechanical Engineers (IMechE).

This project is aligned with the priorities of the Government’s green paper, ‘Building Our Industrial Strategy’, in particular skills development (Pillar 2), cultivating world leading sectors (Pillar 8), and driving growth (Pillar 9).
Rationale for funding

Availability of a workforce with appropriate knowledge and skills plays a vital role in the success of UK advanced manufacturers to compete globally, with a lack of access to a suitably skilled workforce often stated as one of the top 3 barriers to growth [EEF]. In a developing sector such as composites, which is forecast to experience growth rates of 15% per year through to 2020 [UK Composites Strategy 2016], the challenge faced is particularly difficult and more pronounced.

The 2016 UK Composites Strategy, compiled by the Composites Leadership Forum, an industry-led trade body, saw a serious ‘potential risk of decline in market value by 2030 if technology and supply chain is not supported’ – owing to the poor provision of skilled staff. The document further states that “the current pool of people is small and as demand is increasing rapidly this has already become a major inhibitor to growth”.

At present, many composite-using companies have neither the capacity nor capability to provide in-house training programmes to up or re-skill their workforce. Instead, they look to the higher education (HE) sector to provide skills gaps solutions in the delivery of continuing professional development (CPD) short courses (credit and non-credit bearing). However, an endemic lack of industry input into the curriculum design and mode of delivery of HE courses indicates a missing mechanism, leading to low levels of engagement and enthusiasm. Furthermore, the process of selection can be difficult since no official database currently exists to facilitate the distribution of information of current courses incl. providers, content, learning outcomes, depth of content etc. If we are to close the skills gap in composites engineering through the development of innovative curricula, and ensure that we are providing a real service to industry with tangible benefits in design and manufacture with composites, then we must address the three main market failures:

1. Lack of industry input into curriculum design
2. Lack of integrated marketing and information of current HE provisions in learning
3. Lack of application-based learning material in composites engineering tailored to the needs of industry, and which exploits the unique and world-leading composites technology and manufacturing capabilities of High Value Manufacturing Catapults.

To help address this market failure, there is a strong case for the University of Bristol and the University of Plymouth to work jointly with the industrial partners of the National Composites Centre to co-design and co-develop a portfolio of innovative topic-based learning materials.

The Bristol Composites Institute (ACCIS) is a world-leading institute for composites research and education, combining blue-sky research with strong industrial links for exploitation and knowledge transfer. These activities are underpinned by its strong provision in postgraduate learning paths for advanced manufacturing subjects, and its strong links with other leading HE institutions and industry in composites manufacturing - through the EPSRC Future Composites Manufacturing Research Hub and the IOM3 British Composites Society.

The Materials and Structures (MAST)/Composites Engineering is a leading composites R&D facility at the University of Plymouth with many years’ experience in running short courses and workshops in composites design and manufacture, attracting over 2500 delegates industrial delegates. It is the only UK HE institution to offer Engineering Council accredited undergraduate degrees specialising in composites. Professor Summerscales was the inaugural Chair of the British Composites Society (BCS) Education, Professional Development and Recognition (EPDAR) sub-committee from 2009-2014. Dr Jasper Graham-Jones is University of Plymouth School of Engineering Academic Liaison Officer for eleven partner colleges bounded by Bristol, Falmouth, Jersey and Yeovil. The HEFCE proposal presents a timely opportunity to use Plymouth’s expertise and provision as a template for a defined minimum national composites curriculum. Professor John Summerscales has also been involved in discussions with the named co-applicants over a number of years. This project will assist in strengthening links with both NCC and the University of Bristol.
The National Composites Centre (NCC) is a High Value Manufacturing Catapult (HVMC) which provides industrial scale Research and Technology Development facilities to meet the needs of all sectors wishing to capitalise on the high-strength, low weight, corrosion-resistant qualities of composite materials. NCC works with many established users of advanced fibre composites in the aerospace, automotive, rail and other industries, and is also supported by a number of materials, equipment supplier and software houses. The NCC’s status as a world leading centre of excellence in composites, and as one of the largest UK employers of composite skilled staff, gives the project further credibility - providing the necessary support and resources to help realise the goals of the project.

The funding sought here will pay for the time of academic staff from Bristol and Plymouth to work with industry partners at the NCC to quantify curriculum requirements, identify gaps, and develop learning content.
Fit with organisational strategy

The University of Bristol has a strategic commitment to develop postgraduate research training relationships with HE institutions and industry partners. The Bristol Composites Institute (ACCIS) is home to both the EPSRC Centre for Doctoral Training (PhD) and the Industrial Doctorate Centre in Composites Manufacturing (EngD level), supporting a large number of scientists and engineers via an innovative programme of training. Under the EngD programme, research engineers conduct PhD-equivalent research and undertake taught technical courses whilst working closely with an industrial sponsor at the NCC. Previous and current projects have involved AgustaWestland, Airbus, dstl, GE Aviation, Haydale, RNLI, Rolls-Royce, Jaguar Land Rover and Vestas. The significant investment and strong industrial involvement illustrates the scale of the challenges ahead and highlights the importance and expected benefits in seeking to rebalance the economy towards high value manufacturing using composite materials [WECA]. A major highlight of the taught course component is the Design, Build and Test project, which provides hands-on experience and allow students to apply their attained understanding and analysis of composites to real world industrial problems. This pedagogical model of application-based learning (involving a suite of masters’ level taught units) will serve as a template and model for the HEFCE project.

The University of Bristol also has a strategic commitment to review, reshape and expand our portfolio of taught postgraduate masters’ and continuing professional development programmes to ensure that they are fit for purpose in the national and international marketplace in terms of their content, structure and modes of delivery.

In 2014, Phase 2 of the National Composites Centre was built, doubling the size of the centre to enhance its ability to include skills, training and further development opportunities for the UK Composites Industry. However, this investment needs to be complemented more widely by a significant increase in the availability of work-based learning content in the form of contextual CPD and short course learning, as proposed in the HEFCE bid.

The University of Plymouth is one of the very few HE institutions to offer dedicated composite courses at degree level. Since 1987, Plymouth has provided CEng/IEng accredited degree pathways to over 500 graduates, many of whom have risen to important roles in the sector, and has provided a strong provision of accredited short courses to industrial delegates. Plymouth will bring their respective insight and expertise to the HEFCE proposal in the area of curriculum mapping and design, and the associated access of learning resources and other sector data held within systems at Plymouth. The HEFCE activity also complements Plymouth’s School of Engineering Strategy which expects to see a new Engineering Building for teaching, research and industrial collaboration in the near future with increase space allocated to composites.

The University of Bristol and the National Composites Centre are also official delivery partners of the Composites Leadership Forum (CLF), an industry-led body working to coordinate and connect the activities of composite-using companies with skills and training. The 2016 UK Composites Strategy identified an urgent need to develop not only new people with the right skills, but re-skilling and up-skilling those already in work with the necessary composite skills and knowledge. The recommendations made to meet this forecast demand is beyond the scope of NCC Phase 2 and what is currently being provided in the UK, hence the urgent need for this HEFCE proposal.
Wider benefits

A key benefit of this project is the use of education / teaching material to trigger and facilitate wider adoption and usage of composites. The National Composites Centre has received over £70m in technology investment, the next step is to embed a ‘knowledge transfer’ culture in the education/training domain by providing ‘end-to-end’ learning paths for employees. The transfer, wider adoption and engagement with the practical and process aspects of composites are key to de-risking the technology for many employers.

By working with industrial partners of NCC to produce the skilled workforce of the future, through learning and knowledge transfer, helps to anchor and secure market share, growth and jobs in the UK. This will benefit the wider public – through lighter and more fuel efficient aero-engines or cars, safer and more durable structures, or the engineering of more sustainable materials.

This proposal will help support the National Composites Centre and its Tier 1,2 members who at present do not have the resources or critical mass of learning expertise to develop a portfolio of learning objects and material of this scale alone. This project will develop a unique partnership between industry and HEIs to ensure that the curriculum is fit for purpose and that the project will help provide an impact beyond participating institutions and will provide benefits to the local and wider economy. The database of current HE provisions will also direct industrial clients more smoothly towards the most appropriate training course for his/her particular training needs, resulting in healthy competition between providers.

This proposal is also predicated on key Government and HEFCE priorities related to the need for HE to be a key driver in supporting and enhancing local economic activity through producing HE learners equipped with the right skills and knowledge for useful and productive careers, and improved knowledge exchange with employers.

Finally, the wider industrial education and training landscape requires the provision of flexible application-based CPD material rather than conventional full-time or part-time HE programme. This will bring huge benefits to employers as it will allow staff to develop specific capabilities and knowledge as and when required rather than studying for a complete qualification. Individuals can also seek recognised qualifications providing long term professional development and employment security.

Dissemination and review

The project will adopt a range of strategies designed to achieve sustainable impact beyond the 12-month lifetime of the project. Engagement and dissemination during the project will take place via (but not limited to) the following activities:

- Publication and dissemination of outcomes from curriculum mapping exercise to industrial partners and HEIs (learner numbers and course uptake).
- Regular communication of project activities and findings to key beneficiaries (West of England Combined Authority), seeking guidance and feedback where appropriate.
- An on-going communication strategy including the use of quarterly Newsletters and a project website.
- Use the NCC to promote dissemination of the resulting portfolio of training material to a wide range of industrial stakeholders from different sectors via seminars and showcase events.
Inputs, outputs and outcomes

Using the table below detail the key inputs, activities, outputs and outcomes for the project. Include specific targets which are clearly aligned with the HEFCE funding period. Please confirm when any baseline measures will be available.

This table will be used to draft the success criteria and measures for project monitoring purposes, should the bid be approved for funding.

<table>
<thead>
<tr>
<th>Input</th>
<th>Activity</th>
<th>Output</th>
<th>How financed or resourced</th>
<th>Outcomes (short-, medium- and long-term)</th>
<th>Measurable impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 FTE (UoB)</td>
<td>Curriculum mapping exercise: identify the composites learning provision from leading UK HE providers and benchmark this against our international comparators.</td>
<td>Curriculum map and database will provide an accurate status of HE capability and capacity for composites learning by subject area incl. CPD/short courses.</td>
<td>HEFCE &amp; University of Bristol</td>
<td>Establish formal links between the providers and end-users, and to facilitate the distribution of information of current HE provisions.</td>
<td>Quantify provision, current demand, participation rates and capacity of undergraduate, postgraduate, and CPD/short courses in Composites Engineering.</td>
</tr>
<tr>
<td>0.25 FTE (HEFCE-UoB)</td>
<td>Demand model and gap analysis: Curriculum framework design and specification through a structured consultation exercise with industry and academia. Priority of response to gaps in current HE provisions</td>
<td>A learning / curriculum matrix of key topics informed by industry and academia. Requirements for new materials and resource allocation.</td>
<td>HEFCE &amp; University of Bristol</td>
<td>Academic and industrial engagement in curriculum design, teaching and learning. Guarantee that curriculum output is fit for purpose with industrial partners. Clarity on learning development needs and ensure fit for purpose curriculum.</td>
<td>Key metrics: increase in uptake; participating in meetings, events and workshops; identify relevant case studies; providing learners and HE providers with access to equipment and resources; and sharing practice. Increase in enrolment of learners from industry on such courses.</td>
</tr>
<tr>
<td>0.0625 FTE (HEFCE-Ply.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.42 FTE (UoB)</td>
<td>Develop a set of appropriate low-cost learning objects and resources – including texts, course notes, presentation, practical sessions and assessment criteria incl. worked through examples and industrial case studies.</td>
<td>Produce a portfolio of flexible topic-based learning material,</td>
<td>HEFCE &amp; University of Bristol</td>
<td>Make the content and objects available to National Composites Centre.</td>
<td>Increase in industry personnel undertaking CPD training or re-skilling and / or up-skilling programmes.</td>
</tr>
<tr>
<td>0.42 FTE (HEFCE-UoB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1042 FTE (HEFCE-Ply.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.17 FTE (UoB)</td>
<td>Dedicate resources to pilot curriculum at National Composites Centre</td>
<td>CPD/Short course</td>
<td>HEFCE &amp; University of Bristol</td>
<td>Teaching of HE staffs in work-based environment. Assess learning approach in terms of mode of delivery, depth of content and workplace relevance.</td>
<td>Learning experiences and outcomes relating to teaching and learning developments and innovations: e.g. course evaluation feedback; learner and employer satisfaction.</td>
</tr>
<tr>
<td>0.17 FTE (HEFCE-UoB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0417 FTE (HEFCE-Ply.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.08 FTE (UoB)</td>
<td>Lessons learnt and make content available to industrial partners of NCC</td>
<td>Catalogue of learning objects and case studies made available to industrial partners of NCC.</td>
<td>HEFCE &amp; University of Bristol</td>
<td>Resolve IP ownership at publication and in future. Disseminate outcomes of project to relevant stakeholders.</td>
<td>Key metrics: license structure with HE and NCC. Further up-take of CPD/short courses from baseline measures.</td>
</tr>
<tr>
<td>0.08 FTE (HEFCE-UoB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0208 FTE (HEFCE-Ply.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Total project costs and funding per year

### Table 1: Revenue funding

<table>
<thead>
<tr>
<th>Principal use of funds</th>
<th>Academic year 2017-18</th>
<th>Academic year 2018-19</th>
<th>[add other years for full length of project]</th>
<th>Total £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institution’s own funds</td>
<td>1.0 FTE to support curriculum development activities</td>
<td>£58,000</td>
<td>£42,000</td>
<td>£100,000</td>
</tr>
<tr>
<td>HEFCE Catalyst Fund</td>
<td>1.20 FTE (Bristol) and 0.25 FTE (Plymouth) incl travel and co-development costs</td>
<td>£117,000</td>
<td>£83,000</td>
<td>£200,000</td>
</tr>
<tr>
<td>HEFCE other grant</td>
<td>(give detail)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other 1</td>
<td>(name source)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other 2</td>
<td>(name source)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>£175,000</td>
<td>£125,000</td>
<td>£300,000</td>
</tr>
</tbody>
</table>

### Table 2: Capital funding

<table>
<thead>
<tr>
<th>Principal use of funds</th>
<th>Academic year 20XX-XX</th>
<th>Academic year 20XX-XX</th>
<th>[add other years for full length of project]</th>
<th>Total £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institution’s own funds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEFCE other grant</td>
<td>(give detail)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other 1</td>
<td>(name source)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other 2</td>
<td>(name source)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3: Total funding

<table>
<thead>
<tr>
<th>Funding source</th>
<th>Academic year 2017-18</th>
<th>Academic year 2018-19</th>
<th>[add other years for full length of project]</th>
<th>Total £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institution’s own funds</td>
<td>£58,000</td>
<td>£42,000</td>
<td></td>
<td>£100,000</td>
</tr>
<tr>
<td>HEFCE Catalyst Fund</td>
<td>£117,000</td>
<td>£83,000</td>
<td></td>
<td>£200,000</td>
</tr>
<tr>
<td>HEFCE other grant (give detail)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>£175,000</td>
<td>£125,000</td>
<td></td>
<td>£300,000</td>
</tr>
</tbody>
</table>

Is the institution borrowing to fund this proposal? **No.**

**Leverage**

Please complete the table below advising of any leverage that Catalyst Funding would secure. Where possible, provide evidence of committed funds, and detail any specific conditions of these grants.

<table>
<thead>
<tr>
<th>Funding source</th>
<th>Amount</th>
<th>Status*</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Composites Centre, High Value Manufacturing Catapult</td>
<td>£500k</td>
<td>Secured</td>
<td>NCC Composites Transition Programme – April 2018. Enquiries already received for programmes similar in nature to 'conversion course'. April 2018 programme will inform HEFCE Catalyst work.</td>
</tr>
</tbody>
</table>

*Options for status column: secured, secured in principle, secured with conditions, pending outcome, identified but not approached.*
Value for money

Describe how the project represents excellent value for money – this should be against the outputs and targets to justify the costs involved and overall funding request to HEFCE.

Describe how the costs relate to the outputs of the project, and describe how the mix of public, private and institutional funds is proportionate.

We are seeking here a one-off funding of an intense 12-month period of curriculum horizon scanning, course design and development that will lead to a flexible portfolio of learning material that will be initially piloted to a dedicated cohort of learners at the NCC in 2018. Once assured and accredited, this content will then be made accessible to the industrial partners of the NCC (nearly 50 tier 1,2 members) to be used for a variety of levels and audiences. The NCC alone (not including industrial partners) is expected to recruit over 250 research engineers over the next few years so we can expect well in excess of 100 annually once the content is fully developed and accredited. Hence this project has a target of some 1,000 learners over a 5-year period. In terms of cost per head, this represents good value for money. Learner and delegate numbers will be monitored and reported by the project. The additional funding from the University of Bristol to support this HEFCE project, presents a rare opportunity to begin to address the demand for workplace curriculum in composites engineering to secure market growth and jobs, which is directly aligned with the UK Industrial Strategy.

There are several ways in which value for money can also be achieved:

- The combined capacity, expertise and academic and industrial networks of the three partners will considerably reduce consultation, dissemination and networking costs.
- Utilising the expertise and national and local employer links of over 50 composite-using companies via the NCC.
- Controlling costs by using salary rates related to the higher education sector to buy-out staff time for curriculum development activities.

Sustainability: Financial

How will the overall project or its key activities be sustained beyond the HEFCE funding period?

Describe the cost base needed to sustain the project beyond any HEFCE funding period, the other forms of investment and income that will be provided in the longer term, and how they will be secured.

What efficiencies will be generated by the project?

The funding being sought here provides for the modest number of FTEs that need to be dedicated in initial curriculum mapping, design, development, and pilot delivery. After the course material developed by this funding is made available to the NCC and its industrial partners, the University of Bristol and NCC would take on the costs of ongoing updates and revisions, as routine business funded ultimately by regular income streams, e.g. from Catapult funding. There is no immediate plan to monetise the content created by this project, certainly not until content has been professionally accredited by the IMechE and IOM3, although it could in principle be used for delivery of bespoke courses to industry as conversion courses or re-skilling purposes.
**Project risks**

*Identify the top five risks to this project, how they will be mitigated and their probability versus their impact.*

Depending on the information provided in this section, we may also request a full risk register to support our assessment process.

<table>
<thead>
<tr>
<th>Risk</th>
<th>Mitigation</th>
<th>Probability and impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of wide agreement on overall curriculum and content</td>
<td>Mitigated by early establishment of academic and industrial oversight. Bristol and Plymouth are both members of the Bristol Composites Society (BCS) board meetings. Bristol is also a member of the EPSRC Future Composites Manufacturing Hub.</td>
<td>Low probability – High impact</td>
</tr>
<tr>
<td>Identifying and unlocking the people with the right skills to deliver the required academic/teaching materials from their days jobs at the right time, and manage development to time and cost</td>
<td>Take early steps to identify and secure the release of key individuals for the necessary timescales.</td>
<td>Without HEFCE funds – high probability and high impact.</td>
</tr>
<tr>
<td>Attract buy-in and dissemination of products with industry</td>
<td>Mitigated by early promotion of activities at industrial seminars and meeting.</td>
<td>Low probability of poor engagement from NCC and Tier members. High impact.</td>
</tr>
<tr>
<td>Investigate and resolve IP ownership at publication and in future.</td>
<td>Establish license structure with HE and Catapult partners.</td>
<td>Medium probability and high impact if HE and Catapult partners fail to agree licensing structure.</td>
</tr>
<tr>
<td>Course content becomes out of date, obsolete or requires continual updating.</td>
<td>Although course content will require updates over time to reflect emerging and developing technology, the core elements of the course will have reached a level of technological maturity to satisfy the next 10-20 years. Academic and industrial partners are world-leading professionals – at the forefront of current and emerging technology.</td>
<td>High probability that some elements of the course will need updating and refining over time. Low impact if resources continue to be dedicated to maintaining and developing course material.</td>
</tr>
</tbody>
</table>
Accountability and governance

Describe the governance and management structures and arrangements for the project, including the accountable person (the project manager) for delivery. State who is ultimately responsible for project delivery and success – for instance, the Pro Vice-Chancellor or Vice-Chancellor.

The principal investigator of this project is Professor Kevin Potter. The Head of School of Civil, Aerospace and Mechanical Engineering, Professor Ian Bond, at the University of Bristol is ultimately responsible for project delivery and success. The project manager responsible for delivery is Dr Galal Mohamed, Senior Research Associate at the University of Bristol.

Under the umbrella of the Composites Leadership Forum, organisations such as Composites UK, the National Composites Centre, the British Composites Society, and the EPSRC Future Composites Manufacturing Research Hub, will provide quality assurance and accreditation oversight of course development activities on a quarter-yearly basis.

Impact assessment: Equality and diversity

Detail the processes that have been or will be undertaken to review the impact of this project relating to equality and diversity

The project is designed to deliver benefits and positive outcomes to all project stakeholders, particularly to all types of learners irrespective of their different characteristics and backgrounds. The University of Bristol and the University of Plymouth all have significant experience and expertise in addressing the particular needs of the different individuals and groups in the nine protected areas covered by the Equality Act (2010). In particular, they are focused on how their policies, practices and decisions impact on different individuals and groups when thinking about their focus on improving the quality of education, improving learner choice, and enhancing the learner experience. We would therefore expect the project to have a positive impact on equality and diversity issues if the project outcomes are achieved, through supporting a step change in access to high-quality learning resources and short courses for the full range of potential learners across all protected areas. Both HE institutions recognised that the HE sector serves, and draws, on the talents and skills of a diverse population. Furthermore, both HE institutions hold a bronze Athena Swan aware for recognising commitment to advancing women’s careers in STEMM academia.
Confirmation of approval for proposal

Proposals will only be considered if they have appropriate senior university or college support. We cannot accept bids from individuals. Attach a supporting statement or letter from the head of the lead institution and other project partners as appropriate. Attach a supporting statement or letter from Director of Finance at the lead institution.

NB: All letters should ideally be submitted as one document.

In addition to the supporting statements/letters specified above, please also note the attached additional letters of support:

- Letters of support from National Composites Centre and Composites UK
Key milestones

Key milestones based on the template below should be completed and submitted with the business case. We require a summary of the activities involved in the project, the associated key risks and how these will be mitigated, and how the milestones fit with the project’s success criteria, impacts and outcomes.

<table>
<thead>
<tr>
<th>Target</th>
<th>Key milestone</th>
<th>Key risks</th>
<th>Actions to mitigate risk</th>
<th>Completion date</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target 1</td>
<td>Conclusion of Curriculum mapping exercise</td>
<td>Poor engagement and buy-in from partner HEIs</td>
<td>Attract buy-in of curriculum mapping exercise through existing network channels via EPSRC Future Composites Manufacturing Research Hub and the British Composites Society</td>
<td>March 2018</td>
<td>Results will be used to inform availability and level of learning in core composite areas of design, stress, materials and manufacturing.</td>
</tr>
<tr>
<td>Target 2</td>
<td>Demand and gap analysis through structured consultation with industry and HEIs</td>
<td>Lack of wide agreement on overall curriculum and content</td>
<td>Mitigated by early establishment of academic and industrial oversight. NCC will act as a conduit to engage industry buy-in and engagement.</td>
<td>April 2018</td>
<td>Verification and validation that curriculum is fit for purpose and prioritise response to gaps appropriately.</td>
</tr>
<tr>
<td>Target 3</td>
<td>Development of contextual learning objects and materials incl. NCC based case studies</td>
<td>Identifying and unlocking the people with the right skills to deliver the required academic/teaching materials from their days jobs at the right time, and manage development to time and cost</td>
<td>Take early steps to identify and secure the release of key individuals for the necessary timescales.</td>
<td>October 2018</td>
<td>A strong portfolio of work-based learning material that can be initially piloted at the NCC through their workforce development schemes.</td>
</tr>
<tr>
<td>Target 4</td>
<td>Pilot curriculum at National Composites Centre</td>
<td>Clash of schedules due to University teaching timetable and NCC recruitment activities.</td>
<td>Take early steps to engage with UoB and NCC to schedule block delivery of content and ensure resources are available.</td>
<td>November-December 2018</td>
<td>Lessons learnt and feedback to improve learner experience before making content more widely available.</td>
</tr>
</tbody>
</table>
Appendix 7- Monitoring report July 2018

Catalyst Fund: Closing the skills gap and supporting the Industrial Strategy through curriculum development
Interim monitoring report

<table>
<thead>
<tr>
<th>HE Provider</th>
<th>University of Bristol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project title</td>
<td>Composites Curriculum Development</td>
</tr>
<tr>
<td>Project code</td>
<td>N12</td>
</tr>
<tr>
<td>Contact name</td>
<td>Kevin Potter</td>
</tr>
<tr>
<td>Email</td>
<td><a href="mailto:aekdp@bristol.ac.uk">aekdp@bristol.ac.uk</a></td>
</tr>
<tr>
<td>Tel No.</td>
<td>0117 331 5277</td>
</tr>
<tr>
<td>Date report due</td>
<td>31 July 2018</td>
</tr>
<tr>
<td>Date report submitted</td>
<td></td>
</tr>
</tbody>
</table>

Frequency for reports to be submitted to OfS:
The project will be monitored formally at two points:

- 31 July 2018 - Interim monitoring report (incorporating all activity to the end of March 2018)
- 28 February 2019 - Final report

A separate template will be provided for the final report which will also include a financial self-certification form.

Annexe
Annex A: Key milestones table update

---

**Key milestones**

1. In addition to updating the key milestones table in annex A, in this section, provide details of any significant milestones which have not been met with information on why they have not been met, along with mitigating actions.

---

**Project delivery and outputs**

2. In this section, detail the key achievements of the project to date.

The project team has been assembled and is working well.

The initial assessment of UK capacity to deliver composites training has been carried out and an international assessment is to follow.

Work is ongoing with the National Composites Centre to understand its training needs and how it might use the sort of curriculum that that this project will develop.

A draft Composite Curriculum Proposed Structure has been generated based around a series of 54 Masters level 2 Credit Point units and an introductory core of 5 x 2 CP units at UG level to allow learners with no prior background in composites to access the higher level material. The 54 masters level units are assembled into nine blocks of six units each covering Materials, Product Design A & B, Manufacturing Processes A & B, Manufacturing Operations A & B, Performance A & B. This draft structure has been disseminated to academic institutions and other key stakeholders for feedback.

An open meeting was held on 22nd May to present the project and the proposed curriculum structure to potential academic partners. Invitations went out to all those institutions that had been identified as providing a significant level of composites education. Representatives of eight universities attended and two additional
institutions gave their apologies and asked to be kept informed of developments. The institutions we are currently working with are Cardiff, Cranfield, Imperial, Sheffield, Southampton, Wrexham Glyndwr, Ulster & UWE in addition to the lead institutions of Bristol and Plymouth.

It is our belief that the wider aims of developing the capacity of the UK academic sector in composites education requires a collaborative approach across multiple academic groups. To that end a Draft memorandum of Understanding has been circulated to all the institutions that expressed an interest in being a part of this activity and we are currently awaiting feedback. It is our intention to develop a group of collaborating institutions that after the end of this project will continue to work together to deliver common aims.

Based on the current proposed structure (which may be subject to change based on input from our potential academic collaborators) we have started to populate the curriculum structure with Unit Descriptions and second level plans. Roughly half of the Unit Descriptions have been prepared by Plymouth and Bristol and as a first step towards developing collaboration a request has been made for volunteers to deliver Unit Descriptions in their areas of expertise. To date three institutions have agreed to provide these. In addition to the Unit descriptions one element of one unit has been worked through to a lecture slide deck and learning exercises so as to be able to estimate the resource requirements to generate new material across the board.

Alongside the formal curriculum development we are collecting together support material and resource material that could become part of a wider package of teaching support. For example the university of Bristol has access to a very large number of sample structures used in teaching demonstrations. These are being catalogued and photographed and the photographs will become part of the resource base for wider dissemination. As the collaborations develop we will widen this to the other institutions involved.

We attended a Composites Leadership Forum meeting on 24th of May that was intended to capture the industry needs and made a presentation about our project. A follow up meeting to cover the industry view in more detail with key stakeholders is scheduled for 2nd August.

3. In this section, provide details of any significant inputs or outputs which have not been met with information on why they have not been met, along with mitigating actions.

It has taken longer than expected to engage with potential academic partners and collaborators although collaboration is now in evidence. This has been mitigated by bringing forward some aspects of the work (such as development of a lecture slide deck and learning exercises) to level out the resource allocation.

4. Has the project encountered any unanticipated challenges (internal or external) in the course of developing the project? If so, outline how these have been dealt with them.

We have lost a key member of staff due to their move outside the academic sector. We made an attempt to mitigate this by a short term contract for another staff member, but that person has also moved on. This has delayed the work on international comparators, but we are currently about to put in place a solution to allow this work to go ahead. In addition we have taken on additional admin resource to collect data and resources and enable the programme leads to focus on the more technical deliverables.

We have found it difficult to get a clear industry view. The CLF meeting on the 24th of May was focused at too low a skills level to be useful to us. To mitigate we have used the NCC as a surrogate industry view and made direct contact with a number of industry people to check that our draft curriculum would meet their needs, and the meeting on the 2nd of August should give us the clarity that we need.

5. Has there been any change in the key partners involved in the project compared to those listed in the business case submitted to HEFCE in September 2017? If so, provide full details and reasons for changes.
Terms and conditions

6. Please confirm the following terms and conditions, as outlined in the award letter, are being adhered to. Where this cannot be confirmed, please provide additional information.

<table>
<thead>
<tr>
<th>Funding cannot be used to fund business support activity.</th>
<th>Confirm</th>
</tr>
</thead>
<tbody>
<tr>
<td>All provision must commence no later than the 2019/20 academic year.</td>
<td>Confirm</td>
</tr>
</tbody>
</table>

Finance and Risk

7. Complete the second row of the table below.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Catalyst funding awarded</td>
<td>£200,000</td>
</tr>
<tr>
<td>Catalyst funding received from HEFCE/OfS up to monitoring date of 31 July 2018</td>
<td>£133,334</td>
</tr>
<tr>
<td>Catalyst funding spent by monitoring date</td>
<td></td>
</tr>
<tr>
<td>Is the project on track to spend the full awarded Catalyst funding by 28 February 2018?</td>
<td>Yes/No</td>
</tr>
</tbody>
</table>

8. Where there is a different between the funding received and funding spent and/or the project is not on track to spend the full award by February, provide a brief narrative on why this is the case and confirm a date by when the current funding provided will be spent. The OfS is unable to provide funding in advance of need and so we may seek to re-profile the timing of future payments..

9. Has there been any change in the investment profile as outlined in the business case submitted to HEFCE in September 2017? If so, provide full details.

10. Where funding was detailed in the leverage section of the business case submitted to HEFCE in September 2017, provide an update on the status of this funding.

11. Has there been any change to the risk status of the project? If so, provide full details.
## Annex A: Updated key milestones

<table>
<thead>
<tr>
<th>Target</th>
<th>Key milestone</th>
<th>Key risks</th>
<th>Actions to mitigate risk</th>
<th>Completion date</th>
<th>Outcome</th>
<th>July 2018 Update</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conclusion of Curriculum mapping exercise</td>
<td>Poor engagement and buy-in from partner HEIs</td>
<td>Attract buy-in of curriculum mapping exercise through existing network channels via EPSRC Future Composites Manufacturing Research Hub and the British Composites Society</td>
<td>March 2018</td>
<td>Results will be used to inform availability and level of learning in core composite areas of design, stress, materials and manufacturing.</td>
<td>Engagement has generally been positive once the collaborative aspects of the process have been clarified</td>
</tr>
<tr>
<td>2</td>
<td>Demand and gap analysis through structured consultation with industry and HEIs</td>
<td>Lack of wide agreement on overall curriculum and content</td>
<td>Mitigated by early establishment of academic and industrial oversight. NCC will act as a conduit to engage industry buy-in and engagement.</td>
<td>April 2018</td>
<td>Verification and validation that curriculum is fit for purpose and prioritise response to gaps appropriately.</td>
<td>To date we have had no negative comments on the draft curriculum that has been developed. Positive feedback has been received from the NCC on the appropriateness of the material.</td>
</tr>
<tr>
<td>3</td>
<td>Development of contextual learning objects and materials incl. NCC based case studies</td>
<td>Identifying and unlocking the people with the right skills to deliver the required academic/teaching materials from their days jobs at the right time, and manage development to time and cost</td>
<td>Take early steps to identify and secure the release of key individuals for the necessary timescales.</td>
<td>October 2018</td>
<td>A strong portfolio of work-based learning material that can be initially piloted at the NCC through their workforce development schemes.</td>
<td>Good progress is being made in fleshing out the curriculum, collecting and developing teaching resources and in close liaison with the NCC to capture case study material.</td>
</tr>
<tr>
<td></td>
<td>Pilot curriculum at National Composites Centre</td>
<td>Clash of schedules due to University teaching timetable and NCC recruitment activities.</td>
<td>Take early steps to engage with UoB and NCC to schedule block delivery of content and ensure resources are available.</td>
<td>November-December 2018</td>
<td>Lessons learnt and feedback to improve learner experience before making content more widely available.</td>
<td>Planning is ongoing to achieve this.</td>
</tr>
<tr>
<td>---</td>
<td>---------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>--------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>---------------------------------</td>
</tr>
</tbody>
</table>

Lessons learnt and feedback to improve learner experience before making content more widely available.

Planning is ongoing to achieve this.
Appendix 8- Monitoring report February 2019
Catalyst Fund: Closing the skills gap and supporting the Industrial Strategy through curriculum development

Final Report

<table>
<thead>
<tr>
<th>Lead HE Provider</th>
<th>University of Bristol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project title</td>
<td>Composites Curriculum Development</td>
</tr>
<tr>
<td>Project code</td>
<td>N12</td>
</tr>
<tr>
<td>Contact name</td>
<td>Laura Rhian Pickard</td>
</tr>
<tr>
<td>Email</td>
<td><a href="mailto:laura.pickard@bristol.ac.uk">laura.pickard@bristol.ac.uk</a></td>
</tr>
<tr>
<td>Tel No.</td>
<td>0117 3315538</td>
</tr>
<tr>
<td>Date report due</td>
<td>28 February 2019</td>
</tr>
<tr>
<td>Date report submitted</td>
<td>27 February 2019</td>
</tr>
<tr>
<td>Frequency for reports to be submitted to OfS:</td>
<td>The project will be monitored formally at two points:</td>
</tr>
<tr>
<td></td>
<td>• 31 July 2018 - Interim monitoring report.</td>
</tr>
<tr>
<td></td>
<td>• 28 February 2019 - Final report</td>
</tr>
<tr>
<td></td>
<td>• 31 May 2019 – Final report updated with self-certification</td>
</tr>
<tr>
<td>Attached annexes</td>
<td>Annex A: Updated key milestones and risks</td>
</tr>
<tr>
<td></td>
<td>The table submitted with the original business case, as updated in the July interim report has been provided.</td>
</tr>
<tr>
<td></td>
<td>Annex B: Financial self-certification form This will be provided in May.</td>
</tr>
</tbody>
</table>

Project overview

1. Provide a synopsis of your project, including key themes, key words (maximum of five) and link to project website (if applicable).

Keywords: Composites, skills, workforce, growth, industry

Website: https://www.fose1.plymouth.ac.uk/sme/composites/

Synopsis: The aim of this project is to generate an industrially relevant and academically rigorous curriculum which could be deployed to tackle the significant skills gap in composites professionals, vital for delivering on the UK’s National Composite Strategy and allowing the industry to grow to its full potential, forecast by the Composites Leadership Forum to grow by a factor of 5 by 2030. A Masters’ level curriculum of short, industrially focused units has been specified and a small number of trial units developed. Engagement of academics in this novel collaborative curriculum development, utilising each institution’s
expertise, has been very good and feedback from industry and participants in pilot units has been positive. The consortium are investigating numerous options for developing this further and have begun to put plans in place for the next stage.

### Project delivery and outputs

2. With reference to your original business case, please detail to what extent the following have been met, along with any mitigating actions taken.

#### a) Aims and objectives

Identify composites learning provision from leading HE providers- available courses and summaries of their content have been identified and recorded. The data is now being verified and options for user-friendly presentation are being considered. Additionally, numbers of students are being recorded in order to refine our estimates of the current provision of persons with suitable education in composites, particularly at Masters’ level.

Comparison with international benchmarks- this work is underway. The person responsible has moved to a new job so is completing the task as an external contractor.

Generate a framework identifying the material that should be included in a composites curriculum- a curriculum is in place and feedback from both academia and industry has been positive. Descriptions for each short, 2 day unit, are being written, with 47/59 completed and the remainder nearing completion. Reviews are now underway and the first sets of feedback have been received.

For a limited number of units, develop delivery material and trial that material- a preliminary pilot at the National Composites Centre using material from the 5 core (introductory) units was delivered and feedback was positive. A second pilot of a limited selection of core material was carried out at the University of the West of England during a Continuous Professional Development course. Responses were positive again and detailed feedback questionnaires were completed. Two further pilots, of full units from the main curriculum, will be carried out with the National Composites Centre in March and early April. In addition to this, trial material for two additional units will be developed by the University of the West of England and the National Physical Laboratory, subject to invoices being received from these two institutions in a prompt manner to allow time for this to proceed. These units may also be trialled if time permits.

Identify resource requirements to deliver the full set of teaching and associated supporting materials- a resource of industrial case studies and sets of photographs and videos which may be used in teaching have been compiled. In addition, a material supplier has agreed in principle to provide samples for use in teaching when the full course becomes a reality. An approximate calculation of the human time required to develop the full curriculum has been made and will be refined based on the time taken to develop material for each of the trial units.

Identify a sustainable structure by which ongoing delivery of the composites curriculum could be achieved and scaled to the industrial demand- an estimate of industrial demand has been made based on the UK’s National Composites Strategy and discussions are underway with industrial representatives to refine that estimate. A ‘train the trainer’ scheme is under consideration, which may be synergistic with the National Composites Centre’s existing scheme. Discussions with the National Composites Centre, National Physical Laboratory, High Value Manufacturing Catapult and other potential partners regarding the next steps are underway. Options for IP have been discussed and it was concluded that expert opinion should be sought.

#### b) Key milestones

Curriculum mapping exercise- data has been gathered on composites courses in the UK, in academia and industrial training schemes. With a focus on masters level courses, data is currently being reviewed to check accuracy and additional information on student numbers is being sought.

Demand and gap analyses- response of industry and academia to the proposed curriculum has been positive, and the unit description review process is intended to highlight any gaps. The demand from industry for suitably educated composites professionals has been estimated, but would benefit from refinement based on figures for staff
levels in previous projects in the composites industry. The National Composites Centre and contacts at commercial organisations are currently researching this.

Contextual learning objects, materials and case studies- the resource of industrial case studies, many as written by composites companies, covers a range of industries. Images, videos and lecture slides for the trial units have been collated and will be made available. A material supplier has agreed in principle to provide physical samples when the course is running. Universities such as Bristol have many physical parts of varying sizes which are used as examples in teaching.

Pilot curriculum with the National Composites Centre- the first stage pilot with core material was successfully completed, as was the UWE pilot. The second stage pilots, with material from the main curriculum, will be delivered in late March and early April at the National Composites Centre, to a class of staff from NCC and their member companies. Detailed feedback will be sought through questionnaires and lectures will be recorded if all present consent to this.

c) Significant inputs and outputs

Curriculum map output- see above, the data has been gathered and needs to be verified and presented in a user-friendly manner.

Curriculum framework design and specification- this has been done, with input from industrial partners as well as academics from numerous different institutions. The resulting curriculum has a core set of 5 introductory units and 54 specialised units (number may change during review process) arranged in sets of 6 under industrial themes. Unit descriptions for all of these will be provided by the end of the project, with the vast majority already complete and some already reviewed. Each unit is intended to be delivered as a 2 day course with an optional assessment. These units can be combined as appropriate for a given business or project, or taught separately to suit the demand from industry.

Low cost learning objects and resources- many of these are already in place, as discussed above, and lecture notes, practical session guidelines and outlines for assessments from the trial unit development will be added to this by the end of the project.

Pilot curriculum at National Composites Centre- first stage complete, second stage to be done in March and April. Anonymous feedback questionnaires from the second stage will provide material for evaluation of the units, data will be made available at the end of the project. Questionnaires from the pilot at UWE have already been analysed.

Lessons learnt catalogue of learning objects and case studies- case studies are available under the learning objects output above. IP matters require advice from a legal expert. The consortium have suggested that an initial recommendation be sought to inform discussion, with finalizing of licensing agreements to be done in the next stage of the curriculum development, once trial units are available (these will contain no protected IP) to act as examples.

3. Has there been any change in the employers and key partners involved in the project compared to those listed in the original business case? If so, provide full details and reasons for changes.

As in the original business case, the lead institution remains the University of Bristol, with the University of Plymouth as co-lead on the project and the National Composites Centre as a key partner.

As the purpose of the project is to develop a collaborative curriculum with many institutions contributing in their area of expertise, discussions have included the following institutions, many of whom have contributed or agreed to contribute unit descriptions (italics). No funds have been transferred to any of these institutions:

Advanced Manufacturing Research Centre
University of Bath
University of Bolton
Cardiff University
The University of the West of England has also hosted one of the unit delivery trials and have quoted to develop material for a trial unit. This will involve payment, which has not yet been made.

Hexcel Composites have agreed in principle to provide material samples for use during teaching and have contributed case studies. GE Aviation, BAE Systems, Dowty Propellers (GE) and Airbus have expressed interest in providing feedback on the detailed curriculum.

### Terms and conditions

4. Confirm that the following terms and conditions, as outlined in the award letter, are being adhered with.

<table>
<thead>
<tr>
<th>Term</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Funding cannot be used to fund business support activity.</td>
<td>Confirmed</td>
</tr>
<tr>
<td>All provision must commence no later than the 2019/20 academic year.</td>
<td>Confirmed</td>
</tr>
</tbody>
</table>

5. If any terms and conditions have been breached, provide a full explanation.

N/A

### Finance and Risk

6. Complete the table below:

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Catalyst funding awarded</td>
<td>£200,000</td>
</tr>
<tr>
<td>Catalyst funding received from HEFCE/OfS up to 28 February 2019</td>
<td>£133,334</td>
</tr>
<tr>
<td>Unspent Catalyst funding</td>
<td>£27609.46 remaining from Tranche 1 on 20/02/2019</td>
</tr>
<tr>
<td>Total project spend (from all sources)</td>
<td>£TBD, see May update</td>
</tr>
</tbody>
</table>

7. If there is any underspend against the Catalyst funding, provide details and give clear reasons why this has occurred. The OfS will seek to recover any unspent funds.

The project is not yet complete. Future expenses for which we do not yet have estimates include two further pilot units to be delivered at the National Composites Centre in March and April, development of at least one additional unit of material- to be developed by the National Physical Laboratory- and a final full consortium meeting in April.
We also intend to request an expert opinion from a legal professional specialising in IP regarding the options for the future, which will no doubt incur a cost.

It seems likely at this stage that there will be significant underspend, though exact figures cannot be given until the project completes. This is partially due to a pause in work while replacement staff were recruited, leaving limited time to finish the project and hence reducing both staff and unit development costs, as time limitations restricted the number of units which could be worked upon. There is also a large discrepancy between our estimate of unit development costs and the amounts charged by organisations such as the University of the West of England.

Any unspent funds will of course be returned to OfS. At this stage we feel it appropriate to restrict the project to Tranche 1 funding only, and ask that Tranche 2 be cancelled, allowing OfS to redirect the funds to other areas.

A budget summary is provided at the end of this document.

8. Was there any change in the overall investment package for the project, e.g. have investment partners or funding amounts changed from the original business case? If so, provide details.

No overall change. Colleagues from outside Bristol and Plymouth who are undertaking paid work (such as developing material for trial units) are doing so on a strict payment for defined work package basis.

9. Where funding was detailed in the leverage section of the original business case submitted to HEFCE in September 2017, provide an update on the status of this funding.

N/A

10. Was there any change in the risk status of the project? If so, provide full details.

Staffing challenges have been problematic, though we now have a dedicated team working hard to deliver all project objectives.

IP issues require consideration by experts rather than discussion by academics. We are seeking a neutral, external expert to provide a recommendation as a first stage, which will inform discussions in the future. We are aware that this project is funded by the UK taxpayer and hence chose not to use a global license such as Creative Commons at this stage. This matter needs further discussion.

Challenges

11. What challenges or setbacks did your project experience? How were these addressed?

Staffing challenges, as mentioned above, have been a major issue. These were addressed by recruiting a student at the close of an EngD with a knowledge transfer focus on a full time basis and a University of Bristol project manager on a part time basis. Professor Potter has delayed retirement until the closure of this project.

Some areas of the curriculum require very specialized expertise. It was necessary to seek out suitable experts and persuade them to contribute unit descriptions for their area of specialization. Happily, in some cases this resulted in their joining the group and making very useful contributions beyond the unit descriptions.

As the work is being carried out by volunteers across many institutions, in some cases individuals have over-committed and found themselves unable to carry out all the tasks originally volunteered for, resulting in the few unit descriptions remaining incomplete. These have all been reassigned, and if any remain incomplete by mid March then experts local to Bristol or Plymouth- who can be reminded in person- will be found. Fortunately most of the outstanding topics can be covered by these two organisations.

Obtaining figures from industry for staffing requirements, in order to refine our estimates of the demand for qualified personnel, has been and continues to be a challenge. We met with training managers at Nottingham, but were
disappointed to find their time horizons too short for our purposes. We are working with the National Composites Centre and personal contacts in industry in an attempt to address this. The trial units to be delivered at NCC will also provide an opportunity for us to ask participants from their member companies if they can provide us with these figures.

### Dissemination

12. Outline the project’s dissemination plans.

A report will be compiled for external dissemination, along with data from the curriculum mapping exercise, international benchmarking, demand and resource requirement estimates and feedback questionnaires. This will be distributed to all contributing organisations and made openly available online.

The report will include recommendations for future development of this work.

Material, including lecture slides, the case study resource, photographs, videos and all other items which are intended to form part of the final curriculum will be made available to institutions which are part of this project or any future continuation of this project, pending an agreement being reached on IP.

### Sustainability and wider impact

13. Outline the sustainability plan for your project’s key activities.

We have found many academics with interest in seeing this project reach fruition and determination to achieve this. Various options are being discussed for the next stage of the work. Ultimately, it is hoped that a course based on this curriculum will be self-funding, by commercial uptake of the courses. Discussions are ongoing with numerous interested parties.

We are exploring the opportunities for funding a new champion who will take the work beyond the retirements of the current leads. An appropriate funding mechanism might be a personal fellowship, perhaps funded by NCC, RAEng or HVMC. A preliminary proposal has been sent to HVMC.

14. Is the project having tangible beneficial impact on students and employers, and has it improved/enhanced collaborative relationships between higher education and employers?

Participants who attended the pilot courses responded very positively.

Collaboration between different higher education institutions has been significantly improved. A collaborative curriculum is a novel approach and has been well received and developed by volunteers at many institutions. There is also improved collaboration with the National Composites Centre and National Physical Laboratory.

Industrial partners have shown interest in the curriculum and in sending staff to the pilot units. As this is intended to meet a clear- and urgent- need within the composites industry, as the project progresses to the next stage and the course becomes a reality we expect to see very significant benefits to industry.

15. How will the key activities continue to support skills developments for both students and employers beyond the funding period?

The intention is to develop this curriculum into an offering which can be tailored- through picking and choosing of short units- to the needs of different groups and organisations within the composites industry and delivered as required to meet demand. Discussions are underway with the HVMC, NCC and NPL along with other partners.
It is anticipated that a set of teaching support materials will be shared amongst UK academics in the composites sector.

16. **Detail any wider impacts of the project not covered in the sections above.**

Failure to put in place the number of personnel required by the composites industry will compromise the sector growth forecast by CLF in Composites Strategy 2016. This project and follow on activities are intended to tackle this problem, facilitating delivery of growth in the composites sector and related industries and hence making a greater contribution to the UK economy.

### Additional information

17. **Provide the key achievements and lessons learned from the project, which we may cite in our publications or on our website, not already covered in the sections above.**

Multiple universities have contributed to a collaborative curriculum.

The specified curriculum is industrially focused, flexible, and aimed squarely at a large and growing skills gap in a key UK industry.

18. **Do you have any additional comments on your project, or any general feedback for the OfS? For example, are there any other key points which may support continuing policy development?**
Annex A: Updated key milestones

Please just provide a high level status report and confirm any date changes. Further details should be provided in the main body of the report.

<table>
<thead>
<tr>
<th>Target</th>
<th>Key milestone</th>
<th>Key risks</th>
<th>Actions to mitigate risk</th>
<th>Completion date</th>
<th>Outcome</th>
<th>July 2018 update</th>
<th>February 2019 update</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conclusion of Curriculum mapping exercise</td>
<td>Poor engagement and buy-in from partner HEIs</td>
<td>Attract buy-in of curriculum mapping exercise through existing network channels via EPSRC Future Composites Manufacturing Research Hub and the British Composites Society</td>
<td>March 2018</td>
<td>Results will be used to inform availability and level of learning in core composite areas of design, stress, materials and manufacturing.</td>
<td>Engagement has generally been positive once the collaborative aspects of the process have been clarified</td>
<td>Pause in work due to staffing changes has led to some initial data becoming out of date, requiring work to be re-done. This is underway and will be completed soon. Universities will be asked to supply student numbers for taught courses in composites at Masters level or above, to refine estimates of gap in provision of qualified professionals.</td>
</tr>
<tr>
<td>Target</td>
<td>Key milestone</td>
<td>Key risks</td>
<td>Actions to mitigate risk</td>
<td>Completion date</td>
<td>Outcome</td>
<td>July 2018 update</td>
<td>February 2019 update</td>
</tr>
<tr>
<td>--------</td>
<td>---------------</td>
<td>-----------</td>
<td>--------------------------</td>
<td>----------------</td>
<td>---------</td>
<td>-----------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>2</td>
<td>Demand and gap analysis through structured consultation with industry and HEIs</td>
<td>Lack of wide agreement on overall curriculum and content</td>
<td>Mitigated by early establishment of academic and industrial oversight. NCC will act as a conduit to engage industry buy-in and engagement.</td>
<td>April 2018 April 2019</td>
<td>Verification and validation that curriculum is fit for purpose and prioritise response to gaps appropriately.</td>
<td>To date we have had no negative comments on the draft curriculum that has been developed. Positive feedback has been received from the NCC on the appropriateness of the material.</td>
<td>Unit descriptions for almost all of the draft curriculum have been written and reviews are now taking place. Some modification expected based on the review process.</td>
</tr>
<tr>
<td>3</td>
<td>Development of contextual learning objects and materials incl. NCC based case studies</td>
<td>Identifying and unlocking the people with the right skills to deliver the required academic/teaching materials from their days jobs at the right time, and manage development to time and cost</td>
<td>Take early steps to identify and secure the release of key individuals for the necessary timescales.</td>
<td>October 2018</td>
<td>A strong portfolio of work-based learning material that can be initially piloted at the NCC through their workforce development schemes.</td>
<td>Good progress is being made in fleshing out the curriculum, collecting and developing teaching resources and in close liaison with the NCC to capture case study material.</td>
<td>The curriculum structure is complete and most unit descriptions are done. Teaching materials for a small number of trial units are currently under development. Materials from the first two pilot studies are available. A resource of case studies has been compiled along with a set of videos and an inventory of photographs which can be used. Physical objects are available at University of Bristol. Hexcel have agreed in principle to provide samples of their fabrics and...</td>
</tr>
<tr>
<td>Target</td>
<td>Key milestone</td>
<td>Key risks</td>
<td>Actions to mitigate risk</td>
<td>Completion date</td>
<td>Outcome</td>
<td>July 2018 update</td>
<td>February 2019 update</td>
</tr>
<tr>
<td>--------</td>
<td>---------------</td>
<td>-----------</td>
<td>--------------------------</td>
<td>----------------</td>
<td>---------</td>
<td>------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>4</td>
<td>Pilot curriculum at National Composites Centre</td>
<td>Clash of schedules due to University teaching timetable and NCC recruitment activities.</td>
<td>Take early steps to engage with UoB and NCC to schedule block delivery of content and ensure resources are available.</td>
<td>November-December 2018</td>
<td>Lessons learnt and feedback to improve learner experience before making content more widely available.</td>
<td>Planning is ongoing to achieve this.</td>
<td>First pilot at NCC was well received. Second pilot at UWE also went well and quantitative feedback was gathered by questionnaire. Further NCC pilots of two full units to be delivered in March and early April, feedback questionnaires will again be deployed.</td>
</tr>
</tbody>
</table>
Annex B: Financial Self-certification (for May 2019 submission)

<table>
<thead>
<tr>
<th>Provider's legal name</th>
<th>University of Bristol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project title</td>
<td>Composites Curriculum Development</td>
</tr>
<tr>
<td>Catalyst Fund project code</td>
<td>N12</td>
</tr>
</tbody>
</table>

### Statements

I have reviewed the above named project and confirm that:

- The HEFCE/OfS grant for this project has been used for the purposes provided.
- The lead provider has complied with any specific conditions attached to the grant.
- The lead provider has taken reasonable steps to achieve value for money.

### Signature

<table>
<thead>
<tr>
<th>Printed name</th>
<th>Job Title</th>
<th>Date</th>
</tr>
</thead>
</table>

Please note, this self-certification must be signed by the accountable officer (usually the Head of Provider), or an appropriate deputy with the necessary delegated authority.
### HEFCE Composites Curriculum Development Project Budget
#### Summary February 2019

<table>
<thead>
<tr>
<th><strong>Income</strong></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tranche 1</td>
<td>£</td>
<td>133,334</td>
<td></td>
</tr>
<tr>
<td>Tranche 2*</td>
<td>£</td>
<td>66,666.00</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>£</td>
<td>200,000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>DI Salaries</strong></th>
<th><strong>Actual to date</strong></th>
<th><strong>Committed</strong></th>
<th><strong>Total</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic</td>
<td>£ 19,628.47</td>
<td>£ 8,399.60</td>
<td>£ 28,028.07</td>
</tr>
<tr>
<td>Professional/admin</td>
<td>£ 2,611.24</td>
<td>£ 3,217.28</td>
<td>£ 5,828.52</td>
</tr>
<tr>
<td>Hourly paid teachers</td>
<td>£ 4,940.40</td>
<td>£ -</td>
<td>£ 4,940.40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>£ 22,239.71</td>
<td>£ 11,616.88</td>
<td>£ 38,796.99</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>DI non salary</strong></th>
<th><strong>Actual to date</strong></th>
<th><strong>Committed</strong></th>
<th><strong>Total</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumables</td>
<td>£ 150.26</td>
<td>£ -</td>
<td>£ 150.26</td>
</tr>
<tr>
<td>Catering</td>
<td>£ 306.93</td>
<td>£ -</td>
<td>£ 306.93</td>
</tr>
<tr>
<td>Room hire costs</td>
<td>£ 1,030.80</td>
<td>£ -</td>
<td>£ 1,030.80</td>
</tr>
<tr>
<td>Casual staff costs</td>
<td>£ 23,257.04</td>
<td>£ 10,994.52</td>
<td>£ 34,251.56</td>
</tr>
<tr>
<td>External fee for</td>
<td></td>
<td>£ 2,000.00</td>
<td>£ 2,000.00</td>
</tr>
<tr>
<td>international</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UWE Unit Development</td>
<td>£ -</td>
<td>£ 4,188.00</td>
<td>£ 4,188.00</td>
</tr>
<tr>
<td>NPL Unit Development</td>
<td>£ -</td>
<td>£ -</td>
<td>£ -</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>£ 24,745.03</td>
<td>£ 17,182.52</td>
<td>£ 41,927.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Plymouth costs</strong>**</th>
<th><strong>Committed</strong></th>
<th><strong>Total</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel</td>
<td>£ 5,000.00</td>
<td>£ 5,000.00</td>
</tr>
<tr>
<td>Staff</td>
<td>£ 11,394.00</td>
<td>£ 11,394.00</td>
</tr>
<tr>
<td>Estates</td>
<td>£ 1,731.00</td>
<td>£ 1,731.00</td>
</tr>
<tr>
<td>Indirect costs</td>
<td>£ 6,875.00</td>
<td>£ 6,875.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>£ 25,000.00</td>
<td>£ 25,000.00</td>
</tr>
</tbody>
</table>

**Remaining budget** £ 94,275

* to be paid at a later stage

** Plymouth to invoice Bristol

* including Tranche 1 and Tranche 2
Appendix 9- Detailed unit descriptions

COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Core Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Introduction to Composites</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It provides Learners with no prior experience with composites with a general introduction to the core concepts in understanding and applying composites in engineering applications.

**Core subjects to be covered**

1. History of composite materials
2. History of synthetic composites
3. Why use composites
4. Advantages and disadvantages
5. Fibres
6. Reinforcement forms
7. Resins
8. Mechanical properties
9. Other properties
10. Designing with composites
11. Predicting performance
12. Manufacturing processes
13. Shaping reinforcements
14. Traditional processes
15. High performance composites processes
16. High rate processes
17. Applications in aerospace
18. Applications in automotive
19. Applications in renewable energy and other sectors
20. Sustainable composites

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of the development of composite materials
2. Identify the advantages and limitations of these materials
3. Give learners an understanding of the range of materials and process options
4. Provide the learners with an understanding of current and potential applications of composites

**Statement of learning outcomes**

Learners will be able to:

1. Provide a basic overview of the development of composite materials and their applications
2. Understand some of the positive and negative aspects of composites and how these impact on design and application of composites
3. Understand some of the issues and methodologies involved in the selection and design of composite products

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

**Unit title**
Composite Constituents

**Level (Credit points)**
H (2)

**Unit director**
Professor Kevin Potter

**Unit description**
This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” to provide Learners with an understanding of the materials that are used in combination to manufacture composite materials and the products made from them.

**Core subjects to be covered**

1. Glass fibres, manufacture and properties
2. Carbon fibres, manufacture and properties
3. Aramid fibres, manufacture and properties
4. Other fibre types, manufacture and properties
5. Reinforcement forms, unidirectional materials
6. Reinforcement forms, bidirectional materials
7. Reinforcement forms, multidirectional and 3D materials
8. Thermosetting resins, history and resin types
9. Thermosetting resins, curing and cure predictions
10. Thermosetting resins, property development during cure
11. Thermosetting resins, cure monitoring
12. Thermosetting resins, attempts at toughening
13. Thermoplastic resins, commodity types
14. Thermoplastic resins, high performance types
15. Matrix resin mechanical performance & properties
16. Selecting the right fibre, reinforcement form and resin type
17. Core materials, foams
18. Core materials, honeycomb
19. Metal and ceramic matrix composites
20. Sustainable resources for fibres and matrices

**Statement of unit aims**
The aims of this unit are to:

1. Provide Learners with an overview of the fibres used in composites and how their manufacture and structure define their properties
2. Show how fibres are built up into useful forms of reinforcement
3. Identify classes and types of matrix resins by their chemistry and properties
4. Provide the learners with an understanding of how to select combinations of fibre, reinforcement type and matrix to meet specific applications
5. Introduce learners to forms of composite materials using non-polymeric matrices

**Statement of learning outcomes**
Learners will be able to:

1. Relate the composition of a composite to its mechanical properties
2. Understand the positive and negative aspects of different classes of fibres, matrix and other constituents of composite materials
3. Understand some of the issues and methodologies involved in the selection of constituents to deliver specific aspects of performance

**Methods of teaching**
7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**
Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**
2 days of teaching in a block
# COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Core Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Manufacturing of composite products</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

## Unit description

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the methodologies used in the manufacture of composite products.

## Core subjects to be covered

1. Drafting practices and ply direction control rosettes
2. Mapping reinforcements to required geometries
3. Reinforcement deformation
4. Drape models and conformability
5. Reinforcement preparation, nesting
6. Process availability and process selection
7. Manufacturing instructions
8. Prepreg processes, manual reinforcement lay-up
9. Prepreg processes, automated reinforcement lay-up
10. Prepreg processes, consolidation
11. Prepreg processes, preparation for moulding
12. Prepreg processes, vacuum bag and autoclave, winding
13. Prepreg processes, compression moulding
14. Prepreg processes, cure.
15. Dry fibre processes, pultrusion and filament winding
16. Dry fibre processes, rigid tool variants of resin infusion
17. Dry fibre processes, flexible tool variants
18. Tooling materials and tool design
19. Demoulding and post moulding non-destructive inspection
20. Machining and finishing processes

## Statement of unit aims

The aims of this unit are to:

1. Provide Learners with an overview of the processes used in the manufacture of composite products
2. Give learners an understanding of the range of materials and process options
3. Give learners the tools to compare processes and chose the most appropriate manufacturing routes
4. Provide the learners with an understanding of methods to control the manufacturing processes

## Statement of learning outcomes

Learners will be able to:

1. Provide a clear overview of composites manufacturing and control processes
2. Understand the positive and negative aspects of each suite of processes and how these impact on design and development of composite products
3. Understand some of the issues and methodologies involved in the manufacture of robust, high quality and defect-free composite products

## Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

## Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

## Timetable information

2 days of teaching in a block
**COMPOSITES CURRICULUM - Unit Information**

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Core Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Product Design</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the methodologies used in the development of composite products.

**Core subjects to be covered**

1. The product design cycle
2. The product design team
3. Cost and risk through the product design cycle
4. Requirements capture
5. Specification development
6. Stage gates and review processes
7. Conceptual or outline design
8. Methods for generating design concepts
9. Costing in the design process, including minimising wastes
10. Geometry, materials, process decisions
11. Detailed design methods
12. Estimating performance of composite structures
13. Back of the envelope and initial analytical methods
14. Detailed analytical methods
15. Numerical methods and FEA
16. Development of production costs
17. Prototyping
18. Testing and validation
19. Transitioning to production
20. Lessons learned - capturing product development knowledge.

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of the composites product design process in an industrial context
2. Identify the stages in the process and the importance of following a clear process
3. Enable the learners to contribute to product design teams as quickly as possible
4. Provide the learners with an understanding of both best practice and the pitfalls in composites product development

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the processes involved in the design of composites products
2. Understand the staged development of successful composite products
3. Understand some of the issues and methodologies involved in the testing and validation of composite products prior to volume production

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

**Taught block title**  Core Block

**Unit title**  Properties of Composites

**Level (Credit points)**  H (2)

**Unit director**  Professor Kevin Potter

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the units “Introduction to Composites” and “Composites Constituents” to provide Learners with a more in depth understanding of the properties and performance of polymer matrix composite materials and the products made from them.

**Core subjects to be covered**

1. Properties of a single fibre and a dry tow of many fibres
2. Properties of a tow when a matrix is added
3. Properties of a unidirectional laminate of many tows
4. Properties of a laminate at an angle to the fibres
5. Properties of biaxial and pseudo-isotropic laminates
6. Properties of short fibre composites
7. Properties of 3D reinforced composites
8. Properties of post-use recovered fibres
9. Predicting strength and stiffness of arbitrary lay-up laminates
10. Strength and stiffness through thickness
11. Toughness of composite laminates
12. Effects of temperature on properties
13. Effects of moisture on properties
14. Effects of other environments on properties
15. Effects of high strain rates on properties - impact
16. Effects of long loading time on properties - creep and fatigue
17. Electrical properties of composites
18. Fire performance of composites
19. Test methods for composites

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with a more detailed view of the development of mechanical properties in composite materials
2. Demonstrate how laminate mechanical properties may be predicted from fibre and matrix properties
3. Demonstrate how laminate properties vary with loading direction
4. Provide the learners with an understanding of non-mechanical properties of composites and the importance of these in product design

**Statement of learning outcomes**

Learners will be able to:

1. Design a laminate to achieve a specific set of basic mechanical properties
2. Understand the impact of externally applied loads on that laminate
3. Appreciate the likely non-mechanical properties of the laminate that has been designed

**Methods of teaching**  7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**  Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**  2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Polymeric Matrices</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr Edward Archer, Dr Alistair McIlhagger, Ulster University</td>
</tr>
</tbody>
</table>

Unit description

This unit forms part of the Masters level Composites Curriculum. It enables learners to critically appraise alternative thermoplastic and thermoset conversion and fabrication processing routes. Through analysis of the mechanical and physical characteristics of polymers, students should be capable of developing an appropriate strategy for selection of processing routes for a range of material systems and applications. The course will impart an understanding of the polymers at a basic molecular level, but be delivered from a polymer composite engineering perspective rather than polymer chemistry.

Core subjects to be covered

1. Introduction to Polymers
2. Mechanical Properties of Polymeric Materials
3. Molecular arrangement
4. Viscoelasticity and Toughness
5. Crystallinity and Glass transition
6. Thermoplastic Composites
7. Basic principles of operation of injection moulding, blow moulding, extrusion, etc.
8. Productivity issues
9. Temperature control and heating/cooling
10. Thermoset matrix properties
11. Thermoplastic matrix properties
12. Time-dependent response and creep
13. Environmental stress cracking
14. Polymer Testing and Identification
15. Thermal analysis and rheology
16. Recycling strategies
17. Development areas and future research

Statement of unit aims

The aims of this unit are to:

1. Provide Learners with an overview of the polymer types used in the composites sector
2. Identify the advantages and limitations of polymer processing methods
3. Explore aspects of polymer testing and analysis methods
4. Provide the learners with information to support the design of polymer composite products with consideration of environmental effects and time-dependent response.

Statement of learning outcomes

Learners will be able to:

1. Provide a clear overview of thermoplastic and thermoset polymer composite fabrication processes and assess the relative potential of alternative process routes for products and their design
2. Understand the features of polymer processes and how these may be optimised
3. Understand the issues and methodologies involved in the selection and design of polymers for composite products

Methods of teaching | 6 lectures, 2 lab classes and demonstrations, 1 class exercise |
Assessment details if required | Written assignment (85%), 20 minute assessed presentation (15%) |
Timetable information | 2 days of teaching in a block |
## Composites Curriculum – Unit information

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Polymer melt viscosity and chemorheology, cure and degradation</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td></td>
</tr>
<tr>
<td>Unit director</td>
<td>Alex Skordos</td>
</tr>
</tbody>
</table>

### Unit description

This unit focuses on polymeric matrices and their behaviour during manufacturing operations. The coverage includes physical and chemical aspects of material behaviour, materials state transitions taking place during processing, quantitative models and characterisation methods.

### Core subjects to be covered

1. Cure of thermosets
2. Crystallisation of thermoplastics
3. Rheology of thermoplastic matrices
4. Rheology of thermosetting matrices
5. Rheological modelling
6. Cure kinetics
7. Glass transition temperature development
8. Degradation of polymers
9. Material state maps

### Statement of unit aims

The aims of this unit are to:

1. Provide Learners with knowledge of polymer material behaviour during the manufacturing of composites
2. Present the main approaches for characterising material behaviour
3. Provide the tools for quantitative analysis of the phenomena governing material behaviour

### Statement of learning outcomes

Learners will be able to:

1. Understand the physical and chemical transformation polymers undergo during their processing
2. Use quantitative methods to analyse and predict material behaviour
3. Link polymer behaviour with composites processing

### Methods of teaching

6 lectures, 6 computer based tutorials, 2 Lab demos

### Assessment details if required

Written assessment (100%)

### Timetable information

2 days teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Fibres and moulding compounds</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the manufacture, properties and performance of synthetic reinforcing fibres and the associated moulding compounds.

**Core subjects to be covered**

1. Background and history of the development of synthetic reinforcing fibres
2. Glass fibres production
3. Glass fibres properties
4. Carbon fibres production
5. Carbon fibres properties
6. Aramid fibres production
7. Aramid fibres properties
8. Other polymeric fibres
9. Regenerated cellulose/lignin fibres
10. Ceramic and boron fibres
11. Metallic fibres
12. Whisker reinforcements
13. Sheet moulding compounds manufacture
14. Sheet moulding compounds design and applications
15. Bulk (Dough) Moulding compounds manufacture
16. BMC design and applications
17. High performance moulding compounds development (HexMC/Forged composites)
18. High performance moulding compounds design and applications
19. Flow characterisation of moulding compounds
20. Selecting fibres and moulding compounds by application and manufacturing process
21. Future development aims and opportunities

**Statement of unit aims**

The aims of this unit are to:

1. Give Learners an understanding of the development, production and performance of different classes of synthetic reinforcing fibres
2. Provide Learners with an overview of how to select the appropriate fibre for different applications
3. Provide learners with a good appreciation of the different forms of moulding compounds and where they are appropriately used

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the capabilities of the available synthetic reinforcing fibres
2. Select the appropriate fibre and moulding compound type for particular applications
3. Understand the design characteristics of the different classes of moulding compounds

**Methods of teaching**

7 lectures and associated demonstrations and exercises

**Assessment details if required**

Written assignment

**Timetable information**

2 days of teaching in a block.
### Taught block title
Materials

### Unit title
Characterisation techniques

### Level (Credit points)

### Unit director
James Kratz

### Unit description
This unit focuses on experimental techniques to characterise the thermo-mechanical property development of polymeric matrices and microstructure constituents of fibrous composites.

### Core subjects to be covered

<table>
<thead>
<tr>
<th>Thermo-mechanical properties</th>
<th>Microstructure constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thermo gravimetric analysis</td>
<td>7. Optical and electron microscopy</td>
</tr>
<tr>
<td>2. Differential Scanning Calorimetry</td>
<td>8. X-ray computed tomography</td>
</tr>
<tr>
<td>3. Laser flash analysis/ Guarded hot plate</td>
<td></td>
</tr>
<tr>
<td>4. Rheometry/ Dynamic mechanical analysis</td>
<td></td>
</tr>
<tr>
<td>5. Thermo mechanical analysis</td>
<td></td>
</tr>
<tr>
<td>6. Dilatometry / PVT methods</td>
<td></td>
</tr>
</tbody>
</table>

### Core subjects to be covered

<table>
<thead>
<tr>
<th>Thermo-mechanical properties</th>
<th>Microstructure constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thermo gravimetric analysis</td>
<td>7. Optical and electron microscopy</td>
</tr>
<tr>
<td>2. Differential Scanning Calorimetry</td>
<td>8. X-ray computed tomography</td>
</tr>
<tr>
<td>3. Laser flash analysis/ Guarded hot plate</td>
<td></td>
</tr>
<tr>
<td>4. Rheometry/ Dynamic mechanical analysis</td>
<td></td>
</tr>
<tr>
<td>5. Thermo mechanical analysis</td>
<td></td>
</tr>
<tr>
<td>6. Dilatometry / PVT methods</td>
<td></td>
</tr>
</tbody>
</table>

### Statement of unit aims

The aims of this unit are to:

1. Introduce the main approaches for characterising polymer material behaviour
2. Describe instrument operating principles and sample preparation methods

### Statement of learning outcomes

Learners will be able to:

1. Identify relevant characterisation techniques to measure thermo-mechanical properties of polymers and microstructural properties of fibrous composites
2. Define test methods and matrices
3. Interpret experimental results

### Methods of teaching
8 lectures, 6 Lab demos

### Assessment details if required
Written assessment (100%)

### Timetable information
2 days teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Dry fabrics and prepregs</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces learners to the processes used in the manufacture of both dry and preimpregnated reinforcements and how the processes used in the manufacture of reinforcements impact on other aspects of composites manufacturing.

**Core subjects to be covered**

1. Introduction, background and history
2. Weaving processes for reinforcements
3. Weave structure types 2D
4. Weave structure types tailored 2D
5. Weave structure types 3D
6. Simulation of textile structures
7. Stitching and tufting
8. Non-crimped fabric processes
9. Braiding processes
10. Tailored fibre placement processes
11. Felts and other non-wovens
12. Aligned discontinuous reinforcements
13. Binder application processes
14. Prepreg manufacture process
15. Solvent methods
16. Film methods
17. Interlayered prepreg
18. Characteristics of prepregs under mechanical load
19. Reinforcement selection process

**Statement of unit aims**

The aims of the unit are to:

1. Provide learners with an overview of manufacturing processes for dry and impregnated reinforcements
2. Give learners an understanding of the range of reinforcement options available
3. Provide learners with an overview of how to select reinforcements for particular structures

**Statement of learning outcomes**

Learners will be able to:

1. Demonstrate an understanding of the range of reinforcement types commercially available
2. Understand how the reinforcements are manufactured and how those processes may impact on composites manufacturing processes
3. Understand how materials are selected for the manufacture of specific products

**Methods of teaching**

8 lectures, 1 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Characterisation of fabric reinforcements</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites”, “Composites Constituents” and “Reinforcement Types” to provide Learners with a good understanding of the characteristics of fabric reinforcement, including compressibility, drape and permeability.

**Core subjects to be covered**

2. Textile terms and definitions.
3. Areal weight, tow count, cover factor, etc.
4. In-plane characterisation (fabric testing)
5. Through-plane characterisation for single or multiple layers (volume fraction vs pressure, nesting)
6. Thermal characterisation of fabrics
7. Drape (natural) and conformability (assisted) to curved surfaces
8. Automated handling of fabrics
9. Permeability to liquid resin/molten polymers
10. Process-property-microstructure relationships

**Statement of unit aims**

The aims of this unit are to:

1. Give Learners an understanding of the characterisation techniques for flexible materials.
2. Provide Learners with an overview of the advantages and constraints of differing reinforcement architectures.
3. Give Learners the tools to select a reinforcement which balances manufacturability with the required composite properties.

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the range of parameters which define a fabric reinforcement
2. Establish an appropriate testing procedure for each parameter necessary to pre-manufacture handling and composite performance.
3. Understand the issues constraining the use of different fabric architectures.

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
**COMPOSITES CURRICULUM - Unit Information**

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Product Design A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Design Cycle and Requirements Capture</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces learners to the Product Design Cycle, focusing on the evolution of product design for composites, the importance of the early stages in design and requirements capture as a critical part of the design process.

The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

1. The purpose of product design
2. The evolution of design for composite products
3. The Design Cycle
4. Learning from errors in design activities
5. Learning from other industries’ experience
6. Assessment of Design Requirements
7. Functional requirements
8. Geometry requirements
9. Environmental and operating conditions
10. Duty cycles and loadings
11. Cost issues
12. Programme/Contract issues
13. Regulatory requirements
14. Project appraisal
15. Generating a Design Brief
16. Outline design loop
17. Forced decisions
18. Conceptual solutions
19. Concept challenge
20. Development programmes

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of the product design cycle for composites
2. Demonstrate to learners the breadth of information that needs to be captured to deliver a successful design
3. Provide learners with a structure within which to carry out product design

**Statement of learning outcomes**

Learners will be able to:

1. Confidently capture the required data to carry out a design assessment and produce a design brief
2. Use the design brief to examine potential solutions to the design requirements to deliver an outline design that can be developed through further analysis

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Product Design A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Costing in a design environment</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces learners to the principles of costing in a design environment, building on the Unit Design Cycle and requirements capture to provide learners with a more detailed support for costing activities. The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

1. Costing in the design process
2. Costing in design assessment
3. Top down costing – the art of the possible
4. Designing to cost target constraints
5. Bottom up costing
6. Built-up labour rates, advantages and disadvantages
7. Cost estimating 1. Materials including consumables and wastes/disposal
8. Cost estimates 2. Direct manufacturing touch labour Hours
11. Cost estimates 5. Other indirect resources
12. Rework, repair and scrap rate assumptions
13. Activity listing approaches
14. Capturing non-recurring costs
15. Predicting development costs
16. The importance of scenario assessment and “What if?” costing
17. Minimising Non Recurring Costs in design
18. Balancing speed and accuracy

**Statement of unit aims**

The aims of this unit are to:
1. Provide Learners with an overview of the importance of costing as part of the design activity
2. Provide learners with a structure within which to carry out costing as part of product design
3. Provide learners with some tools to use in early stage product design costing

**Statement of learning outcomes**

Learners will be able to:
1. Confidently engage with the need to generate cost estimates as part of the design process
2. Produce first order cost estimates to guide the design process

**Methods of teaching**

- 7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

- Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

- 2 days of teaching in a block
## Taught block title
PRODUCT DESIGN A

## Unit title
Drawing Practices and lay-up rules

## Level (Credit points)
H (2)

## Unit director
Martyn Jones/ Prof Richard Day

## Unit description
This unit forms part of the Masters level Composites Curriculum. It provides learners with detail on good drawing practices and the basis of ply layup rules. It also will enable students to understand and apply industry standard practice through CAD packages for composite design.

## Core subjects to be covered

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Importance of clear drawings for designers, manufacturers and end users.</td>
</tr>
<tr>
<td>2.</td>
<td>Different fibre architectures and influence of warp/weft</td>
</tr>
<tr>
<td>3.</td>
<td>Material properties, (Anisotropic, Orthotropic, Lamina)</td>
</tr>
<tr>
<td>4.</td>
<td>Ply stacking best practice and drafting rules</td>
</tr>
<tr>
<td>5.</td>
<td>Laminate orientation codes</td>
</tr>
<tr>
<td>6.</td>
<td>Ply books</td>
</tr>
<tr>
<td>7.</td>
<td>Standards and drawing conventions – EN4408-1 to ENG4408-5</td>
</tr>
<tr>
<td>8.</td>
<td>Ply stacking sequences</td>
</tr>
<tr>
<td>9.</td>
<td>Importance of balanced layups</td>
</tr>
<tr>
<td>10.</td>
<td>Ply drop off guidelines</td>
</tr>
<tr>
<td>11.</td>
<td>Hole positions and influences</td>
</tr>
<tr>
<td>12.</td>
<td>Laminate draping and darts</td>
</tr>
<tr>
<td>13.</td>
<td>CAD based composites design packages (such as Catia Composite workbench) for Ply zones, stacking and ply book creation.</td>
</tr>
</tbody>
</table>

## Statement of unit aims
The aims of this unit are to:

1. Demonstrate the importance of communicating composites designs
2. Enable designers and manufacturers to understand ply drop off areas and transition zones
3. Show how darts can be used to allow adequate draping over curves
4. Allow students to use industry standard software for composite design.

## Statement of learning outcomes
Learners will be able to:

1. Fully understand the relevance and importance of composites drawing standards
2. Critically evaluate and scrutinise engineering drawings
3. Be proficient in industry standard drafting CAD packages for drawing.

## Methods of teaching
3 lectures, 2 CAD sessions, 1 practical session, 1 direct learning

## Assessment details if required
100% assessment (2 assignments at 50/50)

## Timetable information
4 days
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Product Design A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Design for manufacture</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the concepts of design for manufacture and how those concepts can be applied to the design and development of composite products.

The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

1. Goals of Design for Manufacture
2. Design for Manufacture guidelines
3. Composites specific guidelines
4. Concurrent design
5. The rule of 10s
6. Minimizing handling
7. Understanding manufacturing problems
8. Design for easy fabrication/assembly
9. Design for fixturing
10. Robust design principles
11. The importance of supply chain reliability
12. Process specific design guidelines
13. DfM in RTM and Resin Infusion
14. DfM in prepreg bag moulding processes
15. DfM for automated fibre placement
16. Acquiring process specific information
17. Check-list approach to Design for Manufacture

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of Design for Manufacture concepts
2. To identify how those concepts can be applied in the context of composites products
3. Provide Learners with some tools to apply in a design environment

**Statement of learning outcomes**

Learners will be able to:

1. Identify factors that will impact on manufacturability in terms of ease of manufacture for various processes
2. Identify how the costs of manufacture can be reduced by applying concepts of design for manufacture
3. Understand how to capture design for manufacture information for emerging processes

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
**Taught block title**  |  Product Design A  
---|---  
**Unit title**  |  Acceptance criteria, rework, concessions – Designing out defects  
**Level (Credit points)**  |  M (2)  
**Unit director**  |  Professor Kevin Potter  

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to some aspects of quality in composite components and structures, and how deviations from the design intent have to be handled when dealing with structurally important structures. The principal focus of the unit is the impact of the design process on defects in production, which overlaps with but is not equivalent to Design for Manufacture. The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

| Core subjects |  
|---|---  
1. The quality assessment process  
2. Defining Acceptance Criteria  
3. Rework, repair and the concession process  
4. Direct costs associated with rework, repair and concessions  
5. Production flow disruption and other costs associated with rework, repair and concession  
6. Drawing tolerances, what drives them?  
7. Manufacturing standards, e.g. for accuracy of ply positions or ply/ply gaps  
8. Defining process capability for each step in the process chain  
10. Achievable tolerances related to materials variability  
11. Achievable tolerances related to process variability  
12. Impacts of geometrical features on quality interactions between geometry, part quality and complexity of stress states  
13. Inspecting designs for features expected to generate out of tolerance events  
14. Methods to reduce the probability of defects arising within a fixed design envelope  
15. Estimating the cost of applying methods to reduce defect probability  

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of manufactured quality in composites production  
2. Clarify the costs of poor quality and the impact of a lack of quality on profitability  
3. Provide learners with tools that can help to avoid designs that are prone to defect formation  

**Statement of learning outcomes**

Learners will be able to:

1. Identify appropriate acceptance criteria with regard to process capabilities  
2. Examine designs with a view to identifying potential for defect generation  
3. Identify amendments to designs to minimise the potential for defect generation  

**Methods of teaching**

- 7 lectures, 2 lab classes and demonstrations, 1 class exercise  

**Assessment details if required**

- Written assignment (85%), 20 minute assessed presentation (15%)  

**Timetable information**

- 2 days of teaching in a block
### COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Product design A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit title</strong></td>
<td>Standards and certification</td>
</tr>
<tr>
<td><strong>Level (Credit points)</strong></td>
<td>H (2)</td>
</tr>
<tr>
<td><strong>Unit director</strong></td>
<td>Stefanos Giannis</td>
</tr>
</tbody>
</table>

### Unit description

This unit forms part of the Masters level Composites Curriculum. It builds on the Performance A and B units to provide Learners with a good understanding of the role of composite materials standards and design codes and their use in the certification of composite structures.

### Core subjects to be covered

1. Introduction
2. Need for Regulations, Codes and Standards (RCS)
3. Role of regulators
4. Role of standardisation bodies and classification societies
5. Standards creation and pre-standardisation work
6. Round-robin validation of test methods
7. Design codes and relation to standards including industry standards e.g. AITM (aerospace) and AASHTO/CIRIA (FRP bridges)
8. Composite materials test standards
9. Interpretation of materials test standards
10. Certification pyramid and product validation chain
11. Acceptable means of compliance in certification of composite structures
12. Statistical interpretation of qualification test data including calibration, errors and uncertainty
13. Design data versus experimental data
14. Role of numerical simulation in certification of composite structures including methodology for ascertaining validity of data from the scientific literature used to inform modelling

### Statement of unit aims

The aims of this unit are to:

1. Provide Learners with an understanding of the need for suitable Regulations, Codes and Standards (RCS) for composite materials
2. Give learners an overview of the certification process of composite structures in a number of industry sectors
3. Enable learners to analyse qualification test data and obtain appropriate design data

### Statement of learning outcomes

Learners will be able to:

1. Interpret and use composite materials standards
2. Choose the right test method and standard for qualifying composite materials and certifying structures
3. Understand how to statistically analyse test data to obtain design data for composite materials

### Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

### Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information

2 days of teaching in a block
## COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Product Design B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Micromechanics</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr. Nuri Ersoy</td>
</tr>
</tbody>
</table>

### Unit description

This unit forms part of the Masters level Composites Curriculum. It provides Learners with no prior experience with composites with a general introduction to the basic micromechanical methods to predict the thermomechanical properties of unidirectional composites from the corresponding properties of the constituents.

### Core subjects to be covered

| 1. Review of thermomechanical properties of | 5. Predicting the composites properties using |
| transversely isotropic materials | Representative Volume Elements and Finite Element Method |
| 2. Predicting the composites properties using | 6. Comparison of the thermomechanical and strength properties using predictive |
| rule of mixtures | micromechanical methods and experimental values |
| 3. Predicting the composites properties using | |
| mechanics of materials approach | |
| 4. Predicting the composites properties using | |
| Self-Consistent Micromechanics | |

### Statement of unit aims

The aims of this unit are to:

1. Review the engineering constants required to define transversely isotropic materials
2. Provide the learners with an overview of the concepts of micromechanical methods to predict the thermomechanical properties of unidirectional, transversely isotropic composites.
3. Provide the learners with an understanding of the causes of discrepancies of the predictions of the micromechanical methods and experimental values.
4. Give learners a feeling of how reliably the predicted values can be used in laminate design and analysis

### Statement of learning outcomes

Learners will be able to:

1. Calculate the thermomechanical properties of the transversely isotropic materials using rule of mixtures, mechanics of materials approach and self-consistent field micromechanics
2. Able to construct Finite Element Models of Representative Volume Elements representing unidirectional, transversely isotropic composites.
3. Solve the Finite Element Models by assigning relevant boundary conditions and loads.
4. Interpret and assess the reliability the results of the predictions of micromechanical methods

### Methods of teaching

- 5 lectures, 3 FEA tutorials, 1 class exercise

### Assessment details if required

- Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information

- 2 days of teaching in a block
### Taught block title
Product Design B

### Unit title
Composite laminate design

### Level (Credit points)
H (2)

### Unit director
Dr. Mahdi Damghani

### Unit description
This unit forms part of the Masters level Composites Curriculum. It provides learners having no/limited knowledge of composite structures with a general introduction to the basics and principles of composite laminate design.

### Core subjects to be covered

| 1. Principles of laminate design and design of a composite piece |
| 2. Design and analysis of composite beams |
| 3. Design and analysis of sandwich composite structures |
| 4. Bonded joints |
| 5. Bolted joints |
| 6. Good design practices and design “Rules of Thumb” |

### Statement of unit aims

The aims of this unit are to:

1. Provide the learners with principles of laminate stacking sequence design and laminate sizing under various loading scenarios.
2. Provide means of analysing and designing laminated composite beams.
3. Provide means of analysing and designing sandwich structures. The learners will also be exposed to damage mechanisms in sandwich panels and attaching sandwich structures.
4. Provide understanding of stress distribution and structural damage mechanisms in both bonded and bolted joint in composite structures.
5. Provide existing repair techniques for laminate composite structures.

### Statement of learning outcomes

Learners will be able to:

1. Practically implement composite structures design/sizing and optimisation using hand methods.

### Methods of teaching
6 lectorials (combination of lectures and tutorials).

### Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information
2 days of teaching in a block
Composites Curriculum – Unit information

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Product Design B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Stress analysis - classical</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td></td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr. Hamed Yazdani Nezhad</td>
</tr>
<tr>
<td>Unit description</td>
<td>The taught unit on Stress Analysis (Classical) comprises of mechanics of stress-strain fields, mechanical deformation and strain energy in fibre-reinforced composite materials and laminates in the presence of unidirectional and woven fibres architecture relying mainly upon the principles of material constitutive equations. The unit includes both elastic and elastic-plastic deformation, and excludes mechanics of damage.</td>
</tr>
</tbody>
</table>

Core subjects to be covered

1. Composite materials
2. Laminated composites
3. Concept of a continuum and continuity
4. Concept of homogeneity
5. Concept of isotropy
6. Elements of vector & transformation of axes
7. Matrix mathematics & tensor algebra
8. Direct strain & Shear Strain
9. General three-dimensional stress
10. Constitutive equation for composites
11. Deformation & strain tensor for composites
12. Viscoelastic effects
13. Stresses: Body and surface forces
14. Stress tensor, principal stresses & invariants
15. Stiffness calculations in composites
16. Strength calculations in composites
17. Conservation of energy
18. Definition of strain energy
19. Constitutive relations for elastic composites
20. Elastic-plastic composites
21. Concept of small scale yielding
22. Crack tip stress fields in composite
23. Techniques for structural analysis & design

Statement of unit aims

The aims of this unit are to:
1. Provide Learners with classes and types of composite materials (particle or fibre reinforced) and laminates
2. Provide learners with theoretical estimation methods for composite stiffness, strain, stress & strength
3. Provide state-of-the-art techniques for composite stress analysis methods and composite structural design

Statement of learning outcomes

Learners will be able to:
1. Categorise classes and types of composite materials and laminated composites
2. Estimate stiffness, strain, stress and strength of composite materials and laminates
3. Understand some of methodologies involved in design of composite structures

Methods of teaching
9 lectures, 1 class exercise

Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information
2 days of teaching in a block
## Taught block title
Product Design B

## Unit title
Stress analysis - FEA

## Level (Credit points)

## Unit director
Dr. Hamed Yazdani Nezhad

## Unit description
The proposed unit provides conventional techniques for finite element analysis of composite materials and composite laminates under elastic and elastic-plastic conditions, subjected to mechanical and thermal loading, and in the presence of a pre-existing damage, according to the basics given in unit: Stress Analysis (Classical)

### Core subjects to be covered

1. Basic FEA concepts and definitions
2. Finite element discretisation
3. Principle of virtual work
4. Numerical quadrature
5. Mathematical models: Linear elastic solids
6. Inversion of Stiffness Matrix
7. Nodal displacement
8. Element Shape Functions
9. Strain-Displacement Matrix
10. Mass Matrix
11. Steps towards FEA of composite laminate
12. Modelling in commercial FEA software
13. Role of fibre orientation in composite laminates
14. Thermal stress FEA
15. Elastic and elastic-plastic FEA modelling
16. Damage FEA modelling

### Statement of unit aims

The aims of this unit are to:

1. Provide Learners with sequential steps followed by a FEA giving a concise explanation of each
2. Carry out finite element calculations on composite laminates
3. Provide understanding of the FEA solution for composite materials and structures
4. Understand the engineers role in using numerical results to designing components and the risks (i.e. safety and financial) associated with approximate solutions

### Statement of learning outcomes

Learners will be able to:

1. Carry out the FEA steps for modelling of composite materials and structures
2. Explain why FEA normally gives an approximation and list how this approximation may be improved using mesh refinements and/or hierarchal shape functions
3. Explain how to choose an appropriate element type for a composite material, the rules for connecting different element types together, and why restrictions on element shape apply
4. Working in teams, given a problem in stress analysis or heat transfer in composites, build a representative FEA model using the ABAQUS Software, solve for the steady-state stresses or temperatures including checks for accuracy, and write a report analysing the results obtained

### Methods of teaching
8 lectures Inc. lab classes and demonstrations

### Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information
2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

**Taught block title** | Product Design B
---|---
**Unit title** | Joints, bonded and bolted
**Level (Credit points)** | M (2)
**Unit director** | Professor Kevin Potter
**Unit description**
This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the processes used to join together composite components and structures or to join such structures onto metallic or other non-composite structures from a manufacturing and outline stress analysis perspective.

The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Advantages of bonded joints</td>
<td>12. Disadvantages of bolted joints</td>
</tr>
<tr>
<td>1. Disadvantages of bonded joints</td>
<td>13. Bolted joint configurations</td>
</tr>
<tr>
<td>2. Surface energy and wetting</td>
<td>14. Design considerations</td>
</tr>
<tr>
<td>3. Adhesive types</td>
<td>15. Stresses around a pin joint</td>
</tr>
<tr>
<td>4. Bonded joint configurations</td>
<td>16. Bolted joint failure modes</td>
</tr>
<tr>
<td>5. Deformations and stress distributions</td>
<td>17. Target failure mode</td>
</tr>
<tr>
<td>6. The importance of peel stresses</td>
<td>18. Joint strength versus lay-up</td>
</tr>
<tr>
<td>7. Failure modes and surface preparation</td>
<td>19. Fatigue issues</td>
</tr>
<tr>
<td>9. Fatigue and environmental effects</td>
<td>21. Tolerances and thermal effects</td>
</tr>
</tbody>
</table>

**Statement of unit aims**

The aims of this unit are to:

1. Provide learners with an overview of jointing techniques for composite structures
2. Identify the major features of bonding and bolting structures, distinguishing the advantages and disadvantages of each approach
3. Enable learners to decide which approach to be used in specific design cases

**Statement of learning outcomes**

Learners will be able to:

1. Identify when bonding or bolting is the appropriate solution
2. Carry out an outline stress analysis to estimate the load bearing capacity of the joint
3. Identify likely failure modes

**Methods of teaching**
7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**
Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**
2 days of teaching in a block
# COMPOSITES CURRICULUM - Unit Information

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>PRODUCT DESIGN B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Damage Tolerance</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td></td>
</tr>
<tr>
<td>Unit director</td>
<td>Martyn Jones/ Prof Richard Day</td>
</tr>
</tbody>
</table>

## Unit description

This unit forms part of the Masters level Composites Curriculum. Students who study this module will understand the key points of damage tolerance and how the design of a composite can ensure safety critical structures can survive after failure.

## Core subjects to be covered

| 1. Damage resistance and damage tolerance | 8. Visual inspection guidelines and methods |
| 2. Types/Sources of damage                | 9. Non-destructive testing |
| 3. Design processes to ensure durability  | 10. Mechanical testing processes |
| 4. Structural categorisation             | 11. Structural reliability, A Basis and B Basis |
| 5. Sandwich impact damage                | 12. Standards and procedures |
| 7. Fatigue in composites                 | 14. Use of Finite Element Analysis (FEA) to predict damaged and fracture. |

## Statement of unit aims

The aims of this unit are to:

1. Develop a systematic understanding of damage tolerance and its implication in structural design with composites
2. Develop a critical understanding of impact damage and environmental effects on a composite structure.
3. Assess the implications of component design, material section, transition zones and ply stacking sequences.
4. Allow learners to select appropriate inspection and testing methods for damage

## Statement of learning outcomes

Learners will be able to:

1. Have a systematic understanding of the effect of impact and environmental effects on composite components and its strength
2. Develop a practical knowledge of standards related to damage tolerance and reliability, and how inspection, testing a repair can be undertaken safely
3. Critically analyse designs for damage tolerance to include, matrix and fibre materials, fibre architecture, monolithic/sandwich structures, and ply drop off zones

## Methods of teaching

4 lectures, 2 lab sessions and demonstrations, 2 computer sessions

## Assessment details if required

100% assignment (2 assessments worth 50/50)

## Timetable information

(4 days)
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Processes A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Reinforcement manipulation and preforming</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the handling and manipulation of broad goods reinforcements both dry and preimpregnated and to the requirements for the production of complex preforms for subsequent further processing.

The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

| 1. Handling and manipulating rolls of reinforcement |
| 2. Cutting methods, manual and automated |
| 3. Nesting cutting patterns to minimise waste |
| 4. Pick and place end effectors for handling reinforcements |
| 5. Backing film removal for preimpregnated reinforcements |
| 6. Deformation modes for reinforcements |
| 7. Forming reinforcements to required geometries, draping versus darting |
| 8. Manual lay-up of preimpregnated reinforcements |
| 9. Best practice in the design of lay-up strategies |
| 10. Developing Manufacturing Instruction Sheets for manual lay-up |
| 11. Automation of manufacture using preimpregnated broad goods |
| 12. Preforming of dry/bound reinforcements |
| 13. Binders |
| 14. Preform equipment design |
| 15. Defining a set of preforms to generate a required complex geometry |
| 16. Case studies |

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of reinforcement handling and manipulation processes
2. Demonstrate the means by which reinforcements may be cut, transferred, stacked and otherwise handled
3. Provide learners with the understanding to develop reinforcement handling and preforming approaches

**Statement of learning outcomes**

Learners will be able to:

1. Identify appropriate means of preparing reinforcement packs for subsequent processing
2. Identify the strengths and limitations of different approaches
3. Support the design of preforming equipment and processes

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
## Taught block title
Manufacturing Processes A

## Unit title
Contact moulding

## Level (Credit points)
H (2)

## Unit director
Professor John Summerscales

## Unit description
This unit forms part of the Masters level Composites Curriculum. It builds on the units “Introduction to Composites”, “Composites Constituents” and to provide Learners with a good understanding of the characteristics of open mould process, e.g. spray-up and hand lamination.

### Core subjects to be covered

<table>
<thead>
<tr>
<th>1. Resins and reinforcements</th>
<th>6. Hand lamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Gel-coating</td>
<td>9. Limitations of contact moulding</td>
</tr>
<tr>
<td>5. Spray-up</td>
<td></td>
</tr>
</tbody>
</table>

### Statement of unit aims

The aims of this unit are to:

1. Give Learners an understanding of the basic composite manufacturing processes.
2. Provide Learners with an overview of the (few) advantages and (many) constraints when producing composites by contact moulding.
3. Give Learners the tools to select materials to achieve the best practical result given the process limitations.

### Statement of learning outcomes

Learners will be able to:

1. Provide a clear overview of the low-cost processes for composites manufacture
2. Establish an appropriate working procedure for manufacture low-performance composites.
3. Understand the issues constraining the achievement of high-performance composites by contact moulding.

### Methods of teaching
7 lectures, 2 lab classes and demonstrations, 1 class exercise

### Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information
2 days of teaching in a block
## COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Processes A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Prepreg processes, vacuum bag</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

### Unit description

This unit forms part of the Masters level Composites Curriculum. It introduces learners to the processes used in the manufacture of composites structures from preimpregnated reinforcements in single sided tools. Both autoclave moulding and out of autoclave processing routes will be considered. Cored sandwich panels are a very common form of composites structure and are addressed in this unit.

The course will be delivered from processing science and manufacturing engineering perspectives.

### Core subjects to be covered

| 2. Bleeders, breathers and vacuum bags | 10. Sandwich panel basics |
| 3. Tooling features | 11. Honeycomb properties |
| 4. Autoclaves and ovens | 12. Foam core properties |
| 5. Autoclave tooling | 13. Selecting the right foam or honeycomb core |
| 7. The development of contact between the prepreg and the tool | 15. Machining cores |

### Statement of unit aims

The aims of this unit are to:

1. Provide Learners with an overview of prepreg moulding techniques, including their advantages and disadvantages
2. Provide learners with an understanding of the range of processes available, the features of each process and how those features impact on the design of materials to be processed by those processes
3. Introduce learners to the manufacture of sandwich panels

### Statement of learning outcomes

Learners will be able to:

1. Select appropriate materials and processes to manufacture composite structures in single sided tools
2. Accommodate the characteristics of those processes in the design of composite structures
3. Identify where process control is needed to ensure component quality

### Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

### Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information

2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the well-established manufacturing process of matched tool compression moulding. The process is the predominant technique for high rate, thermoset matrix composite materials. Both pre-impregnated continuous reinforcement and chopped fibre moulding compound variants are covered.

Core subjects to be covered

<table>
<thead>
<tr>
<th>Prepreg</th>
<th>SMC / CFSMC / CFMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The process – Why it’s done and main benefits</td>
<td>9. The process – Why it’s done and main benefits</td>
</tr>
<tr>
<td>5. Surface finish, snap cure systems, tooling &amp; equipment, thickness tailoring issue</td>
<td>13. Surface finish, insert incorporation, tooling</td>
</tr>
<tr>
<td>Nissan GTR boot, Alfa Guilia bonnet</td>
<td>BMW 7 Series C pillar, Lamborghini Huracan wing</td>
</tr>
<tr>
<td></td>
<td>17. Part design guidelines for the process</td>
</tr>
</tbody>
</table>

Statement of unit aims

The aims of this unit are to:
1. Provide Learners with an overview of the compression moulding processes
2. Identify the advantages and limitations of the processes
3. Identify process and quality difficulties
4. Provide the learners with information to support the design of composite products to be manufactured by compression moulding
5. Provide design advice applicable to the processes

Statement of learning outcomes

Learners will be able to:
1. Understand compression moulding process techniques
2. Understand the advantages and disadvantages of compression moulding
3. Understand some of the issues involved in the selection and design of composites for manufacture by compression moulding

Methods of teaching
4 lectures, 1 lab class and demonstrations, 1 class exercise

Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information
2 days of teaching in a block
## COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Processes A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Resin Transfer Moulding</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Kevin Potter</td>
</tr>
</tbody>
</table>

### Unit description

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the manufacture of fibre-reinforced composites by rigid tool resin transfer moulding processes.

### Core subjects to be covered

1. History and development of RTM
2. Advantages and disadvantages of RTM
3. RTM theory and simulation
4. Choosing materials for RTM
5. Reinforcement manipulation and preforming
6. RTM mould tool design
7. Production engineering requirements
8. Component design for RTM
9. Thick section RTM
10. Monitoring and control of RTM
11. Troubleshooting RTM processing problems
12. Suggestions for good practice in the design and development of RTM components
13. Costing for RTM
14. Quality considerations in RTM
15. Case studies
16. Future development directions

### Statement of unit aims

The aims of this unit are to:

1. Give Learners an understanding of the development of the Resin Transfer Moulding process, its advantages and disadvantages
2. Provide Learners with an overview of how parts can be designed for RTM and successfully manufactured
3. Give Learners the tools to operate RTM processes in a production environment.

### Statement of learning outcomes

Learners will be able to:

1. Provide a clear overview of the capabilities of the Resin Transfer Moulding processes
2. Design or make recommendations for the design of products to be manufactured by RTM.
3. Understand the operation of the RTM process in a production environment.

### Methods of teaching

7 lectures and associated demonstrations and exercises, including practical

### Assessment details if required

Written assignment

### Timetable information

2 days of teaching in a block.
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Processes A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Resin infusion processes</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

### Unit description
This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the manufacture of fibre-reinforced composites by infusion processes.

### Core subjects to be covered

1. The RTM- infusion- prepreg continuum.
2. Vacuum integrity of mould tools.
4. Reusable “consumables”.
5. RIFT1: in-plane flow parallel to the layers of reinforcement.
6. RIFT2: through-plane flow from a flow medium or scored core (SCRIMP/VARTM).
7. RIFT3: resin film infusion (RFI).
8. RIFT4: partially pre-impregnated materials.
10. In-mould gel-coating.
11. Infusion of large structures.
13. Simulation software (LIMS/PAM-RTM/Polyworx)

### Statement of unit aims
The aims of this unit are to:

1. Give Learners an understanding of the continuum of processes from RTM through infusion to prepregging.
2. Provide Learners with an overview of the specific variations of infusion processes.
3. Give Learners the tools to optimise infusion manufacturing processes.

### Statement of learning outcomes
Learners will be able to:

1. Provide a clear overview of the range of infusion manufacturing processes.
2. Establish an appropriate manufacturing system for infusion of different composites aligned to the specific requirements of the consumer.
3. Understand the issues constraining the use of infusion to meet specific performance parameters.

### Methods of teaching
7 lectures, 2 lab classes and demonstrations, 1 class exercise

### Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information
2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Processes B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>AFP and ATL</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

Unit description
This unit forms part of the Masters level Composites Curriculum. It introduces Learners to two important automated reinforcement collation processes Automated Fibre Placement and Automated Tape Laying. The course will be delivered from processing science and manufacturing engineering perspectives.

Core subjects to be covered

| 1. History and development of the ATL and AFP processes | 11. Impacts on cured ply thickness and as-laid quality |
| 2. Current status of processes                           | 12. Monitoring and control                             |
| 3. Basic principles of operation, gantry vs robot designs | 13. Advantages and limitations of AFP & ATL            |
| 5. Accuracy and control issues                          | 15. Steering effects and tack                          |
| 6. Temperature control and heating strategies            | 16. Dry Fibre AFP issues                              |
| 7. Thermoset matrix processing                          | 17. Tailored blanks and post-forming                   |
| 8. Thermoplastic matrix processing                      | 18. Principles of part design for AFP & ATL            |
| 9. The lay-up head design and operational issues        | 19. Software tools                                     |
| 10. Geometric conformance                               | 20. Integrating AFP & ATL into a manufacturing plant  |
|                                                           | 21. Costing for AFP & ATL                              |
|                                                           | 22. Development areas and future research              |

Statement of unit aims
The aims of this unit are to:
1. Provide Learners with an overview of the AFP & ATL reinforcement collation processes
2. Identify the advantages and limitations of the processes
3. Identify quality limiting aspects of the processes
4. Provide the learners with information to support the design of composite products to be manufactured by AFP & ATL.

Statement of learning outcomes
Learners will be able to:
1. Provide a clear overview of the advantages and disadvantages of the AFP & ATL processes for reinforcement collation
2. Understand the features of the AFP & ATL processes and how these may be simulated
3. Understand some of the issues and methodologies involved in the selection and design of composites for manufacture by AFP & ATL

Methods of teaching
7 lectures, 2 lab classes and demonstrations, 1 class exercise

Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information
2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Core Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Rapid Prototyping (RP) and Additive Manufacture (AM)</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr Jasper Graham-Jones</td>
</tr>
</tbody>
</table>

Unit description

This unit forms part of the Masters level Composites Curriculum. It builds on the “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the potential routes to manufacture of polymer and composite components by Rapid Prototyping (RP)/Additive Manufacture (AM).

Core subjects to be covered

2. Fused Deposition Modelling (FDM).
4. Liquid binding
5. Stereolithography (SL)
8. Particle, whisker and fibre-reinforcement
9. Open access CAD/public access.
10. Acceptable quality/tolerances/permitted defects.
11. Customisation and complexity.
12. Supports, hinges and origami.
13. 4D-printing (shape shifting post-process).
15. Process simulation and design software

Statement of unit aims

The aims of this unit are to:

1. Give Learners an overview of the variety of processes available within the generic descriptions Rapid Prototyping (RP) and Additive Manufacture (AM).
2. Provide Learners with an understanding of the specific variations of RP and AM processes.
3. Give Learners the tools to analyse RP and AM to optimise processes.

Statement of learning outcomes

Learners will be able to:

1. Choose appropriate processes from the range of Rapid Prototyping (RP) and Additive Manufacture (AM) processes available.
2. Specify the systems required for manufacture by RP or AM for different composites aligned to the specific requirements of the consumer.
3. Understand the issues that constrain the optimisation of RP or AM processes.

Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information

2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

**Taught block title**: Manufacturing Processes B

**Unit title**: Filament winding and pultrusion

**Level (Credit points)**: M (2)

**Unit director**: Professor John Summerscales

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to two important automated processes, Filament winding and Pultrusion. The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

1. The historical development of filament winding (FW)
2. Winding pattern (hoop, helical or polar), geodesic path, Clairaut angle, and friction
3. Software for filament winding design
4. Basic principles of operation: increasing degrees of freedom
5. Fibre feed arrangements and filament wetting
6. Control, productivity and accuracy issues
7. Thermoset matrix FW
8. Thermoplastic matrix FW
9. Influence of process parameters on quality and conformance to design.
10. The history and development of pultrusion
11. Principles of part design for pultrusion
12. Fibre preform management, and wetting, before die entry
13. Consolidation and cure in the die
14. Haul-off and section cutting
15. Pulforming, pulwinding and pulbraiding
16. Quality and costing for FW & pultrusion
17. Development areas and future research

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of the filament winding and pultrusion processes
2. Provide the learners with information to support the design of composite products to be manufactured by filament winding and pultrusion.
3. Identify the advantages and limitations of the processes
4. Identify quality limiting aspects of the processes

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the advantages and disadvantages of the filament winding or pultrusion processes for composites production
2. Understand the features of the filament winding or pultrusion processes and how these may be simulated
3. Understand some of the issues and methodologies involved in the selection and design of composites for manufacture by filament winding or pultrusion processes

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
**COMPOSITES CURRICULUM - Unit Information**

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Processes B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Thermoplastic matrix processes</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Description produced by Sean Cooper, NCC</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the units “Polymeric matrices” “Joints; bolted and bonded” and aims to provide Learners with a good understanding of the characteristics of thermoplastic matrix composite processes, e.g. stamp-forming, compression moulding and injection/overmoulding. The unit also introduces joining of thermoplastic composites by common welding practices.

**Core subjects to be covered**

1. Advantages and disadvantages of thermoplastic matrix composites
2. Introduction to stamp forming
3. Stamping tool and shuttle system design
4. Typical forming defects, e.g. wrinkling, warp
5. Introduction to compression moulding
6. Typical defects voids, e.g. cracking, sinkmarks
7. Introduction to Injection/overmoulding
8. Tool design aspects, cores, hot runner, material transfer end-of-arm tooling
9. Typical defects, e.g. sink marks, short shot, warpage, moisture
10. Introduction to thermoplastic welding, polymer chain reptation/diffusion and interface model
11. Resistance welding process
12. Ultrasonic welding process
13. Induction welding process
14. Thermoplastic composites manufacturing and joining case study examples (various automotive, rail, aerospace)

**Statement of unit aims**

The aims of this unit are to:

1. Introduce learners to thermoplastic matrix processes including thermoforming, compression moulding and injection/overmoulding
2. Give Learners an understanding of thermoplastic composite welding processes including resistance, ultrasonic and induction
3. Provide industry/research examples of the use of thermoplastic composites across aerospace, rail, automotive and other sectors

**Statement of learning outcomes**

Learners will be able to:

1. Discuss the advantages and disadvantages of thermoplastic composites
2. Identify and explain some specific thermoplastic matrix manufacturing processes
3. Understand polymer reptation & welding as a difference to bonded or bolted joints
4. Identify and explain specific thermoplastic matrix welding processes
5. Use appropriate skills for identifying and resolving typical defects for any of the manufacturing or welding processes discussed above

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Processes B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>5.5 Process Automation</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Andrew Mills</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to automated processing, a rapidly developing area for high rate composite component manufacturing. The unit covers six areas of manufacturing; Material lay-up, reinforcement preforming, robotic handling and part trimming/machining, assembly by bonding and assembly by fastening.

**Core subjects to be covered**

1. Automation benefits – speed, labour cost, repeatability, QA
2. Process description, machines, process steps, benefits, challenges for each of the below:
   1. **Lay up**
      - Prepreg – ATL, Tow placement (Fiber placement) FP, pick and place, table rolling.
      - Dry fabrics & tapes – Tape laminating, woven and NCF pick and place
      - Dry tow – Filament winding
      - Application examples – A350 wing skin, A380 rear fuselage, automotive door skin, golf club shaft, wind turbine NCF
   2. **Preforming**
      - Vacuum, diaphragm, pressing, braiding, chopping/spraying
      - Application examples – BMW i3, Audi A8 bulkhead, Huracan A pillar, AM Vanquish wing
   3. **Closed moulding robot handling**
      - RTM preforming loading, resin injection cell
      - Application example – BMW 3 series roof
   4. **Trimming and machining – ultrasonic and water jet cutting**
      - Application example – BMW i3
   5. **Assembly by bonding**
      - Application example - BMW i3, BMC bike frame
   6. **Assembly by fastening**
      - Application example – Airbus A400M

**Statement of unit aims**

The aims of this unit are to:
1. Provide Learners with an overview of the uses of automation in composites moulding processes
2. Identify process difficulties
3. Provide the learners with information to support the design of composite products to be manufactured using automation
4. Provide design advice applicable to the processes

**Statement of learning outcomes**

Learners will be able to:
1. Understand the application of automation for moulding processes
2. Understand the benefits and restraints for the use of process automation
3. Understand some of the issues involved in the selection and design of composites for manufacture using automation

**Methods of teaching**

5 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

**Taught block title**  
Manufacturing Processes B

**Unit title**  
Processes for ceramic matrix composites (CMC) and metal matrix composites (MMC)

**Level (Credit points)**  
M (2)

**Unit director**  
Kevin Potter and John Summerscales

**Unit description**  
This unit forms part of the Masters level Composites Curriculum. It provides Learners with no prior experience with composites with a general introduction to the processes that can be used in the manufacture of components and structures using ceramic matrix composites and metal matrix composites.

**Core subjects to be covered**

1. Background and history
2. CMC- Solid phase powder metallurgy
3. CMC- Solid phase slip casting
4. CMC- Microwave sintering
5. CMC- Reaction bonding
6. CMC- Sol-gel processes
7. CMC- Liquid phase infiltration pyrolysis
8. CMC- Chemical/physical vapour deposition/infiltration
9. CMC- Machining processes
10. Particulate MMC processes – Stir casting
11. Particulate MMC processes – Squeeze casting
12. Particulate MMC processes – Powder metallurgy approaches
13. Particulate MMC processes – nanoscale reinforcements
14. Fibre/whisker reinforced MMC
15. MMC- Fibre reinforced metal injection moulding
16. MMC- Fibre manipulation and preform preparation
17. MMC- Preform infiltration
18. MMC- Fibre reinforced metal Solid state processing
19. MMC- In situ synthesis of reinforced metals
20. MMC- Process comparison and process selection
21. Machining processes for MMC
22. Carbon/Carbon composites: - resin impregnation followed by pyrolysis
23. C/C: Chemical Vapour Deposition from hydrocarbon precursor gas

**Statement of unit aims**

The aims of this unit are to:
1. Provide Learners with an overview of the processes for the manufacture of components and structures by routes to ceramic matrix composites
2. Provide Learners with an overview of the processes for the manufacture of components and structures by routes to metal matrix composites
3. Provide learners with an understanding of the capabilities and limitations of the available processes that can be applied in a part design environment

**Statement of learning outcomes**

Learners will be able to:
1. Identify appropriate processes for the manufacture of components in ceramic and metal matrix composites
2. Understand the ways in which process selection impacts on costs and performance of ceramic and metal matrix composites
3. Understand how to introduce the potential for ceramic and metal matrix composites in a design environment

**Methods of teaching**  
7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**  
Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**  
2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Production costing</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

Unit description

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the concepts of production costing and supports them to be confident in the use of costing approaches.

The course will be delivered from processing science and manufacturing engineering perspectives.

Core subjects to be covered

- 18. Company structures
- 19. Cost centres
- 20. Direct and indirect costs
- 21. Recurring and non-recurring costs
- 22. Costing methodologies
- 23. Job costing
- 24. Standard costing
- 25. Activity based costing
- 26. Direct costing
- 27. Parametric costing
- 28. Target (should cost) costing
- 29. Make or Buy decisions
- 30. Supply chain issues
- 31. Manufacturing equipment procurement
- 32. Factory space and facilities procurement
- 33. Delivery cost estimation
- 34. Introduction to Life Cycle costing
- 35. Commercially available cost modelling software
- 36. The Virtual Composites Company approach

Statement of unit aims

The aims of this unit are to:

5. Provide Learners with an overview of costing for composite products that are to be manufactured in a production environment.

6. Demonstrate how costs are built up in a production environment and how investment decisions can be made

7. Provide learners with an opportunity to use software tools to carry out trade studies

Statement of learning outcomes

Learners will be able to:

4. Identify the right approaches to product costing and understand their strengths and weaknesses

5. Identify the information required to carry out an effective costing and how such information can be obtained

6. Carry out simple costing using a spreadsheet model

Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Process design</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

Unit description

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the need for a controlled structure for process design in composites to achieve reliable production. It identifies the targets for process control and the difficulties inherent in meeting those targets. It provides a methodology whereby robust decisions on process design can be made.

The course will be delivered from processing science and manufacturing engineering perspectives.

Core subjects to be covered

1. The need for process design
2. Identifying expected part thickness
3. Factors impacting mean cured ply thickness
4. Reinforcement consolidation curves
5. Identifying the correct pressure cycle
6. Identifying limiting process parameters for acceptable quality on flat laminates
7. The effect of resin sinks in prepreg mouldings
8. The impact of bridging in internal radii
9. Consolidation effects on external radii
10. Cure scheduling
11. Maximum and Minimum cure temperatures
12. Heat transfer effects
13. Temperature distribution
14. Exotherm effects
15. Cool down and demould temperature
16. Postcure
17. Cure scheduling

Statement of unit aims

The aims of this unit are to:

1. Provide Learners with an overview of the need for a clearly defined process design to deliver a controlled production
2. Demonstrate to learners where control is needed and provide the tools that can be used in process design
3. Clarify the role of process design within a product design framework

Statement of learning outcomes

Learners will be able to:

1. Identify those factors that must be controlled in a composites manufacturing environment
2. Carry out estimates of the impact of poorly controlled processes
3. Integrate process and product design

Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information

2 days of teaching in a block
Composites Curriculum – Unit information

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Process modelling</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td></td>
</tr>
<tr>
<td>Unit director</td>
<td>Alex Skordos</td>
</tr>
</tbody>
</table>

Unit description

This unit deals with the simulation of composites manufacturing covering the main processing steps and the use of simulation for process design.

Core subjects to be covered

1. Drape modelling
2. Forming simulation
3. Filling simulation
4. Consolidation simulation
5. Cure simulation
6. Modelling of residual stress development
7. Model validation
8. Process optimisation
9. Variability and stochastic simulation

Statement of unit aims

The aims of this unit are to:

1. Provide Learners with knowledge of the main methodologies for simulating composites manufacturing
2. Present simulation in the context of practical process design
3. Provide an understanding of the capabilities of simulation tools

Statement of learning outcomes

Learners will be able to:

1. Understand the approaches used to translate relevant physical phenomena to models
2. Practise the use of simulation tools covering aspects of composites manufacturing simulation
3. Understand the role of modelling in the development and design of processing methods

Methods of teaching

9 lectures, 9 computer based tutorials

Assessment details if required

Written assessment (100%)

Timetable information

3 days teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Process monitoring</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

Unit description

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites”, “Composites Constituents” to provide Learners with a good understanding of the quality systems appropriate to composites manufacture.

Core subjects to be covered

1. Quality Management Systems standards (ISO 9000)
2. Environmental Management Systems standards (ISO 14000)
3. Occupational Health and Safety Management standards (OHSAS 18000)
4. Project planning. Technology Readiness Levels (TRL).
5. Problem Solving Techniques
7. Temperature, Pressure, and calibration
8. Viscosity, flow rate, and flow front position
9. Degree-of-Cure: dielectrometry, IR/Raman, ultrasonics and mechanical impedance analysis
11. QFD and PFMECA.
12. Process control: PID, ANN, FL, GA
13. Big Data & Industry 4.0

Statement of unit aims

The aims of this unit are to:

1. Give Learners an understanding of composite manufacturing quality systems.
2. Provide Learners with an overview of the resources available for problem identification and resolution.
3. Give Learners the tools to run an effective and efficient manufacturing system.

Statement of learning outcomes

Learners will be able to:

1. Provide a clear overview of quality systems for composites manufacture
2. Establish appropriate procedures for process control.
3. Understand the issues which enable optimisation of processes.

Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information

2 days of teaching in a block
## COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Process planning</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Kevin Potter</td>
</tr>
</tbody>
</table>

### Unit description

This unit forms part of the Masters level Composites Curriculum. It builds on the units “Introduction to Composites” and “Manufacturing of composite products” to provide Learners with a good understanding of the principles of process planning in a composites manufacturing facility. The baseline assumption is that the activity is being carried out in a quality critical/aerospace environment.

### Core subjects to be covered

1. Defining the design intent in detail to support all subsequent steps
2. Identifying manufacturing data capture and data management requirements
3. Defining the manufacturing process flow, Bill of Materials and Work Breakdown Structure
4. Identifying all materials with associated purchase specifications and storage requirements
5. Tracking life-limited materials
6. Part marking and traceability
7. Identifying all jig and tool requirements
8. Identifying all equipment requirements (e.g. ply cutter, AFP, autoclave or C-scan)
9. Identifying each step in a detailed manufacturing instruction document
10. Materials and equipment capacity and batch scheduling requirements
11. Commercial process planning models
12. ERP systems
13. Interfacing with Quality and MRB systems
14. Tracking design changes
15. Tracking and scheduling rework or repair
16. Integrating process planning into automated composites manufacturing facilities
17. Process planning in a high-volume manufacturing environment
18. Recent developments in process planning

### Statement of unit aims

The aims of this unit are to:

1. Give Learners an understanding of the issues associated with the development of process planning and documentation for new composite product manufacture
2. Provide Learners with an overview of how to develop process planning and the associated documentation to control the manufacture of composite structures

### Statement of learning outcomes

Learners will be able to:

1. Provide a clear overview of the process planning procedures
2. Work as part of a team planning the introduction of composites manufacturing processes

### Methods of teaching

6 lectures and associated group exercises, including industrial examples

### Assessment details if required

Written assignment

### Timetable information

2 days of teaching in a block.
**COMPOSITES CURRICULUM - Unit Information**

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>MANUFACTURING OPERATIONS A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Tooling Design and Manufacture</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td></td>
</tr>
<tr>
<td>Unit director</td>
<td>Martyn Jones/ Prof Richard Day</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. Its purpose is to describe and detail the materials, process and requirements in designing tooling for the manufacture of composite components.

**Core subjects to be covered**

| 1. Overview of different manufacturing processes and the challenges in designing tooling for these applications. | 8. Mechanisms in composite distortion during cure |
| 2. Tooling systems for prepreg and fibre manufacture | 9. Design to compensate for spring back of curved composites |
| 3. Material selection in tooling design | 10. Tolerance build up |
| 4. Thermal endurance requirements | 11. Maintenance of tooling for composite components |
| 5. Conventional mould design | 12. Mould design using CAD (Catia Composites workbench) |
| 6. Advanced tooling design for pultrusion, filament winding etc | 13. Sustainable tooling design |
| 7. Consumables used for tooling materials with reference to release agents | |

**Statement of unit aims**

The aims of this unit are to:

1. Allow learnings to critically assess the tooling material requirements based on material and cure properties
2. Develop a deep understanding of the phenomena that causes cure distortion and how tools are designed to compensate for this.
3. Understand the different manufacturing process and the tooling required for each method
4. How to use and maintain composite tooling correctly and sustainably.

**Statement of learning outcomes**

Learners will be able to:

1. Have a systematic understanding of how to design tooling based on the manufacturing processes utilised
2. Critically evaluate how tooling can contribute to the form and geometry of the final component after cure
3. Develop a practical knowledge of tooling maintenance and operation process

**Methods of teaching**

6 lectures, 1 lab classes and demonstrations, 1 CAD session and 1 class exercise

**Assessment details if required**

100% design task assessment

**Timetable information**

3 days of teaching in a block
### Composites Curriculum – Unit information

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Joining &amp; Assembly</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td></td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr. Hamed Yazdani Nezhad</td>
</tr>
</tbody>
</table>

**Unit description**

The unit provides a knowledge-based, industrial-oriented taught module on assembly and joining of high-performance composite structures, via providing theoretical framework and common practices for composite joints and assemblies.

**Core subjects to be covered**

| 1. Introduction to composite structural Integrity | 12. Process-induced Defects in Composite fastening and bonding |
| 2. Best Practices in Bonding, Bolting and Assembly Approaches | 13. NDT of composite assemblies |
| 3. Thermoplastic welding | 14. Stresses in fasteners and bonds |
| 4. Material removal and surface preparation | 15. Strength variation along degrading interface |
| 5. Mechanical performance of bolted and bonded assemblies | 16. Correlation between defect type and failure mode |
| 6. Stress distribution in adhesively bonded composite joints | 17. Cohesion failures |
| 7. Load path eccentricity in composite joints | 18. Adhesion failures |
| 10. Fatigue failure in bolted and bonded joints | 21. Stress in doubler bonded assemblies |
| 11. Bond failure in environmental conditions | 22. Adhesive failure by shear or peel |

**Statement of unit aims**

The aims of this unit are to:

1. Provide intense knowledge-based industrial oriented learning sessions on composite integration and joining
2. Provide deterioration mechanisms occurring in processing and assembly of composite materials and structures.

**Statement of learning outcomes**

Learners will be able to:

1. Appreciate a variety of integration, repair and joining procedures in composite structures from fastening, thermoset adhesive bonding to thermoplastic welding
2. Understand deterioration mechanisms occurring in processing and assembly of composite materials and structures.
3. Learn about adhesive bond damage tolerance and failure assessment procedures.

**Methods of teaching**

9 lectures Inc. demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
**COMPOSITES CURRICULUM - Unit Information**

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Factory design and layout</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the units “Introduction to Composites” and “Manufacturing of composite products” to provide Learners with a good understanding of the principles behind the design, development and layout of factories to manufacture composite products. The unit starts from the assumption of the need to build a new facility for a single product line.

**Core subjects to be covered**

1. Background to building factories in the UK
2. Investment planning - build to final scale or with scale-up options etc
3. Identifying the detailed production process steps
4. Identifying the associated production process equipment
5. Identifying ancillary process equipment
6. Developing the equipment specifications identifying any special build issues (pits, craneage, air conditioning, clean rooms, nitrogen plants and hard floors etc)
7. What-if scenario planning to identify critical equipment utilisation and similar assumptions – including a range of % right first-time assumptions
8. Mapping production flows – simulating the factory to permit virtual debottlenecks
9. Developing baseline assumptions case to set commissioning targets
10. Identifying space requirements – equipment footprint
11. Identifying space requirements – working area, circulation area, storage and office space.
12. Estimating factory build costs
13. Estimating factory build time
14. Procurement issues
15. Equipment installation and commissioning
16. Initiating production and data collection to check against assumptions and map value streams.
17. Factory efficiency improvement processes
18. Modifying or repurposing existing factories to change product lines or processes
19. Conclusions and lessons learned

**Statement of unit aims**

The aims of this unit are to:

1. Give Learners an understanding of the development of the issues associated with the development of new composites manufacturing facilities
2. Provide Learners with an overview of how to design, procure and commission a factory for composites manufacture

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the factory design procurement and set-up process
2. Work as part of a team developing and delivering new composites manufacturing facilities

**Methods of teaching**

6 lectures and associated group exercises

**Assessment details if required**

Written assignment

**Timetable information**

2 days of teaching in a block.
### Taught block title
Manufacturing Operation B

### Unit title
Agile, Lean, Six Sigma and similar methods

### Level (Credit points)
M(2)

### Unit description
This unit forms part of the Masters level Composites Curriculum. It introduces learners to the administration and quality systems that potentially make an adequate organisation into a best-in-sector operation. The course should be delivered with a focus on exemplar case studies from within the composites industry. The module complements Manufacturing Operations A/Process Monitoring.

### Core subjects to be covered

| 1. World-Class organisational culture | 9. Empowering employees as decision makers |
| 2. Quality management and the gurus | 10. Appropriate supplier/partner relationships |
| 3. Customer needs and requirements | 11. Supply chain management and risk |
| 4. Houses of Quality (QFD) | 12. Effective IT, data integrity, ERP |
| 5. SPC, PFMECA, Kaizen, Poka-Yoke | 13. Change management (or failures) |
| 7. Six Sigma/DMAIC | 15. Integrate ISO9000/14000/27000 & OHSAS18000 |
| 8. Process capability, variability and yield |

### Statement of unit aims

The aims of this unit are to:

1. Provide learners with a broad overview of systems which enable sustainable commercial business.
2. Identify techniques, and case studies, that can be implemented in industry.
3. Provide a framework for critical analysis of composite manufacturing operations.
4. Identify support systems for improvement of manufacturing operations.

### Statement of learning outcomes

Learners will be able to:

1. Clearly describe quality management systems in the context of composites manufacture.
2. Understand the routes to optimisation of composites manufacturing processes
3. Undertake critical analysis of failing commercial systems.

### Methods of teaching
7 lectures, 2 tutorials, 1 group exercise

### Assessment details if required
Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information
2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Tolerancing, variability and defects</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor Kevin Potter</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the factors influencing the geometrical tolerances in composites manufacture, including the impact of variability in both materials and processes. The unit also considers the origins and impacts of a wide range of defects. The course will be delivered from processing science and manufacturing engineering perspectives.

**Core subjects to be covered**

1. Variability in incoming materials
2. Materials specifications and control
3. Thickness variability in bag or “floating tool” moulding
4. Geometric fidelity
5. Spring-in thermoelastic effects
6. Spring-in non-thermoelastic effects
7. What is a defect?
8. Defect Taxonomy
9. Acceptance criteria
10. Rework, repair and concessions
11. Cosmetic errors
12. Delaminations
13. Voidage
14. Fibre waviness and wrinkling
15. Cure related defects
16. Machining defects
17. Defect root cause investigations

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an overview of the factors influencing geometrical tolerances in composites mouldings
2. Provide an overview of the sources of variability in materials and processes and how those variabilities manifest through geometrical fidelity
3. Consider the range of potential defects, their possible impacts and the opportunities for mitigation in the process

**Statement of learning outcomes**

Learners will be able to:

1. Identify sources of variability in composite components and manufacturing processes
2. Generate designs which limit or control variability
3. Identify the potential for defect generation in component designs

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Core Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Machining composites</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the capabilities and limitations of cutting, drilling and other processes for reshaping laminates.

**Core subjects to be covered**

1. Health and Safety considerations (effects of dust on the human body, how to work safely)
2. Fixturing, datum control and clamping
3. Material removal techniques (cutting, sawing, drilling, turning, milling, routing, lapping, grinding, etc.)
4. Traditional tool materials (steel, WC, and diamond/BN) and geometry
5. (Abrasive) water jet machining
6. Ultrasonic machining
7. Electrochemical and electrical discharge machining
8. Laser machining
9. (Photo-)chemical machining
10. Plasma arc methods
11. Special considerations for aramids and natural fibre composites
12. Machining damage (delamination, burr, back-up plates, coolant)
13. Hole quality (cylindricity, diameter error)
14. Cutting forces
15. Process modelling, optimisation and control
16. Condition monitoring and non-destructive evaluation
17. Dimensional inspection
18. Economic and environmental considerations

**Statement of unit aims**

The aims of this unit are to:

1. Give learners an understanding of the options available for removal of material from laminates
2. Provide Learners with an overview of the capabilities and limitations of machining in the context of fibre reinforced composites
3. Give learners the tools to make the most appropriate choice of machining process for a specific application
4. Provide the learners with an understanding of process issues required to machine composites with minimal/zero damage

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the capabilities and limitations of machining for composites
2. Establish which machining processes are the most appropriate choice for a specific application
3. Understand the process issues in machining a wide selection of composites

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Manufacturing Operations B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Surface finishing and painting</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the capabilities and limitations of coating systems.

**Core subjects to be covered**

1. Coating laminates, or laminating-to-coatings
2. Surface preparation
3. Paint formulation and characterisation
4. Paint application
5. Gel-coats formulation and characterisation
6. Open mould gel-coating
7. In-mould gel-coating
8. Metallisation of polymeric surfaces
9. Classification of defects in coatings: to include pinholes, print-through
10. Measurement of quality for surface finishes
11. Functional coatings, including self-cleaning surfaces and anti-fouling systems
12. Removal, repair and disposal of coatings
13. Cost and environmental issues

**Statement of unit aims**

The aims of this unit are to:

1. Give Learners an understanding of the range of coating materials and process options
2. Provide Learners with an overview of the capabilities and limitations of coating systems
3. Give Learners the tools to determine and appropriate coating system for a specific application
4. Provide the Learners with an understanding of process issues constraining the surface finish of composites

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the capabilities and limitations of coating systems
2. Establish an appropriate coating system for a specific application
3. Understanding of process issues constraining the surface finish on composites

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Mechanical properties and testing - anisotropic elasticity</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr. Nuri Ersoy</td>
</tr>
</tbody>
</table>

Unit description
This unit forms part of the Masters level Composites Curriculum. It provides Learners with no prior experience with composites with a general introduction to the basic mechanical properties and how they can be obtained through standardized testing.

Core subjects to be covered

<table>
<thead>
<tr>
<th>1. Orthotropic materials</th>
<th>10. Tension Test Procedure (ASTM 3039)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Transverse isotropy</td>
<td>11. Compression Test Procedures</td>
</tr>
<tr>
<td>3. Engineering properties of orthotropic and transversely isotropic materials</td>
<td>1. IITRI Test Procedure (ASTM D 3410)</td>
</tr>
<tr>
<td>4. Testing standards for Mechanical Properties of Composites</td>
<td>2. ASTM D 695 Test Procedure</td>
</tr>
<tr>
<td>5. Test Specimen Preparation, Strain, and Deformation</td>
<td>12. CLC Test Procedure (ASTM D 6641)</td>
</tr>
<tr>
<td>7. Specimen Preparation and Tab Bonding</td>
<td>1. Iosipescu Shear Test Method (ASTM D 5379)</td>
</tr>
<tr>
<td>8. Strain and Displacement Measurements</td>
<td>2. Two-Rail Shear Test Method (ASTM D 4255)</td>
</tr>
<tr>
<td></td>
<td>4. [±45]ns Tensile Shear Test Method (ASTM D 3518)</td>
</tr>
<tr>
<td></td>
<td>5. Short Beam Shear Test Method (ASTM D 2344)</td>
</tr>
</tbody>
</table>

Statement of unit aims
The aims of this unit are to:
1. Provide Learners with an overview of the concepts of isotropy, orthotropy, and transverse isotropy
2. Identify the engineering constants required to define isotropic, orthotropic, and transversely isotropic materials
3. Provide the learners with an understanding of testing machines, measuring devices, and specimen preparation
4. Give learners an understanding of the standardized test methods to measure the engineering properties of composites

Statement of learning outcomes
Learners will be able to:
1. Acquire an understanding of the mechanical properties of unidirectional fibre reinforced composite materials
2. Identify the tests methods required for mechanical characterization of these materials
3. Comprehend how these materials fail under pure tension, compression and shear loading.
4. Have a preliminary consideration of how the properties measured relate to stress and strength analysis of composite laminates

Methods of teaching
5 lectures, 3 lab classes and demonstrations, 1 class exercise

Assessment details if required
Written assignment (85%), 20 min assessed presentation (15%)

Timetable information
2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Mechanical properties and testing - static strength, failure modes and failure criteria</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr. Nuri Ersoy</td>
</tr>
</tbody>
</table>

Unit description

This unit forms part of the Masters level Composites Curriculum. It provides Learners with no prior experience with composites with a general introduction to the basic strength properties, failure modes, and failure criteria.

Core subjects to be covered

1. Revision of properties obtained by tension, compression, and shear testing.
2. Failure modes under tensile, compressive and shear loading.
3. Multiaxial loading and testing
4. Failure Criteria
   1. Maximum Stress Failure Criterion
   2. Maximum Strain Failure Criterion
   3. Tsai-Wu Failure Criterion
   4. Hashin Failure Criterion
5. Factor of Safety

Statement of unit aims

The aims of this unit are to:
1. Provide Learners with an overview of the strength properties obtained by tensile, compression, and shear tests
2. Provide Learners with an understanding of the failure modes under tensile, compression, and shear, and multiaxial loading
3. Provide the learners with an understanding of industrially relevant failure criteria
4. Give learners an preliminary idea of how to use the failure criteria for design of composite laminates

Statement of learning outcomes

Learners will be able to:
1. Assess the factor safety under unidirectional loading in tension, compression, or shear
2. Identify the failure modes under tensile, compression, and shear, and multiaxial loading
3. Understand how the stresses and failure modes interact in the case of multiaxial loading
4. Have a preliminary understanding of how the various failure criteria can be utilized in design of composite laminates

Methods of teaching

8 lectures, 1 lab classes and demonstrations, 1 class exercise

Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information

2 days of teaching in a block
**COMPOSITES CURRICULUM - Unit Information**

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Mechanical properties and testing - dynamic and fatigue</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the units ‘Mechanical properties and testing – anisotropic elasticity’ and ‘Mechanical properties and testing – static strength, failure modes and failure criteria’ to provide Learners with a good understanding of the performance of composite systems under dynamic and fatigue loading conditions.

**Core subjects to be covered**

1. Introduction and definitions
2. Stress and strain controlled loading
3. Fatigue damage development
4. Monitoring fatigue damage
5. Fatigue testing (tension, compression, fully reversed, shear)
6. Fatigue data representation
7. Factors affecting fatigue performance
8. Predicting performance and life under fatigue loads
9. Delamination growth under fatigue
10. Design for fatigue
11. Low and high velocity impact
12. Impact resistance and impact damage tolerance
13. Impact damage development
14. Factors affecting impact performance
15. Impact test methods and residual properties evaluation
16. Performance under high rate dynamic loading
17. High rate equipment and testing methods
18. Basic principles of crashworthiness and energy absorption mechanisms
19. Crashworthiness testing and simulation

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an understanding of the fatigue and dynamic performance of composites
2. Identify the advantages and limitations of these materials under fatigue and dynamic loading conditions
3. Give learners an overview of the testing methodologies for quantifying the performance of these materials

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the range of fatigue and dynamic test methods
2. Understand some of the issues associated with the use of composites under fatigue and dynamic loading conditions
3. Establish appropriate procedures for using experimental data in the design against fatigue loading and impact threats

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Durability</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the deterioration of composite systems over extended exposure to degrading conditions.

**Core subjects to be covered**

1. Polymer transition temperatures
2. Thermal degradation and fire
3. Moisture diffusion
4. Marine exposure: osmosis and blistering, galvanic corrosion
5. Weathering: electromagnetic and ionising radiation, precipitation and particle erosion
6. Chemical attack: acids, alkalis, solvents
7. Biological exposure: fouling, fungi
8. Mechanical durability: creep, fatigue, impact
9. Environmental stress corrosion interactions
10. Standard methods of test (NPL MAT85)
11. Highly Accelerated Life Testing (HALT)
12. Structural Health Monitoring (SHM)
13. Lifetime prediction

**Statement of unit aims**

The aims of this unit are to:

1. Give Learners an understanding of the limitations of composites arising from degradation mechanisms
2. Provide Learners with an overview of the mechanisms of deterioration of composite performance
3. Give Learners the tools to design commercial structures that will satisfy performance requirements for the whole life cycle

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the mechanisms of deterioration of composites
2. Establish an appropriate composite system for a specific application respecting the operating environment
3. Understand the issues constraining the use of composites in harsh conditions.

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
**Taught block title**  
Performance A

**Unit title**  
Non-structural properties - erosion, wear, electrical and thermal properties

**Level (Credit points)**  
H (2)

**Unit director**  
Stefanos Giannis

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the units under taught block Performance A to provide Learners with a good understanding of non-structural composite material properties and their importance in designing both conventional and multifunctional structures.

**Core subjects to be covered**

<table>
<thead>
<tr>
<th>Core subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction to non-structural properties</td>
</tr>
<tr>
<td>2. Applications requiring non-structural properties</td>
</tr>
<tr>
<td>3. Solid particle erosion</td>
</tr>
<tr>
<td>4. Effect of erosion and abrasion on surface characteristics and performance</td>
</tr>
<tr>
<td>5. Measuring the erosion wear rate on composites</td>
</tr>
<tr>
<td>6. Electrical conductivity and percolation theory</td>
</tr>
<tr>
<td>8. Dielectric performance</td>
</tr>
</tbody>
</table>

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an understanding of the erosion, wear, electrical and thermal performance of composites
2. Give learners an overview of the testing methodologies for quantifying the non-structural properties of composites
3. Identify the advantages and limitations of these materials when designing multi-functional structures

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the diverse non-structural properties of composite materials
2. Establish appropriate procedures for quantifying non-structural performance of composites
3. Understand some of the issues and opportunities associated with the use of composites in multi-functional structures

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Fire and Post Fire Mechanical Performance of Composites</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Prof Baljinder Kandola</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum.

**Core subjects to be covered**

1. The basics of combustion of polymeric materials
2. Fire performance of composites
3. Methods of imparting fire retardancy to composites,
4. Materials selection or design for fire safe composites
5. Fire testing methodologies

**Statement of unit aims**

The aims of this unit are to:

1. To gain an appreciation of the methods used to reduce flammability of composites through an understanding of the underlying processes, and the use of these methods to select appropriate materials in design of composites.
2. To assess various test methods and instruments used for evaluation of fire performance of materials, and important factors to consider in order to achieve a good result
3. To address how improving one type of performance for example flammability can have a detrimental effect on another such as mechanical performance.

**Statement of learning outcomes**

Learners will be able to:

1. Relate composite formulations to their burning behaviours
2. Understand different methods / techniques for studying burning behaviour of polymeric materials
3. Relate composites’ structures and properties to most appropriate design and selections by taking all parameters into account
4. Understand different test methods to evaluate fire and fire retardant performance

**Methods of teaching**

Lectures/lab classes/demonstrations/class exercises/etc

**Assessment details if required**

An assignment in the form of the Integrated Learning Package (ILP) will be provided so that participants will be able to complete the work within xx weeks after the start of the module. The ILP consists of two components in which Part 1 examines the candidate’s basic understanding of the concept, principles and awareness of the module, Part 2 probes and investigate selected classes of answers which are designed to reflect deep understanding of the subject.

**Timetable information**

X days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the sensors and systems appropriate to non-destructive testing of composites, for condition monitoring (CM), structural health monitoring (SHM) and in-service inspection, during processing and service, or for failure analysis.

**Core subjects to be covered**

1. Initial inspection, monitoring in-service (CM/SHM) or failure analysis.
2. Manufacturing defects and service damage
3. Probability of detection.
4. (A) Electromagnetic spectrum; radiography, UV, visible, IR, thermography, THz, microwave, eddy-current, dielectric, electric and magnetic.
5. Synchrotron/x-ray/isotope imaging
6. White light and laser technologies
7. Thermography
8. Dielectrometry/moisture meters
9. (B) Chemical spectroscopy: NMR, Raman, NIR
10. (C) Mechanical vibration: SAM, US, AU/SWE, vibration
11. Ultrasounds
12. Acoustic emission, including CARP codes
13. Computed tomography
14. Embedded sensors
15. Data fusion
16. NDT of coatings
17. Matching techniques and issues.

**Statement of unit aims**

The aims of this unit are to:

1. Give Learners an understanding of the many techniques available for non-destructive testing of composites.
2. Provide Learners with an overview of the specific techniques appropriate to the defect or damage and the substrate material.
3. Give Learners the tools to choose an effective technique for the issue to be investigated.

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the range of non-destructive test techniques
2. Establish an appropriate testing procedure for differing defects or damage conditions.
3. Understand the issues constraining the resolution of each technique, and the ability to detect defects or damage

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
## COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Multifunctional Composites</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Vijay Kumar Thakur</td>
</tr>
</tbody>
</table>

### Unit description

This unit forms part of the Masters level Composites Curriculum. It provides Learners with no prior experience with multifunctional composites with a general introduction to the core concepts in understanding and applying multifunctional composites in engineering applications.

### Core subjects to be covered

1. Introduction of multifunctional composites
2. Why use multifunctional composites
3. Design and manufacture
4. Structural functions
5. Non-structural functions
7. Characterization
8. Multifunctional Polymer Composites
9. Multifunctional Cement Composites
10. Multifunctional Ceramic Composites
11. Multifunctional Metal Composites
12. Multifunctional Bio-Composites
13. Multifunctional Nano-Composites
14. Smart Multifunctional Composite
15. Applications
16. Multifunctional Composites for Energy Storage
17. Multifunctional Composites for Energy Harvesting
18. Multifunctional Composites Aerospace Structures
19. Multifunctional Composites for Automotive
20. Multifunctional Composites for Biomedical

### Statement of unit aims

The aims of this unit are to:
1. Provide Learners with an overview of multifunctional composite materials
2. Identify the needs of multifunctional composite materials
3. Give learners an understanding of the different types of multifunctional composite materials
4. Provide the learners with an understanding of potential applications of multifunctional composite

### Statement of learning outcomes

Learners will be able to:
1. Provide a basic overview of the development of multifunctional composite materials
2. How to engineer multifunctional materials to achieve desired properties
3. Understand approaches for optimizing materials properties and their applications

### Methods of teaching

- 7 lectures, 2 lab classes and demonstrations, 1 class exercise

### Assessment details if required

- Written assignment (85%), 20 minute assessed presentation (15%)

### Timetable information

- 2 days of teaching in a block
# Composites Curriculum – Unit information

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>In-service Damage and Repair</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td></td>
</tr>
<tr>
<td>Unit director</td>
<td>Dr. Hamed Yazdani Nezhad</td>
</tr>
</tbody>
</table>

## Unit description
The unit provides an intense teaching of common academic and industrial practices for in-service damage and repair along with the existing aviation certification and repair regulations. The unit also complements and continues Unit: Joining & Assembly.

## Core subjects to be covered

<table>
<thead>
<tr>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction to damage in composites and composite assemblies</td>
</tr>
<tr>
<td>2. BVID</td>
</tr>
<tr>
<td>3. Damage in bolted and bonded assemblies</td>
</tr>
<tr>
<td>4. Effect of glass transition temperature</td>
</tr>
<tr>
<td>5. Serviceability of composite structures</td>
</tr>
<tr>
<td>6. Limitations of production NDT</td>
</tr>
<tr>
<td>7. Limitations of service NDT</td>
</tr>
<tr>
<td>8. Composite bonded repair</td>
</tr>
<tr>
<td>9. Bonded repair model</td>
</tr>
<tr>
<td>10. Repair failure modes</td>
</tr>
<tr>
<td>11. Selection guidance for fastening options</td>
</tr>
<tr>
<td>12. Load attraction and stresses in repair</td>
</tr>
<tr>
<td>13. Stresses in fasteners and bonds</td>
</tr>
<tr>
<td>14. Strength variation along degrading interface</td>
</tr>
<tr>
<td>15. Real bond defects</td>
</tr>
<tr>
<td>16. How to measure degrading joint strength</td>
</tr>
<tr>
<td>17. Repair of BVID</td>
</tr>
<tr>
<td>18. Bond failure forensics</td>
</tr>
<tr>
<td>19. Sandwich panel service defects</td>
</tr>
<tr>
<td>20. Core-to-spar bond in aircraft structures</td>
</tr>
<tr>
<td>21. Effect of operational thermal stresses</td>
</tr>
<tr>
<td>22. Total load at end of repair vs. design limit load</td>
</tr>
<tr>
<td>23. Stress under repair</td>
</tr>
<tr>
<td>24. Repair failure due to hot bonding and poor heating</td>
</tr>
<tr>
<td>25. Certification of composite joints</td>
</tr>
<tr>
<td>26. Aerospace composite repair regulations</td>
</tr>
</tbody>
</table>

## Statement of unit aims
The aims of this unit are to:
1. Provide categories of damage occurring in service in high performance composite materials and structures
2. Provide industrial repair procedures for in-service damage

## Statement of learning outcomes
Learners will be able to:
1. Appreciate a variety of integration, repair and joining procedures in composite structures from fastening, thermoset adhesive bonding to thermoplastic welding
2. Learn about adhesive bond damage tolerance and failure assessment procedures
3. Learn about composite repair certifications

## Timetable information
2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Recycling and reuse</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

Unit description

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the economic and environmental issues arising from the selection of composite systems.

Core subjects to be covered

1. Sustainability: economic, environmental, equity, governance
2. Directives, regulations and legislation
3. Hierarchy of end-of-life (HEOL) options, establishing ownership of abandoned components, and the circular economy
4. HEOL1: design for end-of-life
5. HEOL2: the manufacture and marketing phase
6. HEOL3: the use phase ~ how are environmental burdens minimised?
7. HEOL4: reuse of (sub-)components
8. HEOL5: reprocessing thermoplastic composites
9. HEOL6: regeneration of raw materials or their precursors from thermosetting systems
10. HEOL7: recovery and/or degradation of reinforcement fibres
11. HEOL8: Incineration, composting, landfill or scuttle
12. Life Cycle Costing
13. Life Cycle Assessment: ISO 14040 series
14. Environmental Impact Classification Factors
15. “Goal and Scope” and allocation in LCA
Software: Simapro, EcoInvent, CES EduPack

Statement of unit aims

The aims of this unit are to:

1. Give Learners an understanding of the economic and environmental issues surrounding the use of composites
2. Provide Learners with an overview of the options for limiting the impact of composites on the environment
3. Give Learners the tools to balance economic and environmental considerations in component design

Statement of learning outcomes

Learners will be able to:

1. Provide a clear overview of the economic issues and environmental burdens of composite systems
2. Establish an appropriate composite system for a specific application
3. Understanding of issues constraining the market for composites

Methods of teaching

7 lectures, 2 lab classes and demonstrations, 1 class exercise

Assessment details if required

Written assignment (85%), 20 minute assessed presentation (15%)

Timetable information

2 days of teaching in a block
This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>Sustainable composites</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>H (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It builds on the unit “Introduction to Composites” and “Composites Constituents” to provide Learners with a good understanding of the capabilities and limitations of “sustainable” composites.

**Core subjects to be covered**

1. Sustainability: economic, environmental, equity, governance
2. Circular economy, Bio-economy
3. Natural fibres (animal, mineral, vegetable)
4. Plant fibres: agriculture and extraction
5. Plant fibres: properties and durability
6. The fibre-matrix interface
7. Plant fibres: composites processing
8. Plant fibre composites: properties and durability
9. Plant fibre composites: end-of life
10. Bio-based polymers
11. Bio-degradable polymers Wood-based composites and panel products
12. Life Cycle Costing
13. Life Cycle Assessment: ISO 14040 series
14. Environmental Impact Classification Factors
15. “Goal and Scope” and allocation in LCA

**Statement of unit aims**

The aims of this unit are to:

1. Give learners an understanding of the range of materials and process options
2. Provide Learners with an overview of the capabilities and limitations of “sustainable” composites
3. Give learners the tools to establish if “sustainable” composites are the most appropriate choice for a specific application
4. Provide the learners with an understanding of process issues constraining the manufacture of natural fibre composites

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the capabilities and limitations of “sustainable” composites
2. Establish if “sustainable” composites are the most appropriate choice for a specific application
3. Understanding of process issues constraining the manufacture of natural fibre composites

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
COMPOSITES CURRICULUM - Unit Information

This unit forms part of the Masters level Composites Curriculum developed by Bristol and Plymouth Universities.

<table>
<thead>
<tr>
<th>Taught block title</th>
<th>Performance B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit title</td>
<td>The broad perspective on composites</td>
</tr>
<tr>
<td>Level (Credit points)</td>
<td>M (2)</td>
</tr>
<tr>
<td>Unit director</td>
<td>Professor John Summerscales</td>
</tr>
</tbody>
</table>

**Unit description**

This unit forms part of the Masters level Composites Curriculum. It introduces Learners to the wider context of composites by considering natural materials, composites with a broader range of matrix systems, and what composites might become. Some content will inevitably overlap with other modules!

**Core subjects to be covered**

1. Particle, whisker or fibre reinforcement
2. Cellulose, chitin and protein
3. Ancient animal artefacts  
   (e.g. bone, antler, ivory, horn)
4. Wooden weapons and workmanship  
   (archery, shields and plant-based products)
5. Structure in nature as a strategy for design  
   (biomimetics)
6. Elastomeric matrices  
   (tyres, hoses, conveyor belts)
7. Self-reinforcing polymers
8. Hierarchical composites
9. Thin-ply flexible structures  
   (including tensile structures)
10. Metal matrix composites  
    (beware galvanic corrosion)
11. Ceramic matrix composites  
    (ceramic, glass, cements, concrete & cob)
12. Carbon/carbon composites
13. Functionally graded materials (FGM)
14. Smart materials  
    (one response for each specific stimulus)
15. Intelligent structures  
    (embedded sensor, control and actuator)

**Statement of unit aims**

The aims of this unit are to:

1. Provide Learners with an extended view of where composites do occur (beyond FRP)
2. Provide Learners with a perspective on how composites may develop in future years.
3. Identify the underlying design principles that have evolved in natural systems
4. Identify appropriate materials for critical performance requirements.

**Statement of learning outcomes**

Learners will be able to:

1. Provide a clear overview of the extended range of properties achievable dependent on the selected components of the composite system
2. Consider where nature has already evolved a solution to a parallel problem and use that to inspire (not imitate) the design of a new component.
3. Understand some of the limitations of existing systems and think outside the box to develop appropriate designs for challenging environments.

**Methods of teaching**

7 lectures, 2 lab classes and demonstrations, 1 class exercise

**Assessment details if required**

Written assignment (85%), 20 minute assessed presentation (15%)

**Timetable information**

2 days of teaching in a block
Appendix 10- Proposal submitted to HVMC

Tackling Manufacturing Skills Shortages

Quad Chart for Composites Curriculum Proposal

<table>
<thead>
<tr>
<th>Demand</th>
<th>Proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Significant skills shortages in UK Advanced Manufacturing, critical level in Composites</td>
<td>• Fund a Catapult Fellowship in Composite Skills Development</td>
</tr>
<tr>
<td>• Potential for UK Composites market to grow by £108bn in 10yrs</td>
<td>○ Sustain activity post-HEFCE</td>
</tr>
<tr>
<td>○ 50 000 – 100 000 new jobs</td>
<td>○ Develop sustainable training model</td>
</tr>
<tr>
<td>• Must move from hand skills to tech skills</td>
<td>• Develop and trial full curriculum</td>
</tr>
<tr>
<td>• Need 2000 composites trained grads/year</td>
<td>○ Masters level</td>
</tr>
<tr>
<td>○ 400 Masters, 100 Doctors</td>
<td>○ Creative Commons for max usage</td>
</tr>
<tr>
<td>• Only UK Industrial Doctorate Centre in Composites Manufacturing to close</td>
<td>○ Multi-university collaboration</td>
</tr>
<tr>
<td>○ Final intake 2020 (next year)</td>
<td>○ Deliver in academia or industry</td>
</tr>
<tr>
<td>○ Delivers only 10% of requirement</td>
<td>○ Industry already involved</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Stakeholders</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Funding proposal for delivering and trialling full Composites Curriculum</td>
<td>• UK Composites Manufacturers</td>
</tr>
<tr>
<td>• Feedback on HEFCE project trials</td>
<td>• UK Composites Material Suppliers</td>
</tr>
<tr>
<td>• Development of full curriculum</td>
<td>• ~15 Academic institutions</td>
</tr>
<tr>
<td>• Material made available under suitable IP regime</td>
<td>• HVMC Centres</td>
</tr>
<tr>
<td>○ NCC</td>
<td>○ NCC</td>
</tr>
<tr>
<td></td>
<td>○ AMRC</td>
</tr>
<tr>
<td>• Trials of options for course delivery</td>
<td></td>
</tr>
</tbody>
</table>

Why Composites?

This is demographically a critical time in Composites. The first flowering of advanced composites was the late 1950s to the early 1970s, driven by people who are now retired. The second wave, who entered the industry in the mid-1970s, are on the brink of retirement, including the two leads on the HEFCE project.

We are in danger of losing critical experience if we do not move to capture it now.

The curriculum content has been specified and trial units delivered. The HEFCE project shows good engagement from academia in Composites and a willingness to deliver a collaborative course, utilising the differing expertise of each institution. We can rapidly develop the skills model alongside teaching and learning materials, which can be applied to other critical skills shortages in advanced manufacturing.

The immediate need is to identify and fund an academic champion to sustain the activity beyond the current project. The champion will co-develop with industry and the Catapult a vision and funding proposal for a sustainable model of developing advanced training capacity in the UK, allowing the industrial strategy to come to fruition without skills shortages limiting national opportunities.

The HVMC has played a crucial role in the development of the UK Composites Strategy and the very significant government investments that have been made and is ideally placed to provide leadership and direction to the skills developments needed in parallel to the technology and strategy developments. Lack of suitably trained staff will render the UK’s National Composite Strategy undeliverable. This proposal is intended to deliver a method to remedy that problem.
Appendix 11- Staff figures from BMW’s i3 programme

BMW have provided the following information on staffing levels needed for the i3 production:

**Initial stage; 10 – 6 years before start of production**
- Research and Development “Skunk Works”
  - Incubators – Present in Body-in-white, Crash and Durability 5 – 10 people, composite trained and highly experienced Engineers and PhDs
  - Sizing and Construction – Engineering level, 5 – 10 people
- Manufacturing
  - Incubators – 5 people with background in composite manufacturing, highly experienced Engineers and PhDs
  - Production development – 5 -10 engineers or highly experienced technicians

**Development stage; 6 - 2 years before start of production**
- Research and Development
  - Additional engineering staffing up to 20 people
- Manufacturing
  - Prototype manufacturing at max. capacity
  - Up to 40 technicians
- Outreach
  - Staffing should be available to perform internal training and built knowledge base

**Industrialization stage, 2 – 0 years**
- Research and Development
  - Scaling internally, not necessarily additional recruitment
- Manufacturing
  - Scaling to automotive volume
  - Focus on quality control and NDE, process optimization, additional 10 engineers
  - Additional technicians for at volume manufacturing, 20 technicians
- Plant and assembly
  - Quality control and process management, 10 engineers
  - Technicians not necessarily composite trained

Rumours state that 2billion$US\textsuperscript{24} were spent on development of the i3 and it is calculated to be profitable at 20,000 units per year\textsuperscript{25}. Sales in 2015 were 22,000 per year\textsuperscript{26} and reached 34,000 per year in 2018\textsuperscript{27}. Prices in the UK start at £30680\textsuperscript{28} per car. This gives a 2018 BMW i3 global market size of ~£1x10^9.

\textsuperscript{24} http://www.forbes.com/sites/neilwinton/2014/05/15/bmws-electric-brand-will-lower-co2-cost-a-lot-and-pay-off-big-long-term/#256bf620167b [online, 30/08/19]
\textsuperscript{26} BMW Group. Annual Report. 2015.
Appendix 12- Estimate of demand signal

NOTES

Purpose
Cross check KP figures with overall UK student numbers
Seek alignment with previous manpower estimations (PS 2010)

Comments

W/S KP-Based
Take capital intensive FTE figure - least worst case
But need to highlight increased technology / automation platforms
Alternatively use extremes to represent all / part composites needs
Beige box contains EngineeringUK figures, assume representative from 2015 (latest)
(Depressing as UK headline numbers)
This shows that KP workings come up with a reasonable level of need

Baseline seems to be to
1. Grow composites content within Graduate level (during course or CPD)
2. Significant increase of Masters input, although we need to assess current UK numbers
3. At least double Doctorates BUT this does not track R&D that leads to automation

PS View
Clear need to increase 'total composites' people at '5%-end'
Equally clear that significantly greater demand for spreading composites across professions
We will need to comment on the non-graduate portion of the workforce
Ambitious with the anticipated high levels of automation...... (circular argument)

W/S
Strategies
Figures from E&Y 2010 and CLF 2014 reports
Unfortunately not consistent measures / definitions (Revenue, GVA, etc. or what is a composite)
Major discrepancy is a delay to aero growth beyond 2015 E&Y figures
Overall, we can make case to use upper CLF figures
Then consistent with annual FTE growing value approach
CAGR for workforce comes out around 6% which builds in the higher output values (productivity)

PS 2010
Included to illustrate how we might approach a more detailed breakdown
By 'region' and sector
### Workforce Estimates from:

<table>
<thead>
<tr>
<th>Year</th>
<th>EY Est</th>
<th>ACF Est</th>
<th>ACF Record</th>
<th>ACF Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>15,510</td>
<td>15,510</td>
<td>15,510</td>
<td>15,510</td>
</tr>
<tr>
<td>2011</td>
<td>16,968</td>
<td>16,483</td>
<td>16,483</td>
<td>16,483</td>
</tr>
<tr>
<td>2012</td>
<td>19,938</td>
<td>19,938</td>
<td>19,938</td>
<td>19,938</td>
</tr>
<tr>
<td>2013</td>
<td>21,414</td>
<td>21,414</td>
<td>21,414</td>
<td>21,414</td>
</tr>
<tr>
<td>2014</td>
<td>22,890</td>
<td>22,890</td>
<td>22,890</td>
<td>22,890</td>
</tr>
<tr>
<td>2015</td>
<td>24,595</td>
<td>24,595</td>
<td>24,595</td>
<td>24,595</td>
</tr>
<tr>
<td>2016</td>
<td>26,179</td>
<td>26,179</td>
<td>26,179</td>
<td>26,179</td>
</tr>
<tr>
<td>2017</td>
<td>27,824</td>
<td>27,824</td>
<td>27,824</td>
<td>27,824</td>
</tr>
<tr>
<td>2018</td>
<td>29,469</td>
<td>29,469</td>
<td>29,469</td>
<td>29,469</td>
</tr>
<tr>
<td>2019</td>
<td>31,113</td>
<td>31,113</td>
<td>31,113</td>
<td>31,113</td>
</tr>
<tr>
<td>2020</td>
<td>34,238</td>
<td>34,238</td>
<td>34,238</td>
<td>34,238</td>
</tr>
<tr>
<td>2021</td>
<td>37,362</td>
<td>37,362</td>
<td>37,362</td>
<td>37,362</td>
</tr>
<tr>
<td>2022</td>
<td>40,486</td>
<td>40,486</td>
<td>40,486</td>
<td>40,486</td>
</tr>
<tr>
<td>2023</td>
<td>43,610</td>
<td>43,610</td>
<td>43,610</td>
<td>43,610</td>
</tr>
<tr>
<td>2024</td>
<td>46,734</td>
<td>46,734</td>
<td>46,734</td>
<td>46,734</td>
</tr>
<tr>
<td>2025</td>
<td>49,858</td>
<td>49,858</td>
<td>49,858</td>
<td>49,858</td>
</tr>
<tr>
<td>2026</td>
<td>52,983</td>
<td>52,983</td>
<td>52,983</td>
<td>52,983</td>
</tr>
<tr>
<td>2027</td>
<td>56,107</td>
<td>56,107</td>
<td>56,107</td>
<td>56,107</td>
</tr>
<tr>
<td>2028</td>
<td>59,231</td>
<td>59,231</td>
<td>59,231</td>
<td>59,231</td>
</tr>
<tr>
<td>2030</td>
<td>65,479</td>
<td>65,479</td>
<td>65,479</td>
<td>65,479</td>
</tr>
</tbody>
</table>

### Total W/F based on FTE Output (Productivity)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>29,000</td>
<td>32,000</td>
<td>35,000</td>
<td>38,000</td>
<td>41,000</td>
<td>44,000</td>
<td>47,000</td>
<td>50,000</td>
<td>53,000</td>
<td>56,000</td>
<td>59,000</td>
<td>62,000</td>
<td>65,000</td>
<td>68,000</td>
<td>71,000</td>
<td>74,000</td>
<td>77,000</td>
<td>80,000</td>
<td>83,000</td>
<td>86,000</td>
<td>89,000</td>
</tr>
</tbody>
</table>
Therefore need to impact

<table>
<thead>
<tr>
<th>% of graduates</th>
<th>Assume intensive composites</th>
<th>Assume some composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NEEDS DEFINITION
THIS FEELS OK - OR UNDERSTATED

POST GRADUATES PER YEAR

<table>
<thead>
<tr>
<th></th>
<th>Composites of UK total</th>
<th>Composites of UK total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lower</td>
<td>upper</td>
</tr>
<tr>
<td>Of graduate numbers, Masters</td>
<td>20% 50 1% 250 6%</td>
<td></td>
</tr>
<tr>
<td>Of graduate numbers, Doctorates</td>
<td>10% 25 2% 125 11%</td>
<td></td>
</tr>
</tbody>
</table>

Current UK Masters output
KP statement of
Current Doctorate output

<table>
<thead>
<tr>
<th></th>
<th>of lower</th>
<th>of upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10%</td>
<td>4%</td>
</tr>
<tr>
<td>15</td>
<td>60%</td>
<td>12%</td>
</tr>
</tbody>
</table>
### FROM STRATEGIES

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Demand (Em)</td>
<td>£1,255</td>
<td>£1,993</td>
<td>£2,252</td>
<td></td>
</tr>
<tr>
<td>Aero</td>
<td>£675</td>
<td>£1,048</td>
<td>£1,009</td>
<td></td>
</tr>
<tr>
<td>54%</td>
<td>53%</td>
<td>45%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auto</td>
<td>£143</td>
<td>£389</td>
<td>£565</td>
<td></td>
</tr>
<tr>
<td>11%</td>
<td>20%</td>
<td>25%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>£437</td>
<td>£557</td>
<td>£678</td>
<td></td>
</tr>
<tr>
<td>35%</td>
<td>28%</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### CLF 2014

<table>
<thead>
<tr>
<th>CLF 2014</th>
<th>'RECORD'</th>
<th>FORECAST 2015</th>
<th>FORECAST 2020</th>
<th>FORECAST 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aero</td>
<td>£273</td>
<td>£1,155</td>
<td>£3,590</td>
<td></td>
</tr>
<tr>
<td>Defence</td>
<td>£383</td>
<td>£952</td>
<td>£1,146</td>
<td></td>
</tr>
<tr>
<td>Auto</td>
<td>£380</td>
<td>£530</td>
<td>£3,490</td>
<td></td>
</tr>
<tr>
<td>Rail</td>
<td>£55</td>
<td>£98</td>
<td>£155</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>£362</td>
<td>£640</td>
<td>£1,520</td>
<td></td>
</tr>
<tr>
<td>Marine</td>
<td>£220</td>
<td>£270</td>
<td>£370</td>
<td></td>
</tr>
<tr>
<td>O&amp;G</td>
<td>£15</td>
<td>£337</td>
<td>£1,100</td>
<td></td>
</tr>
<tr>
<td>Renewables</td>
<td>£601</td>
<td>£685</td>
<td>£1,100</td>
<td></td>
</tr>
<tr>
<td><strong>£1,551</strong></td>
<td><strong>£2,289</strong></td>
<td><strong>£4,667</strong></td>
<td><strong>£12,471</strong></td>
<td>2010 based on E&amp;Y + 2015 discrepancy</td>
</tr>
</tbody>
</table>

### Discrepancy (CLF - E&Y)

<table>
<thead>
<tr>
<th>Discrepancy (CLF - E&amp;Y)</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>£296</td>
<td>£2,415</td>
</tr>
<tr>
<td>13%</td>
<td>52%</td>
<td></td>
</tr>
<tr>
<td>Aero</td>
<td>(£775)</td>
<td>£146</td>
</tr>
<tr>
<td>Aero (inc Defence)</td>
<td>(£392)</td>
<td>£1,098</td>
</tr>
</tbody>
</table>

Other sectors growth, ? renewables
<table>
<thead>
<tr>
<th>Auto</th>
<th>£</th>
<th>(9) £</th>
<th>(35) £</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Workforce Calculation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use FTE Output Value</td>
<td>2010</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>150,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>Calculated Total</td>
<td>15,510</td>
<td>22,890</td>
<td>31,113</td>
</tr>
<tr>
<td></td>
<td>62,355</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Previous upside forecast</td>
<td>10,950</td>
<td>22,791</td>
<td></td>
</tr>
<tr>
<td>WF growth from 2015</td>
<td></td>
<td>8,223</td>
<td>39,465</td>
</tr>
<tr>
<td>Growth</td>
<td></td>
<td>36%</td>
<td>172%</td>
</tr>
<tr>
<td>CAGR</td>
<td></td>
<td>6%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Initially stable productivity
Reflects growing automation

FEELS OK
Appendix 13- Example Assessments from Existing Courses
Integrated Learning Package, University of Bolton
All material on this page Copyright University of Bolton

Guidelines for Integrated Learning Package preparation

Extracts taken from the Programme Handbook

"Written work is in the form of an assignment or an integrated package and consists of three parts, each with set times and deadlines for submission. All coursework is assessed in parts and feedback will be given during the allocated period of self study. Such work may take the form of essays, assignments, projects, seminars, case study analyses etc.

The first part of the assessment will consist of questions requiring short answers, and simple problem solving exercises. This will develop the participant’s knowledge and comprehension with a certain degree of application to new problems. It is expected that all participants, who have satisfactorily completed the learning package will be able to complete this part without difficulty. This will boost the confidence of participants and encourage them to complete the more challenging work to follow.

The second part will consist of two parts. The first is a series of in-depth problems with structured questions leading participants to their solution, and in so doing, develop problem solving skills. The second is a comprehension exercise from a published scientific work. This will require participants to apply the knowledge and understanding they have acquired, and expose them to techniques of investigation and problem solving.

These will prepare participants for the final part of the assessment, which will involve synthesis and evaluation of the material they have now become familiar with, and using it to propose a solution to a novel problem, though the medium of a case study. This will require independent trawling for appropriate data sources and supporting information and a full account of the reasons for their choice of solution. The nature of the problems posed will be open-ended, and without a unique (i.e. right or wrong) solution. Key skills will be developed, and assessed at appropriate stages during each part of the assignment”.

29 Material included with the kind permission of Professor Baljinder Kandola
Students have up to a maximum of 3 months by which to complete these works, tutorial and help is offered via email, post and telephone calls.

All material on this page Copyright University of Bolton

**M.Sc. Advanced Materials**

**Materials and Fire Retardants**

**Integrated Learning package: Fire Retardants**

**Part 1 (20 marks)**

Explain the term intumescence with regards to flame retardancy. Give examples of commercially available intumescent flame retardants and state applications where intumescent flame retardants perform effectively as compared to other flame retardant systems.

**Part 2 (30 marks)**

Existing UK fire (safety) regulation for nightwear requires the fabric to be tested in accordance with BS 5438. However, a high street departmental store requires that the fabrics used to manufacture nightwear gives minimal burn injuries in the event of fire. Discuss the flammability criteria to be considered and propose a possible test method to assess severity of burn injuries.

**OR**

Industrial fabrics are usually high count, tightly woven materials that find applications in highly engineered structures where high strength, dimensional stability, fire resistance and low cost are essential requirements. Discuss the possibility of using thermoplastic nanocomposite fibres for producing such industrial fabric.

**Part 3 (50 marks)**

A supplier is required to provide ship building company with fire doors for a passenger cruise liner. Considering the fire hazard on-board, discuss and critically analyse the types of material and environmentally friendly flame retardant treatments that could be used for fire doors. Furthermore, smoke and toxicity is a major fire hazard in mass transport vehicles. While selecting the materials as well as FR treatment, discuss smoke and toxicity regulations and suggest possible methods of reducing smoke and toxicity hazard.

Your input on this ILP should not be less than 4000 words
M.Sc. Advanced Materials

Materials and Fire Retardants

Integrated Learning package: Fire Retardant Composites

Part 1 (20 marks)

A fibre reinforced composite contains two or more components and for certain applications spacers are used between laminates to increase volume.

Discuss how different components influence the flammability of a composite structure.

Part 2 (30 marks)

Discuss three different resins commonly used in composites, their positive and negative characteristics, flammability and toxicity. You can include thermoplastic and thermoset resins in your discussion.

Discuss different methods of reducing the flammability of composites prepared from each resin type using 8 layers of glass or carbon fabric reinforcement.

Part 3 (50 marks)

The use of composites in aerospace, marine and automotive systems as a means of decreasing weight and enhancing survivability, without reducing personnel safety, has been considered for sometime. For each application, there are different fire, smoke and toxicity, and other relevant regulations. For load bearing structures, retention of mechanical properties after heat/fire exposure also needs to be considered.

Undertake a study with ONE of the commercial applications and considering the fire hazards, discuss the type of materials and fire retardant treatments that could be used. You need to discuss this in view of different regulations for that particular application.

Your input on this ILP should not be less than 4000 words
References:

M.Sc. Advanced Materials
Materials and Fire Retardants

Integrated Learning package: Fire Retardants

Part 1 (20 marks)
Explain the term flame retardancy. Discuss different type of flame retardants based on:

- Chemical composition and effectiveness
- Method of application to different polymer polymers
- Environmental issues during processing and service life
- Durability to environmental factors

Part 2 (30 marks)

You have been tasked to flame retard a thermoplastic and a thermoset polymer. Critically review various options of flame retarding these two polymer types taking one example of your choice for each polymer and its potential end use application.

Part 3 (50 marks)

An aerospace company approached a supplier to provide seats for a new aircraft. Considering the fire safety regulations for aerospace, discuss and critically analyse the types of material and environmentally friendly flame retardant treatments that could be used for these seats. Furthermore, smoke and toxicity is a major fire hazard. While selecting the materials as well as FR treatment, discuss smoke and toxicity regulations and suggest possible methods of reducing smoke and toxicity hazard.

Your input on this ILP should not be less than 4000 words
Integrated Learning package: Fire Retardant Composites

Part 1 (20 marks)

A new flame retardant chemical has been synthesized in our laboratory and you are tasked to study its effectiveness as a flame retardant in a polymer. The chemical can be melt blended with the polymer. Discuss various methods that can quantitatively and qualitatively demonstrate its flame retardant properties.

Part 2 (30 marks)

You are provided with a copy of the paper entitled ‘DNA: a novel, green, natural flame retardant and suppressant for cotton’, by Alongi et al, Journal of Materials Chemistry A (2013). Briefly summarise this paper and apply the knowledge you have acquired from the lecture notes and literature to discuss strengths and weaknesses of this paper.

Part 3 (50 marks)

You will be provided with:

- A polymer
- A + Phosphorus based flame retardant
- A + Nanoclay

Perform appropriate small scale and lab scale flammability tests in the laboratory. Analyse the results and relate to the mechanism of action of different types of flame retardants. Based on results suggest strengths and weaknesses of each test. Provide overall flammability index of these samples.

Your input on this ILP should not be less than 4000 words
References:


Question 1
Read the paper “Effects of Defects on the Interlaminar Performance of Composites” (\textsuperscript{1}), authored by Makeev, Nikishkov, Seon and Armanios. Within a maximum of 2000 words:

1) Illustrate the technique employed by the authors to detect the presence of porosity in ASTM 6415 curved-beam coupons and describe the main features of the voids in terms of shape and locations; 

[5%]

2) Discuss the influence of the void location and size on the measured static interlaminar tensile strength. In particular, consider the following two aspects of the work by Makeev et al.: 2.a) Is it possible to back-calculate the interlaminar strength of the void-free material from the experimental data? 2.b) What do the stress criteria originally proposed by Whitney and Nuismer and employed in the paper postulate?

[15%]

3) Discuss the influence of porosity on the fatigue performance of curved-beam coupons. 

[10%]

You may reference additional sources from the literature where appropriate to either support or rebut the results obtained in the paper and the conclusions drawn therein.

\footnotesize{\textsuperscript{10} Material included with the kind permission of Dr Giuliano Allegri}
Question 2
The interlaminar tensile strength of a prepreg-based glass-epoxy composite system has to be characterised adopting the ASTM D6415 standard. L-bend coupons have been tested by means of the four-point bending rig shown in Fig. Q2.1. The material can be considered quasi-isotropic; it has a longitudinal Young's modulus of 161 GPa and a transversal Young's modulus of 11.4 GPa. The cured ply thickness is 0.127 mm and the coupons have been manufactured laying-up 32 plies with 0° orientation.
In the testing rig, the roller diameter is $D = 10$ mm, while the roller distance is $d_r = 12.5$ mm. All the other rig and coupon dimensions not explicitly stated here comply with those prescribed in the standard.

![Figure Q2.1: Sketch of loading rig for ASTM D6415](image)

During the tests, the rig displacement $\Delta$ has been measured by means of a video displacement gauge; the applied force has been recorded by means of a calibrated 10 kN load cell. A total of 5 coupons were tested, all showing sudden failure with no sub-sequent reloading. The crosshead displacement and load values at failure are listed in Tab. A2.1.

<table>
<thead>
<tr>
<th>$\Delta$ (mm)</th>
<th>$P$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>2.90</td>
</tr>
<tr>
<td>5.2</td>
<td>2.84</td>
</tr>
<tr>
<td>4.9</td>
<td>2.93</td>
</tr>
<tr>
<td>4.8</td>
<td>2.45</td>
</tr>
<tr>
<td>5.0</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Table A2.1: Displacement and load at failure

1) Compute the interlaminar tensile strength values corresponding to each of the test results presented in Tab. A2.1, using the exact solution from Lekhnitskii; [20%]

2) Calculate the B-basis allowable for the interlaminar tensile strength from the data in Tab. A2.1, rejecting eventual outliers by means of the maximum normed residual criterion [10%]
Question 3
The mode II fracture toughness of a fibre-reinforced carbon/epoxy composite has to be characterised according to the ISO 15114:2014 standard, i.e. using "end loaded split" (ELS) coupons. The material cured ply thickness is 0.1375 mm. Unidirectional 0° specimens are manufactured by laying up a square plate comprising 24 plies, with a Teflon release film of negligible thickness inserted between the 12th and 13th ply. After autoclaving, the plate is cut into coupons 190 mm long and 20 mm wide.

1) A compliance calibration is carried out on one of the coupons using the "inverse ELS" configuration illustrated in the standard. The results of the calibration tests are the following:

<table>
<thead>
<tr>
<th>L \ clamp (mm)</th>
<th>C (mm/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5.832E-03</td>
</tr>
<tr>
<td>60</td>
<td>9.261E-03</td>
</tr>
<tr>
<td>70</td>
<td>1.563E-02</td>
</tr>
<tr>
<td>80</td>
<td>2.439E-02</td>
</tr>
<tr>
<td>90</td>
<td>3.594E-02</td>
</tr>
<tr>
<td>100</td>
<td>3.930E-02</td>
</tr>
<tr>
<td>110</td>
<td>5.065E-02</td>
</tr>
</tbody>
</table>

Table A3.1: Data from compliance calibration

where “L clamp” represents the distance between the loading axis and the clamp. From the data presented in the table above, estimate:

a) The flexural modulus of the coupon; [5%]

b) Estimate the clamp correction to the specimen length Δ_{clamp}. [5%]

![Figure Q3.1: Arrangement of loading block in ELS coupons](image-url)
2) One of the coupons described above is tested in the “direct ELS” configuration. A tip shear force is applied via a loading block, having the dimensions shown in Fig. Q3.1. The coupon is clamped at a distance of 110 mm from the loading axis. The length of the insert film is 60 mm from the loading axis; before the actual test, the coupon is pre-cracked in mode II, thus giving an initial crack length of 62 mm.

The following tip displacement and shear force values are recorded during the test as the delamination propagates in the gauge section:

<table>
<thead>
<tr>
<th>Displacement (mm)</th>
<th>Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.7</td>
<td>115.7</td>
</tr>
<tr>
<td>14.9</td>
<td>114.6</td>
</tr>
<tr>
<td>15.0</td>
<td>106.1</td>
</tr>
<tr>
<td>15.1</td>
<td>104.0</td>
</tr>
<tr>
<td>15.3</td>
<td>88.9</td>
</tr>
<tr>
<td>15.4</td>
<td>96.1</td>
</tr>
<tr>
<td>15.9</td>
<td>86.2</td>
</tr>
<tr>
<td>16.7</td>
<td>77.3</td>
</tr>
<tr>
<td>16.8</td>
<td>87.5</td>
</tr>
<tr>
<td>16.9</td>
<td>83.8</td>
</tr>
<tr>
<td>17.0</td>
<td>78.4</td>
</tr>
<tr>
<td>17.9</td>
<td>79.6</td>
</tr>
<tr>
<td>18.1</td>
<td>79.4</td>
</tr>
<tr>
<td>18.4</td>
<td>77.9</td>
</tr>
<tr>
<td>18.5</td>
<td>77.7</td>
</tr>
<tr>
<td>18.6</td>
<td>76.5</td>
</tr>
</tbody>
</table>

Table A3.2: Data from ELS test

a) Plot the mode II R-curve corresponding to the data in Tab. A3.2 using the CBTE method and including the effects due to large rotations and the presence of the loading blocks;  

[20%]

b) Discuss how mode I pre-cracking would have affected the R-curve trend.  

[10%]

*******
IDC in Composites Manufacture

Unit 7 - Design for Manufacture of Composite Structures (AENG M0024)

Unit Director: Dr Carwyn Ward

Engineers' House (Clifton Down, Bristol): Monday - Friday (Wednesday and Thursday AM only);
University of Bristol (Bristol Composites Institute (ACOIS) and the Queens Building Laboratories):
Wednesday PM, and; off-site visit: Thursday PM
21-25 January 2019

Preamble

This document sets out the assignment activity for Unit 7.3. The assignment has been separated into two parts, with an 80:20 split delivered as a written assignment and a video log (respectively). The total mark is out of 100. The intention is that course participants will deliver both parts at the same time, and that the submission deadline is 16.00 on Friday 29th March via the submission point on Blackboard. The Unit 7.3 course documents folder on Blackboard will have examples of previous assignments for reference, and in particular showing good examples of the video log. The Unit Director is available to discuss the assignment content in person or by email, for aspects such as development ideas and reviewing an interim report, up to one week before the submission deadline.

Part 1. Written Assignment - 80 marks total

As a typical written report, of style to be determined by the author, please complete all of the following sections (but it must be clearly readable to the examiners). Note that it is advisable that the report is set out as per the sections below, for ease of marking. It is not necessary to employ the outputs of the Unit 2 written submission as your product/structure choice. New choices of component etc. are allowed for this assignment, if not encouraged.

1. Redesign of a structure currently made in advanced composites

   (60 marks, 10 pages max.)

   a. Identify the critical design requirements of the product/structure, and how the current product/structure is manufactured

   (10 marks)

   b. Identify any aspects of the current design that might be expected to give rise to problems (such as defects and variations) in manufacture or in-service; and how these might be tackled by risk management in the manufacturing processes, without undertaking a full redesign of the product/structure

   (15 marks)

   c. Carry out a conceptual redesign of the product/structure to improve the manufacturability of it, whilst still meeting your previously identified critical design requirements

   (15 marks)

   d. Comment, and provide evidence, on the anticipated impact of the improved manufacturability of the product/structure, concentrating on the costs of manufacture, and its robustness to defects or variations

   (10 marks)

2. Design for experimental simulation of a manufacturing process

   (30 marks, 6 pages max.)

   Consider the manufacturing process for the part that had been redesigned, and explore how you would design an experiment that would allow for the simulation of all or part of the manufacturing.
process in a standard desk-top uniaxial testing machine. To achieve this task the aim is to first understand the manufacturing process sufficiently such that all of the important process variables are understood. It will then be possible to extract the repeatable and controllable key process variables as experimental inputs that will work within the confines of the test machine, in order to deliver measurable experimental outputs that will enable understanding of the process. It may be important to consider visual recording tools such as video cameras for aspects of the experiment, as much as direct measurements through force or displacement. The following are four different examples of published works demonstrating the experimental simulation of manufacturing processes or elements of a manufacturing process, and can be used as examples for how to achieve this task (although only two of the examples employ the use of a uniaxial test machine):

- DH-JA Lukaszewicz (2011) Optimisation of high-speed automated layup of thermoset carbon-fibre preimpregnates. Thesis (PhD) University of Bristol

**Part 2. Video Log Assignment - 20 marks total**

Produce a short (5 minutes max., playing time) animation or video (self-playing presentations will be considered) that presents the product/structure used in Part 1, its redesign process, and any special point of interest the author/director may want the viewer to consider. The submission should aim to take the form of a reflective log of the submission activity, and should be suitable for a generalist audience at “A-level” schooling standard.

(20 marks, video/animation)

C Ward
January 2019
Simulation of Resin Flow and Cure in Liquid Composite Moulding Processes

A floor panel is to be produced using liquid moulding technology (rigid double-sided RTM mould). The component is made from a balanced carbon 2×2 twill fabric and high temperature epoxy resin. The in-plane dimensions of the panel are \(1.0 \times 1.0\) m. The component is made of 28 plies. To meet nominal structural requirements (where manufacturing was not considered), the plies needs to have orientation of 0° with respect to the panel edges.

For RTM process, a pressure pot or a pump (max. flow rate \(8.3 \times 10^{-2}\) m³/s) is to be used. The maximum admissible injection pressure, which must not be exceeded for safety reasons, is 0.4 MPa (absolute value). Thickness of cavity in RTM must be chosen to reach nominal fibre volume fraction of 60%. For conservative design a vacuum pump is considered to be not available – hence, pressure at vents is 0.1 MPa and entrapment of air behind the flow front bears a risk of an impregnation defect. In addition, the effective surface heat transfer coefficient of the non-heated side of the curing assembly is 2.5 W/m²/K, and the initial degree of cure of the resin is 3.5%.

Assume that the heat transfer can be approximated by an 1-D through thickness solution of the heat conduction problem, with one sided following the temperature of a heated tool and the other approximated by a natural convection boundary condition (the effective surface heat transfer coefficient is given below) and an ambient temperature of 25°C. The component can be considered fully cured when the minimum degree in it is 92.5%. The mesh and geometry are defined in an input file “CourseWork_2018.p0” (mesh) and “CourseWork_2018.igs” (geometry).

For the RTM simulations activate the air entrapment option. Injection gate or vents can be placed either on the boundary of the geometry or inside the cavity. For circular injection gates use a radius of 0.01 m.

Discussion: questions to address in presentation/report

Infusion. Design the position of vents, injection gates, and/or runners to optimise the injection configuration with respect to complete filling of the cavity, minimisation of the fill time, and preventing impregnation defects.

Consider internal race tracking along the concave corners of the panel. Calculate and assign the permeability of the race-tracking channels assuming no fillets in the mould corners.

Using cure kinetics model and rheological properties of the resin, choose infusion temperature to make sure that the mould is filled before resin gels (assume that 20% degree of cure cannot be exceeded during the infusion).

Draping. Consider the lay-up and draping of preform prior to infusing it [1]. Optimise draping procedure to minimise possibility of wrinkling on the one hand, maximising performance (by aligning the fibre angles to the nominal configurations suggested by the design where possible) and avoiding excessive deviation from the nominal fibre volume fraction (trying to avoid below 50% or higher than 70%).

---

32 Material included with the kind permission of Dr Dmitry Ivanov
**Draping and infusion.** Consider the evolution of permeability caused by shearing of preforms. Consider distribution of fibre volume fraction over the part. Manually define zones where the fibre orientation can be considered constant. Calculate and assign representative values of fibre orientation and permeability to the segments of the panel (assuming that the properties are constant over the zone area). Consider local permeabilities in injection simulation - how does the draping change the infusion characteristics, such as flow front shapes and fill times, of this component (see [2] as an example)?

**Consolidation.** Consider fibre paths where defects are most likely to occur. Calculate the excessive length of fibres associated with the differential compaction in consolidation process. Indicate areas with high risk of wrinkling and other fibre path defects. Suggest a defect mitigation strategy. Estimate force required to close the mould.

**Cure.** Find the recommended cure profile for the resin (Hexcel RTM6) (recommended by supplier of the resin or suggested in literature) and simulate the cure of the component. Report and comment on the temperature and degree of cure evolution. Identify the cure time, compare this with the cure profile recommendation, and suggest optimum cure cycle. Can you suggest a better cure cycle for this component? - shorter curing time but without exceeding 5°C of data sheet curing temperature anywhere through the thickness of the laminate.

**Cure and variability.** For a representative thickness, simulate the influence of variability by executing extreme case scenarios for the stochastic variables of the process. Approximate the probability distribution of cure time resulting from process variability. Discuss the recommended cure cycle in light of stochastic simulation. Comment on the role of stochastic and deterministic simulations. Discuss the contribution of cure to flow during injection (coupled flow/cure simulations are not required).

**Input data and models**

Cure kinetics of the injected resin is well described by the following model:

\[
\frac{d\alpha}{dt} = \frac{Ae^{(-E_{RT})}}{1 + e^{(\alpha - \alpha_n - \alpha_T)}} (1 - \alpha)^m \alpha^n
\]  

(1)

The thermal properties of the curing composite and the cure kinetics parameters of the kinetics equation are given in Table 1, whilst the effective surface heat transfer coefficient the non-heated side of the curing assembly is 2.3 W/m²°C, and the initial degree of cure of the resin is 3.5%.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The density of the epoxy kg/m³</td>
<td>1.11×10³</td>
</tr>
<tr>
<td>Thermal conductivity of the composite in the thickness direction, W/m⁰°C</td>
<td>0.32</td>
</tr>
<tr>
<td>Specific heat capacity of the composite, Jg/ºC</td>
<td>1.6</td>
</tr>
<tr>
<td>Total reaction heat, Jg</td>
<td>460</td>
</tr>
<tr>
<td>A, 1/s</td>
<td>22000</td>
</tr>
<tr>
<td>E, J/mol</td>
<td>58000</td>
</tr>
<tr>
<td>n</td>
<td>1.3</td>
</tr>
</tbody>
</table>
IDC, Unit 5. Processing Simulation and Control in Composite Manufacture, AENGM0019, September 2018.

<table>
<thead>
<tr>
<th>m</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>68</td>
</tr>
<tr>
<td>(a_g)</td>
<td>(-2.25)</td>
</tr>
<tr>
<td>(a_g) (1^\circ)K</td>
<td>0.0072</td>
</tr>
</tbody>
</table>

Viscosity evolution of RTM6 can be described by Castro-Macsko model:

\[
\eta = \eta_0 \exp \left( -\frac{C_1(T-T_0)}{C_2+T-T_0} \left( \frac{a_g}{a_g-a} \right)^{A+B}\right)
\]  

Material parameters for the viscosity model are derived by Lionetto et al [4] and summarised in Table 2.

**Table 2: Parameters for resin viscosity model**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_1)</td>
<td>31.6</td>
</tr>
<tr>
<td>(C_2, K)</td>
<td>33.5</td>
</tr>
<tr>
<td>(a_g)</td>
<td>0.42</td>
</tr>
<tr>
<td>(T_{pe}, K)</td>
<td>258</td>
</tr>
<tr>
<td>(\eta_0, P\times s)</td>
<td>(2.0\times10^6)</td>
</tr>
<tr>
<td>A</td>
<td>5.58</td>
</tr>
<tr>
<td>B</td>
<td>7.20</td>
</tr>
</tbody>
</table>

Process variability is governed by uncertainty in the parameters listed in Table 2, whilst all variables are considered uncorrelated.

**Table 3. Uncertainty of the cure process.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool temperature</td>
<td>Normal</td>
<td>2 °C</td>
</tr>
<tr>
<td>Surface heat transfer coefficient</td>
<td>Normal</td>
<td>0.4 W/m² K°C</td>
</tr>
<tr>
<td>Activation energy</td>
<td>Normal</td>
<td>1000 J/mol</td>
</tr>
</tbody>
</table>

For each material zone calculate thickness and permeability. The in-plane permeability for non-sheared fabric of fabric use:

\[
K_p = C_p \left( \frac{1-f}{f^2} \right)^3
\]

where \(C_p\), for 0° and 90° directions of the twill fabrics are given in Table 2. To calculate out-of-plane permeability (if needed) use the formulae of Gebart:
All material on this page Copyright University of Bristol

IDC, Unit 5. Processing Simulation and Control in Composite Manufacture, AENGM0019, September 2018.

\[ K_L = C_L \left( \frac{f_{\text{max}}}{f} - 1 \right)^{1/2} R^2 \]  \hspace{1cm} (4)

Assign thickness, porosity and a fabric with the appropriate permeability to each zone in the model. Permeability of sheared preform can be estimated using approach of Demaria et al. [3] (please note, that the model is not fully validated yet).

\[ K_3(\alpha) = \frac{K_3(\alpha = 0)}{\cos(\alpha)} \left( \frac{\cos(\alpha) - f_0}{1 - f_0} \right) F_{\text{geo}}(\alpha) \]  \hspace{1cm} (5)

\[ F_{\text{geo}}(\alpha) = \frac{1}{\cos(\pi / 2 - \beta_0)} + \frac{\cos(\alpha)}{\sin(\beta_0)} \]

where \( \beta_0 = \frac{\pi}{4} \)

where \( \alpha \) is the shear angle, \( \beta_0 \) - is the initial orientation of the principal axis with respect to
the warp direction, the directions 1 is at an angle of \( \alpha / 2 \) to the warp direction, and the directions 2 is at an angle of \( (\alpha + \pi) / 2 \) to the warp direction. Based on Quickform simulations
assign representative shear angle and fibre volume fraction to each of the zones.

Use the approximation Gutowski to assess the preform compressibility:

\[ \sigma(f) = \sigma_0 \frac{\sqrt{f/f_{\text{lim}} - 1}}{(f_{\text{lim}}/f - 1)^{1/2}} \]  \hspace{1cm} (6)

Table 4: Properties of biaxial carbon twill preform

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The areal density (ply mass/surface area) of the fabric, g/m²</td>
<td>370</td>
</tr>
<tr>
<td>The density of carbon fibres, g/cm³</td>
<td>1.78</td>
</tr>
<tr>
<td>Initial fibre volume fraction</td>
<td>40%</td>
</tr>
<tr>
<td>Maximum practically achievable fibre volume fraction, ( f_{\text{lim}} )</td>
<td>70 %</td>
</tr>
<tr>
<td>Maximum theoretically achievable fibre volume fraction, ( f_{\text{max}} )</td>
<td>91 %</td>
</tr>
<tr>
<td>Diameter of carbon fibres</td>
<td>7 ( \mu ) m</td>
</tr>
<tr>
<td>( \sigma_0 ), coefficient in the Gutowski approximation of fabric compressibility, Pa</td>
<td>1.1 Pa</td>
</tr>
<tr>
<td>( C_{\alpha} ), Coefficient in the estimation of permeability, m²/MPa</td>
<td>0.82*10⁻¹⁰</td>
</tr>
<tr>
<td>( C_{\perp} ), Coefficient in the estimation of permeability by Gebart through thickness</td>
<td>16/9π√6</td>
</tr>
</tbody>
</table>
IDC, Unit 5, Processing Simulation and Control in Composite Manufacture, AENGM0019, September 2018.


Undergraduate assignment - University of Plymouth

All material on this page Copyright University of Plymouth

School of Engineering - Plymouth University

MATS 348 Composites Engineering  Academic Year 2017/18  Spring Semester 2018

Three samples of marked coursework (one each of good, average and poor) are normally copied for the module course record. These may subsequently be made available to external assessment teams for higher education quality assurance or professional accreditation. For the module, it is assumed that you give permission for your work to be archived for this purpose unless you include a letter with your submission stating that you withhold permission and stating your reasons (e.g. the data used has been released by a company with which you are associated).

The aim of this module is "to integrate the input from the two associated modules [MATS447 and MFRG311] with hands-on experience of handling these materials and structures from design through manufacture to testing. All processes should be logged as in a quality system". You are required to keep a logbook throughout this assignment to document all stages of the development and this should be available for review by staff teaching the course during timetabled periods. The assignment has been redefined to provide formative feedback and hence reduce your assessment load, and with all marks assigned to the final report/associated logbook. The component is simply a vehicle for your critical thinking! Marks are awarded when the product performance closely aligns with the initial specification and/or theoretical/numerical models and/or where clear understanding of reasons for "failure" are presented.

There will be obligatory review meetings in Brunel 007 held, at least once a week, normally on Monday at 11:00-13:00, monitored by barcode scanner.

This year, the components for consideration are:
(a) cycle brake lever, (b) long board truck bar, (c) subsea locking mechanism.

SUGGESTED MILESTONES (all at the start of the timetabled session, except for final Report submission which should adhere to normal Faculty procedures)

05 Feb 18 [individual] An outline specification for the component.
12 Feb 18 [individual] Undertake appropriate design calculations and consider the tooling/jigging and manufacturing route, COSHH and risk assessments.
19 Feb 18 [team] Devise an outline design manufacturing route and testing programme [JS away].
05 Mar 18 [team] Completion of mould tools for the component to be produced.
16 Apr 18 [team] Submit a component for inspection/discussion with the course staff.
30 Apr 18 [team] Manufacture of revised/further prototypes or more extensive testing may be undertaken (this could happen in parallel with earlier work). All mechanical testing should be complete by this date.
10 May 18 [individual] Draft report for discussion with course staff. The following may be used as an outline structure for the topics to be considered in the report. This is for guidance only and departures (especially additional considerations) from this format may be appropriate:
- content of the work with appropriate references,
- design calculations,
- limitations/assumptions in the design method,
- description and assessment of the manufacture,
- robustness/sensitivity of the design to manufacturing limitations,
- test procedures,
- test results and discussion of potential failure modes,
- implications of failure at this stage for the design/prototyping process,
- resources used/required for more effective development of the system, and
- future viability with comprehensive costing.

The final report should stand alone with a main [group] text of 2000 words maximum and appropriate Appendices (notably summary reports of the individual stages and agreed team procedures and analysis). You should distinguish yourself from your colleagues by literature review and critical analysis/discussion of the findings in an [individual] Appendix to the group report not exceeding 2000 words.

The [for BSc] should be handed in with the report. Deadline 3:00 PM on Thursday 17 May 2018. Late submissions will be marked but no marks carried forward unless there are valid extenuating circumstances.

Additional guidance on the expectations for assignments can be found at these URLs:
- https://www.bsc1 plymouth.ac.uk/cms MATS447/technical_Report.htm
- https://www.bsc1 plymouth.ac.uk/cms MATS447/coursework.htm
- https://www.bsc1 plymouth.ac.uk/cms MATS447/honours.htm
- https://www.bsc1 plymouth.ac.uk/cms MATS447/plagiarism.htm

33 Material included with the kind permission of Professor John Summerscales
Coursework 1 – ICE COMPOSITES

Ice-composites can be made of adding fibres such as wood pulp (as in paper) to water and freeze it. Ice-composites were proposed during World War II to the British Royal Navy as a candidate material for making a huge, unsinkable aircraft carrier as the fibre reinforcement can turn brittle ice into materials with improved strength and toughness.

In this coursework you are asked to make and test ice-composites. You can make the ice composites in your home (or neighbours) freezer. Try to perform some systematic parameter variation such as changing the fibre type, fibre surfaces or surface treatments, fibre content, fibre length, fibre orientation or matrix (ice) properties etc. Whatever you can come up with. You are free to set up your own experiments and material parameters incl. different materials. Examples are cellulose from toilet paper, newspaper etc. but also synthetic fibres from textiles or hybrid combinations.

Composite behaviour should be tested against an unreinforced ice plate and tests can include a variety of mechanical and physical tests such as bending strength, toughness, impact strength, thermal conductivity etc. Try to quantify your composite parameters and properties as much as possible (so you can plot some graphs of property versus material property) but you should be doing all of this with simple home equipment such as weighing scales, rope, water buckets for loading, hammers, drop weights etc. or whatever you can get your hands on. The results should be presented in a report and your findings should be discussed and explained on the basis of composite theories.

The report should include:

1. Intro on ice-composites
2. Experimental section on your materials, processing and testing
3. Presenting your results and a discussion of these results
4. Conclusions
5. References

Extra marks will be given for originality in materials and testing.

You can work in teams of maximum two or on your own. You can choose your own partner.

Have a look at a scientific paper on composites in the literature to get an idea how a good report/paper looks like.

Coursework should be submitted on QMplus. Use correct submission point and only one submission (per group) is allowed.

Have fun!

Han Zhang

---

34 Material included with the kind permission of Dr Han Zhang
### MODULAR PROGRAMME-COURSEWORK ASSESSMENT SPECIFICATION

#### Module Details

<table>
<thead>
<tr>
<th>Module Code</th>
<th>Run</th>
<th>Module Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>UFMF/L-15-M</td>
<td>Jan 18/19</td>
<td>Mechanics of Composites</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module Leader</th>
<th>Module Coordinator</th>
<th>Module Tutors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramin Amali</td>
<td>Ramin Amali</td>
<td>Ramin Amali, David Fisher</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component and Element Number</th>
<th>Weighting: (% of the Module's assessment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>60%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element Description COURSEWORK</th>
<th>Total Assignment time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Independent study 85 Hours</td>
</tr>
</tbody>
</table>

#### Dates

<table>
<thead>
<tr>
<th>Date Issued to Students</th>
<th>Date to be Returned to Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>31/01/2019</td>
<td>20 working days after submission</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Submission Place</th>
<th>Submission Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackboard</td>
<td>04/04/2019</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Submission Time</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2:00 pm</td>
<td></td>
</tr>
</tbody>
</table>

#### Deliverables

- Report (Microsoft Word + PDF)
- Files (Spreadsheet + Final Abaqus® files)

---

35 Material included with the kind permission of Dr Ramin Amali
Task 1- Laminate Analysis

A laminate is subjected to three forces and three moments as shown in Figure 1

![Figure 1- A laminate subjected to forces and moments](image)

Where

- \( N_x \) = normal force resultant in the \( x \) direction (N/m)
- \( N_y \) = normal force resultant in the \( y \) direction (N/m)
- \( N_{xy} \) = shear force resultant (N/m)
- \( M_x \) = Bending moment resultant in the \( x \) direction (Nm/m)
- \( M_y \) = Bending moment resultant in the \( y \) direction (Nm/m)
- \( M_{xy} \) = Turning moment resultant (Nm/m)

This laminate is made of plies each having a thickness of \( t \) and an angle of \( \theta \) with the \( x \) axis (global coordinate). The material properties of one ply in its principle directions are given in Table 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1 )</td>
<td>Longitudinal modulus of elasticity (Pa)</td>
</tr>
<tr>
<td>( E_2 )</td>
<td>Transverse modulus of elasticity (Pa)</td>
</tr>
<tr>
<td>( G_{12} )</td>
<td>Shear modulus (Pa)</td>
</tr>
<tr>
<td>( \nu_{12} )</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>( \nu_{21} )</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>Longitudinal Coefficient of thermal expansion (m/m°C)</td>
</tr>
<tr>
<td>( \alpha_2 )</td>
<td>Transverse Coefficient of thermal expansion (m/m°C)</td>
</tr>
<tr>
<td>( \beta_1 )</td>
<td>Longitudinal moisture swelling coefficient (m/m/kg/kg)</td>
</tr>
<tr>
<td>( \beta_2 )</td>
<td>Transverse moisture swelling coefficient (m/m/kg/kg)</td>
</tr>
</tbody>
</table>

The strength of each ply on its principle directions and also the maximum ply’s shear strength are given in Table 2.

<table>
<thead>
<tr>
<th>Table 2 - Allowable strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{1_{\text{tensile}}} )</td>
</tr>
<tr>
<td>( S_{1_{\text{compressive}}} )</td>
</tr>
<tr>
<td>( S_{2_{\text{tensile}}} )</td>
</tr>
<tr>
<td>( S_{2_{\text{compressive}}} )</td>
</tr>
<tr>
<td>( S(S_{12}) )</td>
</tr>
</tbody>
</table>
Part A - 20%

The laminate (made of 10 lamina) is subjected to forces, moment, change of temperature $\Delta T$ and a moisture concentration of $\Delta m$. Design an interactive spreadsheets to calculate the

1. Factor of safety of each ply and the whole laminate based on maximum stress criterion
2. Factor of safety of each ply and the whole laminate based on Energy Based Interaction Theory – Tsai-Hill Criterion
3. Factor of safety of each ply and the whole laminate based on Interactive Tensor Polynomial Theory - Tsai-Wu Criterion

Part B - 10%

A laminate is made of $N$ plies, where $N$ is variable parameter; each ply having a thickness of $t_k$ and an angle of $\theta_k$ with the x axis (global coordinate). This laminate is subjected to forces, moments, change of temperature $\Delta T$ and a moisture concentration of $\Delta m$. Design an interactive spreadsheets to calculate the

1. Factor of safety of each ply and the whole laminate based on maximum stress criterion
2. Factor of safety of each ply and the whole laminate based on Energy Based Interaction Theory – Tsai-Hill Criterion
3. Factor of safety of each ply and the whole laminate based on Interactive Tensor Polynomial Theory - Tsai-Wu Criterion

Deliverables

A spreadsheet for the given task labelled with your name and student number

Note:

You will need this spreadsheet for the Task2.
Task 2- Design and analysis of a composite pressure vessel 70%

Introduction - filament winding

Filament winding is used for the manufacture of parts with high fibre volume fractions and controlled fibre orientation. Fibre tows are immersed in a resin bath where they are coated with low or medium molecular weight reactants. The impregnated tows are then literally wound around a mandrel (mould core) in a controlled pattern to form the shape of the part. After winding, the resin is then cured, typically using heat. The mould core may be removed or may be left as an integral component of the part.

The filament winding process was originally invented to produce missile casings, nose cones and fuselage structures, but with the passage of time industries other than defence and aerospace have discovered the strength and versatility of filament winding. Examples of products created using the process of filament winding include:

- Tubes
- Transmission poles
- Aircraft fuselages
- Gas, water, or tanks
- Cement Mixers
- Pipes

Brief

Your task is to use your laminate design spreadsheets and the Abaqus® finite element analysis software package to design a laminate layout for a pressure vessel as shown in figure 7. The pressure vessel subjected to an internal pressure of 60bar. Your final design must have a factor of safety of 1.5.
Figure 2- General layout of a composite pressure vessel subjected to internal pressure

The pressure vessel is supported by two concrete supports as shown in figure 2. The concrete supports are assumed to be rigid compared to the pressure vessel. The environmental effects of moisture may be assumed to be negligible.

There are two inlets on each spherical end cap of the pressure vessel and there are two outlets on the top and bottom of cylindrical part as presented in figures 2 and 3. Diameters of inlets and outlets are given to be 60mm.

Dimensions of the pressure vessel are given in Figure 3 and Table 3

Figure 3- All Dimensions in mm
Table 3 - Dimensions for the inner radius and position of supports

<table>
<thead>
<tr>
<th>First Initial</th>
<th>R (mm)</th>
<th>D (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>310</td>
<td>1600</td>
</tr>
<tr>
<td>B</td>
<td>330</td>
<td>1600</td>
</tr>
<tr>
<td>C</td>
<td>350</td>
<td>1600</td>
</tr>
<tr>
<td>D</td>
<td>370</td>
<td>1600</td>
</tr>
<tr>
<td>E</td>
<td>390</td>
<td>1600</td>
</tr>
<tr>
<td>F</td>
<td>410</td>
<td>1600</td>
</tr>
<tr>
<td>G</td>
<td>430</td>
<td>1600</td>
</tr>
<tr>
<td>H</td>
<td>450</td>
<td>1600</td>
</tr>
<tr>
<td>I</td>
<td>430</td>
<td>1600</td>
</tr>
<tr>
<td>J</td>
<td>420</td>
<td>1500</td>
</tr>
<tr>
<td>K</td>
<td>390</td>
<td>1500</td>
</tr>
<tr>
<td>L</td>
<td>370</td>
<td>1500</td>
</tr>
<tr>
<td>M</td>
<td>350</td>
<td>1500</td>
</tr>
<tr>
<td>N</td>
<td>340</td>
<td>1500</td>
</tr>
<tr>
<td>O</td>
<td>320</td>
<td>1700</td>
</tr>
<tr>
<td>P or Q</td>
<td>380</td>
<td>1700</td>
</tr>
<tr>
<td>R</td>
<td>390</td>
<td>1700</td>
</tr>
<tr>
<td>S</td>
<td>420</td>
<td>1700</td>
</tr>
<tr>
<td>T</td>
<td>400</td>
<td>1700</td>
</tr>
<tr>
<td>U or V</td>
<td>410</td>
<td>1700</td>
</tr>
<tr>
<td>W</td>
<td>420</td>
<td>1700</td>
</tr>
<tr>
<td>X or Y or Z</td>
<td>430</td>
<td>1700</td>
</tr>
</tbody>
</table>

Material properties for the lamina in the principal directions are given in Tables 4 and 5.
Procedure

**Engineering Analysis of the pressure vessel**

1. Research on filament winding method (to determine the limitation of this method and preferable angles of fibres etc.).

2. Use the theory of pressure vessels (without consideration of the pressure vessel’s weight) to determine the applied longitudinal and hoop forces per unit length (Nₓ, Nᵧ, Nₓᵧ, ...)

3. Use your spreadsheet to determine the best layout for the applied forces- using Solver will help significantly.

4. Use your theoretical laminate layout from step 3 to analyse the pressure vessel using Abaqus®

5. Perform a mesh study to determine the optimum size of mesh

6. If your FOS is within limit go to step 7 otherwise change the thickness or angle of fibres to achieve the given FOS

**Advance Analysis**

7. Investigation on design and analysis of inlet and outlets and how this effect the FoS

8. Investigation on the effect of weight of the pressure vessel on FoS

9. Investigation on environmental effect when temperature change; ΔT=20° on FoS
Note 1 -
You need to document every step of your work. Remember that ONLY your report will be marked.

Note 2 -
The output of this coursework will be a report in the style of a 10 page conference paper. Please use the provided template (Manuscript_template)

Marking scheme

<table>
<thead>
<tr>
<th>Research</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Literature review</td>
<td></td>
</tr>
<tr>
<td>• Theory of pressure vessels,</td>
<td></td>
</tr>
<tr>
<td>connectors, etc.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engineering Analysis of the pressure vessel</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Use of spreadsheet</td>
<td></td>
</tr>
<tr>
<td>• Application of Abaqus®</td>
<td></td>
</tr>
<tr>
<td>• Application of Loads/ Boundary conditions/ Mesh study</td>
<td></td>
</tr>
<tr>
<td>• Design Iterations</td>
<td></td>
</tr>
<tr>
<td>• FoS</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advanced Analysis</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Design and analysis of the inlet and outlets</td>
<td></td>
</tr>
<tr>
<td>• Consideration of the weight of the pressure vessel</td>
<td></td>
</tr>
<tr>
<td>• Temperature change</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Documentation</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Format</td>
<td></td>
</tr>
<tr>
<td>• Structure</td>
<td></td>
</tr>
<tr>
<td>• Referencing</td>
<td></td>
</tr>
</tbody>
</table>

Deliverables

A report (MSWord + PDF) for task 2 + Final Abaqus® files
Appendix 14- Legal Advice Note

The included Legal Advice Note was prepared by Veale Wasbrough Vizards in August 2019. The provided pdf document follows this page.

Appendix 15- Example Units

The material presented on the following pages was developed as part of this project.

*Tolerancing, Variability and Defects* was written by Professor Kevin Potter. His initial slides were converted into a second version and set of handouts by Desmond He and Chiara Petrillo. The hand layup exercise was written by Dr Michael Elkington.

*Production Costing* was written by Professor Kevin Potter and Dr Carwyn Ward. It includes an interactive ‘Virtual Composites Company’ spreadsheet developed by Adam M Moss. The initial slides were converted into a second version and set of handouts by Kirk Willicombe, who also wrote a worked example for the spreadsheet.

*Mechanical Properties and Testing- Anisotropic Elasticity* was written by Dr Nuri Ersoy.

*Standards and Certification* was written by Dr Stefanos Giannis, Dr Michael Gower and Dr Graham Sims, plus NPL’s Training Team, under the supervision of George Pask.

Pdf copies of these documents are included following Appendix 14.
Engineering courses joint venture

Advice note

August 2019
1 **Background**

1.1 This note sets out our high level advice on the options available to formally establish a collaboration (the "Consortium") between the University of Bristol ("Bristol") and a number of other universities and other institutions which is intended to develop a course of study in engineering that can be delivered to industry on a commercial basis (the "Programme").

1.2 As we understand it, the key features of the Consortium are:

1.2.1 Participants taking courses on the Programme can either undertake units of study relevant to their role for CPD purposes or can choose to apply for a Masters qualification with one of the institutions and use the units as credit towards the qualification;

1.2.2 There are currently 18 institutions likely to be involved as members of the Consortium ("Members"), but their involvement is likely to differ in some respects.

1.2.3 Many of the Members will be Universities which are also charities, but other institutions (including some non-charitable institutions) are also likely to be Members.

1.2.4 It is likely that that a Member (a "Lead Member") will take responsibility for the administrative operation of the Programme.

1.2.5 The majority of the Programme content will need to be developed by the participating Members (or existing undergraduate materials will need to be suitably adapted). Members will therefore contribute material to the Consortium, together with the time and expertise of their employees.

1.2.6 Candidates’ employers will be responsible for payment of the fees required in order to participate in the Programme.

1.2.7 Academics participating in the Programme (or the Member by which they are employed) will be paid by the Consortium for their teaching time.

1.2.8 The aim is that the Consortium will be self-funding in the future, with any surplus being fed back into investment in the Programme. There is also the potential for grant funding to support the establishment and development of the Programme.

1.3 We assume that the key objective in relation to the establishment of the Consortium is to identify a model that will:

1.3.1 Provide Members of the Consortium with an appropriate opportunity to participate in it, recognising that some Members will wish to participate for different reasons and in different ways, with a clear articulation of the Members' respective rights and obligations.

1.3.2 Provide the Consortium with a robust and effective governance structure that will best support the effective development and delivery of the Programme.

1.3.3 Provide the Consortium with the ability to use Consortium Members' background and foreground intellectual property rights ("IPR"), while protecting the IPR to ensure that it is not used for commercial purposes.

1.3.4 Enable new Members to join the Consortium and existing Members to withdraw from it.

1.3.5 Cater for the termination of the Consortium if it is no longer required.
1.3.6 Be consistent with the legal and regulatory obligations of the Consortium Members, particularly as regards those Members with charitable status (such as Universities, which are generally exempt charities). These will also include any EU procurement and State aid obligations.

1.4 In preparing this note, we have assumed that the overriding objective of the Consortium is to deliver education to individuals drawn from industry via the Programme and that, while this may also benefit those individuals’ employers (by enhancing their employees’ skills and knowledge), those employers will be drawn from across the engineering industry and any benefit to them is not intended to be any more than incidental to the delivery of education to individual participants.

1.5 This is an important point because we understand that the majority of Members of the Consortium will, like Bristol, be Universities with charitable status. Specific legal rules apply to charities in terms of the activities they are able to carry out and support, particularly as regards the application of their funds and other assets such as IPR. We comment on this aspect in more detail in paragraph 8 below.

2 Governance models

2.1 There are essentially two governance models that can be used to establish the Consortium. These are:

2.1.1 A contractual collaboration (see paragraph 3 below).

2.1.2 A joint venture (“JV”) vehicle model (involving a separate legal incorporated limited liability company or limited liability partnership) (see paragraph 4 below).

2.2 We have set out below the key features of each governance model.

3 Contractual collaboration

3.1 The Consortium could be structured as a contract (a "Consortium Agreement") between its Members. Subject to our comments at paragraph 3.11 below, this is essentially a purely contractual arrangement.

3.2 As a contractual collaboration, the Consortium itself would have no legal existence in its own right and would only be capable of engaging with third parties (e.g. Programme participants, industry employers etc.) via one or more of the Consortium Members themselves.

3.3 This has a number of implications:

3.3.1 An application for funding for Consortium activities by a Member may have an impact on the Member’s ability to apply for funding (e.g. from the same source) for its own activities.

3.3.2 An application by a Member for funding may not be able to capitalise fully on the strength in the Programme and Consortium brand.

3.3.3 Where Consortium funding is received by a Member, additional arrangements would be necessary for the funding to be spent by the other Members in order to deliver the Programme. Cross-invoicing arrangements may be required.

3.3.4 Other Consortium assets (e.g. IPR) could also only be held by one or more of the Members, with access granted to the other Members to enable them to be used to deliver the Programme.
3.3.5 Consortium contracts could only be entered into by one or more of the Members. This means that primary liability under a contract will lie with the Member which has entered into it, unless there are any additional arrangements between it and the other Members to meet any liabilities which do arise (e.g. by way of an indemnity). Typically, the most practical approach is likely to be that one Member acts as the "lead" Member for this purpose.

3.3.6 A Member's own requirements in relation to e.g. authorising and signing contracts and procurement processes in relation to the grant of a contract may have an impact on the efficient and effective delivery of the Consortium's activities.

3.3.7 Payments to or by the Members in respect of Consortium activities may have VAT implications for the individual Members.

3.4 Given the potential issues identified above in relation to a contractual collaboration, there are a number of areas which a Consortium Agreement should expressly address in order to mitigate against risks and assure the efficiency of the structure.

3.5 In particular, the Consortium Agreement should articulate the rights and obligations of the Members in relation to the Consortium (including their obligations in terms of its funding and their entitlement to any surpluses). It would be possible for the Consortium Agreement to establish different levels of participation in the Consortium for different categories of Member, depending on the scope of the rights and the obligations (in terms of e.g. the staff time, IPR etc. they will contribute to the Consortium) they wish to acquire. This could create a structure within which there is a group of "full" Members with greater rights (and corresponding obligations) in relation to the Consortium, with a category of "associate" Members who are obliged to contribute less to the Consortium but have a lower level of corresponding obligation and fewer rights. Other categories could also be provided for.

3.6 Where there are different levels of participation by different categories of Members, it may be desirable for their respective rights and obligations to be set out in separate category specific contracts which are supplemental to the Consortium Agreement.

3.7 The Consortium Agreement should also articulate the governance arrangements for both the Programme and the Consortium. With a potentially significant number of Members participating in the Consortium, it will be important to ensure that there is a sufficiently streamlined and effective governance structure for both of these aspects. This could be by e.g. establishing a Consortium board (the "Board") made up of a group of individuals nominated by the Members with delegated authority to make a range of decisions, but within a range of e.g. 5 to 10 individuals in order to facilitate effective decision-making.

3.8 If there are different categories of Member, one option would be for the "full" Members to appoint the members of the Board, perhaps with a minority being appointed by the "associate" Members. There are a number of different options that could however be adopted; the key point will be striking a balance between fair representation and governance efficiency. It will also be very important to articulate clearly the range of delegated powers exercisable by the Board (with a range of appropriate authority levels).

3.9 The following issues should also be addressed:

3.9.1 The Consortium Agreement should regulate how and who should award and enter into contracts for the delivery of Consortium activities taking into account the specific requirements of the Members in relation to EU procurement, contract authorisation and signing. On the assumption that a Lead Member takes responsibility for the administration of the Programme and it may be that the Lead Member is also best placed to act as the "lead" in terms of contracting for the
delivery of Consortium activities. If so, the other Members of the Consortium would likely need to e.g. indemnify the Lead Member against any liabilities it incurs when acting as the lead in relation to contracts.

3.9.2 In general, the Consortium Agreement should in any event specifically address how liabilities as between the Members should be apportioned. For example, a Member which enters into a contract to enable the delivery of a Consortium activity should in our view have a clear entitlement to the relevant funding required to make payments under it and to an indemnity from the other Members in relation to any liabilities which arise under it.

3.9.3 The Consortium Agreement should also regulate how funding for Consortium activities should be applied for and by whom. The Consortium Agreement should also regulate the entitlement of the Members to Consortium funding, so that there is a clearly described mechanism for a Member’s Consortium costs and expenses to be met and a clear basis on which any liability to VAT can be assessed (and please see our comments on VAT below).

3.9.4 The Consortium Agreement should regulate the ownership and use of Consortium assets (including any IPR - please see our more detailed comments in relation to this aspect in paragraph 9 below). Again, it may be that the Lead Member should hold Consortium assets on behalf of the other Members, subject to any restrictions set out in the Consortium Agreement.

3.9.5 The Consortium Agreement should contain clear provisions for a Member to exit or enter the Consortium, with appropriate notice and clear provisions in relation to a departing Member’s entitlement to Consortium assets.

3.9.6 The Consortium Agreement could also cater for the termination of the Consortium as a whole and how any Consortium assets should be dealt with on termination.

3.9.7 The Consortium Agreement should include some clear provisions confirming that the Consortium is not a legal partnership (for the reasons explained at paragraph 3.11 below).

3.9.8 The Consortium Agreement should set out an agreed list of any decisions which can only be taken by the Consortium Board with the consent of the Members.

3.9.9 The Members’ voting rights in relation to the Consortium, including any provisions which require unanimity rather than a majority vote (where e.g. there is some major change proposed to the structure of the Consortium or a proposal to admit an additional Member) should also be set out.

3.9.10 The Consortium Agreement could also potentially cater for the Members delegating arrangements for signing documents on a single, standard basis. This would depend on the constitutional arrangements of each of the Members and their internal rules on delegated authority.

3.9.11 The terms of any grant funding will require the Lead Member of the Consortium to ensure that the grant funding does not give rise to any State aid issues (where State aid is relevant) so we would expect the Consortium Agreement to include provisions regarding the provision of information in connection with State aid enquiries and to ensure that Members have appropriate monitoring and audit arrangements in place.

3.10 Provisions of this kind will in our view mitigate some of the legal risks associated with the contractual collaboration model mentioned above. However, they will not make any material change to the fundamental issues in relation to asset-holding, primary liability for
contracts and applications for funding and will not affect a Member’s own requirements in relation to the authorisation and signing of contracts and procurement. These are factors that derive from the Consortium having no legal existence separate from its Members.

3.11 We should add that in certain circumstances, a contractual collaboration can constitute a legal partnership. A legal partnership has a number of implications, of which the most important are that all partners are generally both jointly and individually liable for the debts and other liabilities of the partnership and that one partner has the ability to bind its other partners. Clearly, the implications for an individual partner in terms of liability are potentially significant, notwithstanding that a well drafted partnership agreement will generally adjust liabilities and set authority levels to mitigate risk for the partners.

3.12 The test of whether a legal partnership exists is a mixed question of fact and law. But the key question is whether the Members of the Consortium intend to work together with a view to making a profit. Our view is that this is unlikely given the overriding objective of establishing the Consortium and the charitable status of many of the Members.

3.13 In our view, therefore, it should be possible to ensure that the Consortium is not established or operated as a legal partnership. But only a Court could decide this conclusively and there is always a risk (albeit in our view a low risk which can be mitigated against) that a third party with a potential claim could seek to bring it on the basis that all Members are partners in a legal partnership and jointly and severally liable in respect of the claim.

4 Joint venture vehicle

4.1 Setting up a separate legal entity (a "Newco") as a vehicle for a JV collaboration is an established alternative to a contractual collaboration.

4.2 This model differs from the contractual collaboration model because the Consortium would be established via a separate legal entity established solely for that purpose and which will be owned by the some or all of the Members.

4.3 A JV vehicle can be established as a limited liability company (an "LLC") or as a limited liability partnership (an "LLP").

LLC

4.4 An LLC is very often used as the vehicle for carrying out a collaboration, particularly on a JV basis. An LLC is established with one or more members who own and control the LLC, which is under the day to day control of a board of directors. An LLC can be established as a company limited by shares or by guarantee. An LLC’s limited liability and incorporated status will generally protect both its members and directors from exposure to liabilities incurred by the LLC. An LLC can have charitable status.

4.5 Investment in an LLC which is established as a company limited by shares is possible by way of equity (i.e. the shareholders subscribe for their shares and the price they pay is used to fund the LLC’s activities) or by way of loan (or a combination of loan and equity finance). Funding can also be raised by way of grant. An LLC established as a company limited by guarantee can only raise funds by way of loan and grant.

4.6 Using an LLC limited by shares to establish Newco would enable its members to participate in any profits generated by it in proportion to their percentage shareholdings, with a right to receive any dividends declared out of its profits. We have however assumed that it is not intended that funding should be raised by way of equity (on the basis that funding will be obtained by way of grant and fees paid by employers) nor that there will be any requirement to distribute profit to the Members (on the basis that any profits will be re-invested in the Programme). For these reasons, we have assumed that, if Newco is established as an LLC,
this should be by way of a company limited by guarantee. This would be in the line with the approach often adopted in a collaboration which is focused on educational output rather than generating a commercial profit.

4.7 An LLC is potentially liable to pay tax on its profits, unless it has charitable status and the profits are generated in the course of carrying out a trading activity which advances its charitable objects. There is further information about the tax position in paragraph 8 below.

LLP

4.8 An LLP is also sometimes used as the vehicle for establishing a collaboration, particularly on a JV basis. An LLP is established by 2 or more members who own and control the LLP, which is under the day to day control of a group of “designated members”.

4.9 Investment in an LLP is possible by way of capital contribution by the LLP’s members or by way of loan (or a combination of capital and loan finance). In principle, funding can also be raised by way of grant.

4.10 The members of an LLP participate in its profits in proportion to shares agreed between them, with a corresponding right to receive a proportion of the LLP’s profits. Like an LLC, an LLP has a limited liability and incorporated status, which will generally protect the LLP’s members from exposure to liabilities incurred by the LLP. An LLP cannot have charitable status.

4.11 The key difference between an LLP and an LLC is that an LLP is “tax transparent” i.e. its profits and losses are treated as the profits and losses of its members for tax purposes. This can be advantageous where taxable profit is generated because it can enable those of an LLP’s members which are charities to take advantage of the exemptions and reliefs from tax which they are eligible for.

Our recommendation

4.12 As we have indicated, the key advantage of using an LLP to establish Newco would be its “tax transparent” status, which may allow those Members of the Consortium who are also charities to take advantage of the exemptions and reliefs from tax which they are eligible for (and assuming that if Newco is established as an LLC it does not have charitable status, which would enable it to claim exemption from tax on profits generated by a trade which promotes its charitable objects in any event).

4.13 This will however only be relevant if and to the extent that Newco generates significant taxable profits (unless Newco is a charity, any profit would need to be reinvested in the Programme after tax). On the assumption that any profit will be low, our view is that any tax advantage is likely to be outweighed by the fact that an LLC is a very familiar vehicle for establishing a JV vehicle which most Members will be familiar with in terms of participation. An LLP is likely to be less familiar and will also involve the Members in addressing their participation in the LLP in their own tax returns.

4.14 On balance, therefore, we would recommend that the new entity should be an LLC rather than an LLP, unless there is a likelihood that Newco will generate significant taxable profits and will not itself be a charity, so that the profits can be sheltered by using an LLP’s tax transparent status. We have assumed in the remainder of this note that Newco should therefore be established as an LLC.

5 Newco

5.1 In relation to the Consortium, setting up Newco is likely to involve the following arrangements:
5.1.1 Newco would be co-owned by some or all of the Members of the Consortium and regulated by a set of articles of association which would give each Member equal rights in relation to it.

5.1.2 Newco would be under the day to day control of a board of directors who would act as the Consortium Board and make decisions in relation to the delivery of the Programme. The directors will owe Newco a range of duties under company law.

5.1.3 The Consortium Agreement entered into by the Members will regulate the Members' rights and liabilities in relation to Newco and also between themselves.

5.2 Newco's governance structure would reflect the arrangements the Members determine are required for the effective operation of the Consortium and delivery of the Partnership. As with a contractual collaboration, it would be possible for Newco's members to be "full" Members of the Consortium (with corresponding rights under company law in relation to it), while other "associate" Members would not be members of Newco.

5.3 Equally, Newco's articles can reflect the desired composition of the board required to make decisions in relation to the operation of the Consortium and the delivery of the Programme. As with a contractual collaboration, there are a number of different options that could be adopted in the context of Newco; the key point will again be striking a balance between fair representation and governance efficiency. It will also be very important to articulate clearly the range of delegated powers exercisable by the Board (with a range of appropriate authority levels).

5.4 The Consortium Agreement would also deal with a range of issues, including most of those identified in paragraph 3.9 above in the context of a contractual collaboration. The key provisions would be:

5.4.1 The role of Newco within the Consortium, identifying those activities that it will carry out and those activities which would continue to be carried out by collaboration between the Members themselves.

5.4.2 Provisions in relation to funding for Consortium activities (and any specific funding for Newco).

5.4.3 Provisions in relation to Consortium contracts (including those contracts that would be entered into by Newco and the procurement obligations that would attach).

5.4.4 Provisions for Newco to hold Consortium assets including e.g. IPR.

5.4.5 The Lead Member's role as the entity responsible for the administrative operation of the Programme, which it may do under a sub-contract issued by Newco (rather than, as envisaged within a contractual collaboration as lead contractor on behalf of the Consortium Members).

5.4.6 Entry to and exit from the Consortium by the Members.

5.4.7 The termination of the Consortium, including provisions for the distribution of any Consortium assets.

5.4.8 The distribution of any Consortium surpluses (including surplus profit within Newco) amongst the Members or (as we understand is the intention, their reinvestment in the Programme).

5.4.9 An agreed list of any decisions which can only be taken by the Consortium Board with the consent of the Members.
5.4.10 The Members' voting rights in relation to the Consortium, including any provisions which require unanimity rather than a majority vote (where e.g. there is some major change proposed to the structure of the Consortium or a proposal to admit an additional Member).

5.5 The key advantages of using a JV Newco as against a contractual collaboration are:

5.5.1 Newco is a legal entity in its own right which is capable of entering into contracts, incurring liabilities and holding assets independent of the Members.

5.5.2 Unless they were to provide a guarantee of Newco's liabilities (which is unlikely to be required), the Members' liabilities for contractual and other obligations taken on by Newco will in almost all cases be limited by its limited liability status.

5.5.3 This will also mean that liabilities can be dealt with as between the Members with a greater degree of clarity and equality. Instead of e.g. one Member (i.e. the Lead Member) incurring primary liabilities under Consortium contracts, Newco will take the liabilities on, with the Members' respective obligations in relation to the contracts regulated by the Consortium Agreement.

5.5.4 Using Newco is less likely to have an impact on individual Members' ability to raise grant funding.

5.5.5 It should also be possible for Newco to be given delegated authority to sign documents on a single, standard basis. This would help simplify the administration of the Consortium but would depend on the constitutional arrangements of each of the Members and their internal rules on delegated authority.

6 Specific issues

6.1 There are a number of specific issues that need to be taken into account in analysing the pros and cons of using Newco.

Procurement

6.2 The rules on procurement may be relevant to some of the Members and Newco if and to the extent that Newco were to provide services to the Members under the Consortium Agreement in exchange for e.g. any funding provided by them. The procurement rules generally apply to Universities and other state funded organisations (although some Universities have decided that they fall outside the scope of the rules).

6.3 The procurement regime would therefore potentially apply to contracts awarded by the Members to Newco, and contracts awarded by Newco. The full procurement regime applies where the total spend by a Member on a particular service from Newco over the whole of the contract term for that service exceeds the relevant threshold. At present, this threshold is £182,302 plus VAT for contracting authorities, such as Universities. There are separate rules for lower value contracts and a "lighter touch" regime for some types of services contracts with a higher threshold, for example, for the provision of teaching services. We can advise further on this if required.

6.4 To avoid the difficulties that the procurement rules would create by requiring Members to tender for services, it may be possible to structure Newco under an exemption. This would allow Members in order to meet the conditions for exemption:

6.4.1 the Members must jointly exercise over Newco a control which is similar to that which they exercise over their own departments

6.4.2 the Members should have a representative on the decision making body of NewCo
6.4.3 Newco must perform more than 80% of its activities for the Members rather than for the wider market

6.4.4 There must be no direct capital participation from other parties. This would need to be carefully considered if any of the Members are privately funded institutions.

6.5 The corollary is that Newco can only provide up to 20% of its services to third parties, such as third party employers, in order for the exemption to apply to Newco to allow the Members to procure services from it outside of the procurement rules.

6.6 We recommend that the procurement position is looked at in more detail if Newco is the preferred option in order to establish the Consortium and to see whether this will work commercially.

State aid

6.7 The State aid rules prohibit the grant of aid or any other measures which would confer upon an organisation carrying out commercial activities a benefit, which could distort or potentially distort competition in the market and has an impact on EU trade. Payments made in breach of the State aid rules are unlawful and are liable to be returned to the body which made them together with interest at the statutory rate. There is also a risk that third parties who have not received aid can bring claims for damages.

6.8 It will therefore be important to ensure that any aid received through grant funding or from Universities is structured so that it does not give rise to State aid, either at the level of the Members, Newco or the employers.

6.9 There are a number of exemptions from the State aid rules or ways in which the financial arrangements can be structured so as not to amount to aid, and which we can explore in more detail when appropriate. For example, State aid granted to Members for the provision of education and the transfer of know-how is unlikely to be caught. Members will need to ensure that employers are paying market rate for their employees to participate in the engineering courses. Careful consideration will also need to be given to the allocation of intellectual property rights in the course materials and where they are owned from a State aid perspective.

6.10 Again, we recommend that further advice is taken on the State aid position if Newco is the preferred option in order to establish the Consortium.

Employees

6.11 If Newco is established it could, as a separate legal entity, employ staff to carry out its activities. If Newco does acquire its own employees, it will need to operate PAYE and account for tax and NICs on salaries. It will also require an HR function in order to manage its employees, albeit that this service could be purchased from a University or third party.

6.12 There are however alternative approaches and it may be that Newco’s requirement for the services of staff could be addressed by the supply of services of e.g. the Lead Member’s staff and/or the secondment of staff by one or more of the other Members.

6.13 Again, we recommend that further advice is taken on the employment position if Newco is the preferred option in order to establish the Consortium.

VAT

6.1 We have not carried out any analysis of the VAT position in relation to the Consortium, but recommend that the position is looked at in more detail if Newco is the preferred option in order to establish the Consortium.
6.2 There would be a cost to administering and accounting for VAT in relation to Newco, although this may not be significantly higher than the total cost to the Members of administering any VAT correctly under the contractual collaboration model.

Administration

6.3 As a separate legal entity, Newco will require a degree of administration in order to ensure that it complies with company law and other relevant legal regimes:

6.3.1 Statutory books will need to be maintained and changes in Newco's directors notified to Companies House.

6.3.2 Annual accounts will need to be prepared and filed with Companies House. Newco is likely to qualify as a small company, which means that it will be permitted to file abbreviated accounts and that these accounts will not need to be audited. The criteria for being a small company are that at least two of the following factors apply to Newco:

(a) annual income of under £6.5m;
(b) assets of under £3.26m; and
(c) fewer than 50 employees.

6.3.3 Newco's directors will need to hold and minute meetings.

6.3.4 Newco will require a registered office and must use letterheads etc. that comply with company law requirements.

6.3.5 Newco will need its own bank account(s) under the control of its directors (potentially with delegated authority) and will need to issue invoices for its charges to the Members and third parties.

6.3.6 As indicated above, Newco may require additional services in respect of VAT and HR, which will carry a cost.

7 Comparative analysis

7.1 In terms of the comparative advantages and disadvantages of using Newco as against a contractual collaboration, our view is that the advantages are:

7.1.1 Using Newco will clearly meet the objective of creating a legal entity which can enter into contracts, incur liabilities and hold assets in its own right, thereby avoiding the need for one or more of the Members to fulfil this role.

7.1.2 Newco will limit the Members' liability for Consortium activities and will avoid one or more of the Lead Member or other Members from carrying primary liability for those activities.

7.1.3 Newco would be a vehicle that could be used to obtain funding in its own right, maximising the Consortium's brand and limiting the potential for Consortium applications for funding to impinge on the ability of the Members to raise funds.

7.1.1 Newco can hold and exploit Consortium assets centrally for the benefit of the Members.

7.1.2 Payments for Consortium activities carried out by Newco will be made via Newco, avoiding the cross-invoicing arrangements that may be required under a contractual collaboration.
7.2 In terms of the disadvantages:

7.2.1 The JV vehicle model will involve an additional step (in terms of establishing and operating a Newco) in comparison to a contractual collaboration.

7.2.2 This can involve a degree of additional complexity (and associated cost), although this is in our view relatively limited in practice.

7.2.3 Newco creates the potential for procurement and State aid risks to arise, albeit that the range of exemptions and de minimis reliefs that are available may mitigate any risks to an extent. Further advice is likely to be required in relation to these issues.

7.2.4 Using Newco will create additional administrative obligations (please see paragraph 6.3 for further information in relation to this) and may carry an additional cost in terms of HR, corporate governance and administering and accounting for VAT.

7.3 For these reasons, we would generally recommend using a Newco within the JV model where a collaboration involves a degree of risk none of the parties establishing the consortium wish to accept (even with the risk mitigations we have mentioned in paragraph 3.9 and 3.10 above) and the scale of the collaboration (be that in terms of funding, income, value of output etc.) justifies it. But it may be that one or more of the specific advantages mentioned in paragraph 5.5 above (including e.g. any impact on funding) will override this.

8 Newco's status

8.1 While we recommend (and have assumed) that any Newco which is used should be set up as an LLC (in order to confer limited liability on the Consortium's Members), there are some options in relation to Newco's status.

8.2 The key decision will be whether to establish Newco as a charitable or non-charitable company.

8.3 If established as a charity, Newco would in our view need to be registered with the Charity Commission and its principal charity law regulator would be the Commission. While some charities which are controlled by exempt charities such as Universities can themselves be exempt, our understanding is that not all of the Members will be charitable so that this option will not be available.

8.1 Eligibility for charitable status depends upon the scope of an entity's objects (i.e. what it is entitled to do constitutionally) and also on what it does in practice to advance those objects. In terms of the Consortium, providing education is charitable and for the public benefit. Where benefits accrue to employers then there is a risk that they receive too much "private benefit" as a consequence, which would mean that the Consortium's activities would not be charitable. However, private benefit which is reasonable and incidental to activities which are for the public benefit is acceptable. The test for what is incidental is not clearly defined, so there is the scope for particular activities which are primarily aimed at e.g. benefiting business owners to be non-charitable. This is significant because activities carried out by a charity which are non-charitable can give rise to a breach of charity law and in some cases tax liabilities.

8.2 This point is relevant to those Members which are themselves charities in any event, because any support they provide for the collaboration must advance their own charitable (and, in the case of those Members who are Universities, educational) objects.

8.3 In our view, the degree of private benefit to employers is likely to be incidental to the delivery of education, particularly because (as we assume to be the be the case) all relevant employers within the engineering sector will be able to pay to allow their staff to access the
Programme. In addition, those Members which are themselves charities (including e.g. charitable Universities) will presumably have taken the view that their involvement with the Consortium will advance their own charitable educational objects without giving rise to too great a degree of private benefit (if not, there would be restrictions on their own ability to participate in the Consortium).

8.4 For these reasons, and based upon our understanding of the overriding objective in relation to the Consortium and the delivery of the Programme, our view is that Newco would be capable of being registered by the Charity Commission as a charity. The approach of the Charity Commission cannot however be guaranteed.

8.5 Subject to this, and by way of comparison, the main advantages of charitable status as against non-charitable status are:

8.5.1 Profits derived from charitable activities are free of tax. This would mean that Newco could reinvest any profits in the Programme free of tax. This factor suggests that charitable status may be preferable if Newco is likely to generate significant profits which are to be reinvested in the Programme. Please note however that if the only "full" Members of Newco are charitable, then it would be possible in principle for profits to be donated to them free of tax even if Newco is not charity, with the possibility that they may then be returned to Newco. We can advise on this possibility in more detail if that would be helpful.

8.5.2 Charitable status can better enable access to some grant funding. However, this will in our experience depend on the requirements and expectations of the funder. In Newco's case, it may be that many funders will take into account that it is owned and controlled by some Members with charitable status even if it is itself non-charitable. Subject to any specific requirements from funders for charitable status to ensure eligibility for funding, this factor is in our view neutral.

8.5.3 Charitable status will generally enable an entity to claim mandatory relief at 80% (and discretionary relief at 20%, dependent on local authority policy) from NNDR for which it is liable as the rateable occupier of property provided that the occupation is for exclusively charitable purposes. In Newco's case, we assume that the nature of its activities may mean that it is not the rateable occupier of any property for NNDR purposes in any event. If so, this factor is also in our view neutral.

8.5.4 A charity can be eligible for some exemptions and zero rating reliefs from VAT. Because we have not carried out an assessment of the activities that Newco will carry out, we do not know whether charitable status is likely to be relevant for VAT purposes. For the moment, therefore, we have assumed that this factor is therefore also neutral in terms of status.

8.5.5 If Newco were to be a charity and it shares common charitable objects with those of its Members which are Universities and they have common charitable activities, the Universities will have the flexibility to provide financial and in-kind support to Newco on a non-arm's length basis should this be required. However, it would be possible for the Universities to provide non-arm's length support to Newco even if it were non-charitable provided that the activities being funded are themselves charitable. So the flexibility for the Universities to provide non-arm's length support depends upon activities that Newco will carry out being charitable (which, as we have indicated above, is in our view likely to be the case) rather than on its status as a charity or not. In our view, this factor is also therefore neutral in terms of status.

8.6 Again by way of comparison, the main disadvantages of charitable status as against non-charitable status are:
8.6.1 A charity is subject to a charity law and regulation, which generally imposes greater legal requirements than company law and would mean that Newco is regulated by the Charity Commission. A non-charitable LLC is also easier to establish and subject to a lighter touch legal regime than a charity.

8.6.2 Establishing Newco as a charity will involve more time and complexity and will also add to the cost of establishing the Consortium. An application to the Commission can often take between 3 and 6 months to complete (sometimes longer).

8.6.3 A charitable company's directors are its charity trustees under charity law and owe a more extensive range of duties to a higher standard than the directors of a non-charitable company, with a correspondingly greater potential for personal liability in respect of breach (albeit that this risk is managed very effectively by many charities).

8.6.4 Because of the duties owed by charity trustees, there is greater scope for conflict between the duties owed by a charity's trustees and the duties and/or interests they may owe to or have in other charities including, in Newco's case, those Members which are also charitable. Such conflicts are often manageable, but they can complicate the governance position in practice.

8.7 On this basis, and on balance, our recommendation is that Newco should be established as a non-charitable company because of its greater flexibility provided there is no positive tax aspect that outweighs this.

8.8 Please note that it would also be possible to establish Newco as a "community interest company" or "CIC". A CIC is a form of company developed specifically for use by social enterprises which do not qualify for charitable status. The main advantage of using a CIC is that it has a formal "asset lock" within its articles which limits its ability to distribute assets to its members and lenders. This is seen by some funders as a recognisable "not for profit" status which may be relevant in terms of eligibility for grant funding, albeit that this is more likely in the context of funding for UK community based activities. Subject to that, there are in our view no key advantages in establishing Newco as a CIC rather than as a standard private company limited by guarantee.

9 Intellectual property considerations

9.1 We understand that that the key IPR involved as part of the Consortium will be copyright in the Programme content. There will also be trade mark and branding considerations - see paragraph 9.8 below.

9.2 The following aspects need to be carefully considered regardless of the governance model chosen:

9.2.1 to what extent will the Members need access to, or licences to use, confidential information, know-how and other IPR of the other Members, including both pre-existing IPR contributed to the Consortium (i.e. existing undergraduate course material) ("Background IPR"), or IPR developed in the course of the Consortium (i.e. its "Foreground IPR"):

(a) during the term of the Consortium; and

(b) following its termination?

9.2.2 who will own the Foreground IPR developed during the course of the Consortium?

9.2.3 who can exploit the IPR so created?; and

9.2.4 are there any restrictions on exploitation of the IPR and if so, what are they?
9.3 Therefore, for either model, the Consortium Agreement must address the fundamental issues of who owns the IPR, and what use the respective Members can make of it.

9.4 As a preliminary point, unless the IPR in the Programme content are assigned to a Member on behalf of the Consortium (or to Newco) (which will give that party legal ownership of such IPR), it will need to have licences in place. It is important to specify the type of licence (which will be dependent on what the relevant party is willing to offer). A licence can be exclusive, sole or non-exclusive:

9.4.1 An exclusive licence grants rights to the licensee to the exclusion of all others, including the licensor.

9.4.2 Under a sole licence, the licensor may exploit the rights itself but may not grant licences to any others.

9.4.3 A non-exclusive licence leaves the licensor free to exploit the rights itself and to grant licences to others.

9.5 Background IPR:

Contractual collaboration

9.5.1 We understand that the majority of the Programme content is to be developed by the participating Members for the purposes of the Consortium (and therefore will be Foreground IPR). However, it may be the case that existing undergraduate materials will need to be suitably adapted. Therefore, a Member will need to contribute its Background IPR. As such materials will have been developed for an independent purpose, it is unlikely to be reasonable to ask for an assignment of such Background IPR. The Consortium Agreement will need to include a licence from each Member to the other Members to use its Background IPR for the duration of the Consortium (or for the duration of that Member’s participation in the Consortium) and only for the purposes of delivery of the Programme (i.e. the Members are not permitted to make any further use of such IPR outside of their involvement in the Programme). It also needs to be considered whether all Members would need such rights, or whether the Background IPR licence only need to be given to the Lead Member, or the Member responsible for the administration/delivery of the Programme.

9.5.2 The scope of use of a Member’s Background IPR needs to be clearly defined in the Consortium Agreement to mitigate against the risk of a Member using it for other purposes and so that the Members are all clear as to their input and how materials will be used.

9.5.3 The Members will also need to consider what is intends to happen to such Background IPR if a Member leaves the Consortium. It may be the case that the Members (or the Lead Member) need to use it indefinitely (or at least for the remainder of an academic year whilst still delivering that aspect of the Programme). To the extent that such Background IPR is required in order to make use of the Foreground IPR (e.g. new Programme content is developed using undergraduate materials as a basis), then it is in the interests of the Consortium for Members to licence such IPR on a permanent basis - so that a Member's withdrawal does not prejudice the delivery of the Programme.

Joint venture vehicle

9.5.4 A licence of Background IPR will still be required from each Member. However, such a licence will only need to be to the Newco as that will be the legal entity responsible for the delivery of the Programme. The licence should be granted on
arm's length terms as the Consortium may well continue beyond the applicable Member’s interests in the joint venture vehicle.

9.6 Foreground IPR:

Contractual collaboration

9.6.1 The starting position is that the rights in and to Foreground IPR (i.e. the Programme content commissioned specifically for the Programme), belong to the party that created it (an "Inventing Party") (see paragraph 9.7.1(f) below with regard to our comments about consultants/employees). In the case of contractual collaboration, the Inventing Party will be the relevant Member, or a relevant third party if content is commissioned to be undertaken by a party who is not part of the Consortium.

9.6.2 Unless otherwise expressly provided in the Consortium Agreement, the Consortium will not have an express right to use such content. It will also have no say as to its use (or any restrictions on use by the Inventing Party). This remains the case even if work is commissioned and paid for by a Member (on behalf of the Consortium). Therefore, it is vital that the Consortium Agreement clearly sets out the scope of use and grants rights to the other Members for the purpose of the Consortium. It is also important to include restrictions on the Inventing Party’s use, so that such Member is not in a position to use the Programme content (which has been paid for by the Consortium) for a competing course. By way of an example, whilst one of the existing agreements for unit development during the pilot stage gives the Consortium wide rights to use the materials 'as it sees fit', nothing in that agreement prohibits the Inventing Party from using the materials or its own purposes (including commercial purposes). We do not recommend that this is the basis of ownership/use for Programme content going forward.

9.6.3 In terms of ownership of such Foreground IPR, and in order to protect the Consortium, the options are as follows:

(a) The Inventing Party retains ownership of the Foreground IPR, provides a licence to all the other Members to enable them to use it for the purposes of the Programme only. We would also recommend the inclusion of contractual restrictions on all Members use of such Foreground IPR (including the Inventing Party), so that none of the Members are in a position to use the Foreground IPR to develop a competing programme or otherwise use it for its own purposes (unless otherwise agreed). We would recommend an exclusive licence so that the Inventing Party is prohibited from making the Programme content available to any third party. A licence, as opposed to an assignment (see paragraph 9.6.3(b) below), gives rise to the risk that the Consortium cannot make use of such Foreground IPR if the Inventing Party leaves the Consortium (unless it is clear that the licence is to continue if this happens). In any event, the licence needs to be sufficiently clear and detailed to cover all proposed uses by the Members (but this may be difficult to ascertain at this point, and it may be the case that certain uses require the consent of the Inventing Party in the future). It will need to be considered whether all Members need a right to use the Foreground IPR for the purposes of the Programme, or whether the licence only needs to be with the Lead Member for the purposes of the delivery of the Programme.

(b) The alternative is that the Inventing Party assigns (transfers legal ownership) of the Foreground IPR to one Member (e.g. the Lead Member). This has the benefit that the Lead Member can then use such Foreground IPR without further restriction. However, in the spirit of the Consortium, you may
consider including a contractual restriction so that the Lead Member is restricted from using the IPR for any other purpose. This option has the benefit that, subject to any contractual restrictions set out in the Consortium Agreement, the Lead Member is permitted to use such Foreground IPR for any purpose. If a Member withdraws from the Consortium the IPR can still be used. From a practical point of view, one party owning all Foreground IPR is likely to be easier to manage (i.e. the Lead Member can sub-licence or otherwise exploit such rights and it does not need to seek consent of the Inventing Party). The Consortium Agreement should also include a licence back to the Inventing Party (and potentially all other Members) to enable the Members to make use of such Foreground IPR as part of their respective roles in the Consortium (and, if applicable, for academic and research purposes - see paragraph 9.7.1(c) below).

9.6.4 It is important to establish whether any IPR generated during the course of the Programme will be generated by a Member independently, without recourse to any other Member. Or whether, in practice, IPR may be generated jointly. If IPR are to be generated jointly, then more complex provisions in the Consortium Agreement will need to be included. Whilst most IPR can be jointly owned, and it is often suggested that the use of this mechanism provides a simple and natural approach to sharing rights in the fruits of a collaboration, we do not recommend this. This creates an additional level of complexity and in general, only allows the co-owners to exploit the jointly held rights by agreement. In effect, no party is permitted to use such IPR for any purpose without the consent of the other parties. Considering the number of Members this likely to be unduly onerous and would prejudice the operation of the Consortium and the value of the Programme.

Joint venture vehicle

9.6.5 If Programme content is developed by an employee or a director of Newco, then it will automatically vest in Newco. However, we think this is unlikely to be the case here and it will be that Newco will commission content from a Member institution (or other third party). Newco will therefore need to enter into either a licence, or an assignment with the relevant Inventing Party, either independently or as part of the Consortium Agreement to ensure that it has all necessary rights to make use of the Foreground IPR as part of the Programme.

9.6.6 As set out above, the management of IPR and exploitation is easier if this is under the control of one party, and therefore this favours adopting the joint venture vehicle model, as one legal entity will hold all the required rights in order to facilitate the Programme. However, the same outcome can be achieved under the contractual collaboration model if there is a Lead Member who is willing to take on this role.

9.6.7 It may also be appropriate to include a 'licence-back' from the Newco to the relevant Member institutions, if the Members wish to make use of any Foreground IPR for academic and research purposes.

9.7 IPR protection and other considerations

9.7.1 Regardless of the governance model, in order to protect the Members and the reputation of the Programme:

(a) The Consortium Agreement will need to include promises from the Members that their respective Background IPR does not infringe the rights
of any other person. The same will also be required from the Inventing Party
with regard to the Foreground IPR.

(b) There needs to be a clear mechanism with regard to commissioning content.
This will be dealt with under the terms of the Consortium Agreement with
regard to the Members’ respective contributions, but there also needs to be
a clear mechanism within the Consortium Agreement if third parties are
engaged. This is so that Programme IPR sits with the Consortium (either by a
Lead Member or via Newco) and such third party cannot make use of such
IPR in a way that would conflict or restrict the Consortium’s activities.

(c) If the Members wish to make use of the Programme IPR for academic and
research purposes outside of the Programme, then this right needs to be
clearly included within the Consortium Agreement. The scope and permitted
uses need to be clearly defined and potentially an approval mechanism may
need to be included.

(d) The Consortium Agreement also needs to make clear the Members’
respective scope of use – both for the duration of the Consortium and clarity
as to what the Members are to do if the Consortium is terminated. We
recommend that the proposed scope of use is clearly set out at the outset,
so that all Members understand how their IPR will be used. It will be very
difficult to manage if each Member contributes IPR on different terms.

(e) The Members may also consider the inclusion of exclusivity provisions within
the Consortium Agreement (i.e. that the Members are not permitted to
enter into arrangements that would conflict or compete with the
Programme). However, this needs to be considered carefully so as to not
unduly restrict the activities of the Members.

(f) The Members need to be clear as to the individual that develops the
Foreground IPR. If the content is developed by an employee of a Member or
other institution, then unless there is an agreement to the contrary then the
relevant employer will own the Foreground IPR (and the licence or
assignment can take place via the Consortium Agreement). This is not the
case if the Consortium engages with contractors or consultants and
therefore extra steps may need to be taken to ensure that the relevant IPR
sits with the correct party on behalf of the Consortium.

(g) The Members also need to consider IPR when applying for funding as the
relevant funder may have conditions with regard to IPR ownership that may
conflict with the terms of the Consortium Agreement.

9.8 Branding

9.8.1 We have assumed that the Programme will be marketed under a particular name,
logo and brand. This has the potential to be a valuable IPR. The Consortium
Agreement needs to clearly set out how and when this can be used, so that this is
used in a consistent manner so as not to dilute the brand. In terms of ownership, we
would recommend that one Member takes responsibility for this on behalf of the
Consortium (for example, the Lead Member under a contractual collaboration). This
party would then be in a position to register the IPR if applicable, or otherwise
manage its exploitation. If a joint venture vehicle is used, then Newco would own
the relevant IPR in the brand.
9.8.2 We assume that the Members would also require a right to use each other's name and logo as part of the delivery and advertising of the Programme (or that the Lead Member is permitted to do this on behalf of the Consortium). If a joint venture vehicle is used, then Newco would need a licence in order to make use of the Members' name and logo. We recommend that brand guidelines are developed and attached to the Consortium Agreement so that each Member's (or Newco's) permitted use is clearly defined.

9.9 Termination

9.9.1 It is in the interests of the Consortium that if an individual Member withdraws or is removed from the Consortium, then the other Members can continue to use its IPR for the purposes of the Programme. However, this may not be possible in practice e.g. if particular know-how or courses can only be delivered by that Member. In any event, the Consortium Agreement needs to clearly define the duration of any licences.

9.9.2 If the contractual collaboration option is chosen, and a Lead Member appointed to hold all Programme IPR, then consideration needs to be given to circumstances where that Lead Member wishes to withdraw or is removed from the Consortium. A clear mechanism should be included within the Consortium Agreement to address this.

9.9.3 If the joint venture vehicle route is taken forward, the Consortium Agreement will need to identify different "exit routes", each with different consequences in terms of the vesting of any intellectual property rights.

9.10 Data

9.10.1 In addition, as the Consortium is likely to involve the pooling or sharing of data (for example if a participant wishes to use course credits towards a master's degree at a Member institution) the Members need to ensure that the Members put arrangements in place to ensure that they have all relevant legal grounds to share the data (particularly personal data).

9.11 Summary

9.11.1 Regardless of the model chosen, we recommend that the Programme IPR sits with one party (either a Lead Member under a contractual collaboration or Newco). We do not recommend joint ownership.

9.11.2 It is in the best interests of the Consortium that Programme content IPR are made available to it on an exclusive basis (either by way of an assignment of the relevant IPR to a Lead Member, or to Newco, or by way of an irrevocable exclusive licence to the Lead Member or to Newco). This prohibits the Inventing Party from making use of that material unless this has been otherwise agreed.

9.11.3 If an exclusive basis cannot be agreed, then we recommend that clear restrictions are included within the Consortium Agreement so as to protect the interests of the Consortium.

9.11.4 Any other proposed use of the content (e.g. for academic and research purposes) needs to be clearly set out in the Consortium Agreement, so that Members can make use of the Programme content as anticipated, but are not permitted to make use of it for their own commercial purposes.
Materials Variability and Materials Specifications

Kevin Potter
Learning Objectives

Learners will be able to:

• Identify sources of data for composites materials

• Understand how to read a material specification document

• Identify the sources of variability in the materials used in composites manufacture

• Distinguish between materials variability and process variability
Requirements for data

• Any product design requires reliable data:

  Data relating to performance of the manufactured part

  Data relating to the manufacturing process

• May have to be derived within a strict regulatory framework – e.g. in aerospace

• Data quality is critical to the design process.
Materials selection data issues

Within Aerospace:

• A reasonable data base exists for 5 or 6 standard resin system.

• Publically available database:

  Composite Materials Handbook (CMH 17) and NCAMP system

  - CMH Vol 1. Guidelines for Materials Characterization
  - CMH Vol 2. Materials Properties
  - CMH Vol 3. Materials Usage, Design and Analysis

• Organizations like Granta make some of this material available in a more user friendly format.
Materials selection data issues

Outside aerospace: the situation is MUCH worse

Huntsman epoxy resins selector guide:

- No practical limit to the number of formulations that can be derived from this list
- No way of funding even the lowest level of data capture across the range of systems that are commercially available

![Pie chart showing resin and hardener quantities](chart.png)

- Basic resin: 25
- Premium resin: 17
- Tri/tetra functional resin: 25
- Reactive diluent: 11
- Hardeners: 60

© University of Bristol 2018
Materials selection data issues

Other aspects of performance required:

- Creep
- Fatigue
- Residual stresses
- Resin cure shrinkage
- Thermal expansion
- Fire performance
- Thermal conductivity
- Electrical conductivity
- Surface energy
- Edgewise impact response
- Rain erosion
- Chemical resistance

This sort of performance data is not collected in a database such as CMH17, and probably can not be.
Main issue:

No single publically available dataset for composite system can cover all aspects of the design and manufacture.

“How do we best work with the available information sources to manage risk in the design and development of critical composite structures?”
Sources of data

We need to take a view on the reliability of the data available to us.

Worst Best

Supplier data Textbooks Academic papers In-company test data CMH 17 or NCAMP data
Supplier data

- Best understood as a marketing tool

- Data is limited to a few headline properties:
  - Generally presented as single values
  - Often described as typical values
  - Variability is rarely presented

- There will always be a caveat on the datasheet that the supplier disclaims any and all responsibility for the use of any data supplied.

- Be a little skeptical when assessing supplier data.
### Textbook data

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Written by people with significant expertise and experience</td>
<td>• Sources of general understanding instead of data repositories</td>
</tr>
<tr>
<td></td>
<td>• Data tends to be normalised or have the detail stripped out</td>
</tr>
</tbody>
</table>

Used wisely to piece together the information needed for design they can be very valuable.
## Academic literature data

<table>
<thead>
<tr>
<th>In principle</th>
<th>In practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High quality</td>
<td>• Top rated Journals will try to uphold these standards</td>
</tr>
<tr>
<td>• Sufficient detail provided</td>
<td>• Some papers fall short of these standards</td>
</tr>
<tr>
<td>• Results able to replicate</td>
<td></td>
</tr>
</tbody>
</table>

- Can be valuable when used with care
- In some cases represent the only open source of useful data (e.g., true resin cure shrinkage)
- ESDU datasheets, design guides and software – reliable data source

© University of Bristol 2018
In-company test data

- In principle: every detail of the generation of the data is under the direct control of the organization (ideal situation).

- Require the organisation has the right facilities, systems, experience and skills to plan and carry out the manufacturing and test procedures to the highest standards.

- Otherwise, data can still be all but worthless.
NCAMP

National Center for Advanced Materials Performance (NCAMP):

• Qualify material systems

• Populate a publically available materials database

• Started as a FAA-funded program within the National Institute for Aviation Research at Wichita State University

• Stemmed from NASA's 1995 Advanced General Aviation Transport Experiment (AGATE).

• Both the FAA and EASA accept composite specification and design values developed using the NCAMP process.
NCAMP

Advantage:

• Extremely rigorous process to ensure the reliability of data

• All raw data included:
  - Stress-strain curves
  - Pictures of specimens and test setups
  - M&P specifications
  - Pedigree information

Disadvantage:

• High cost

• Limited range of composite systems are covered
Data Structure and gaps

NCAMP covered:

- Quasi-static mechanical responses in/out of plane for UD and multidirectional laminates.
- Cure kinetics and rheology
- Density and Tg
- H&S, Toxicity and disposal requirements
- Purchase specifications

NCAMP lacked:

- Fatigue, creep, stress rupture or fracture toughness
- Consolidation, drape, cure shrinkage, resin expansion or any other aspects of manufacturing data
- Other non-mechanical aspects of materials performance
Data Conclusions

1. Unless the data you need is in NCAMP there is no validated and verified data freely available.

2. There is no freely available dataset for any composite material that covers all possible aspects of performance required for design of critical structures.

3. Design data will need to be drawn from multiple sources and understanding the strengths and weaknesses of those sources is critical.

4. Outside aerospace the lower cost material systems are much less well characterised and good data is scarce at best.
Manufacturing related properties

A reliable and robust manufacturing process design requires data on:

- Cure kinetics
- Rheology and tack
- Consolidation behaviour
- Permeability
- Resin distribution
- Surface quality
- Thermal conductivity through thickness
- Steering limits for AFP tape
- Drape properties
- True resin cure shrinkage

None of the information in red is likely to be readily available or form part of any purchase specification.
Material specifications base fibre tows

PAN based carbon fibre tow specification (Defined by NCAMP NMS818):

- Whether tow is twisted, and twist details if it is
- Filament count
- Surface treatment and sizing
- Spool type and any respooling permitted
- Properties*
- Part marking to guarantee traceability and storage life

* Including strength, stiffness strain to failure, density, mg/m, sizing content - all to specific test specs and procedures for data reduction, and reported against specification limits
Material specifications woven cloth

Start from calling up the carbon fibre spec and build on that to include factors such as:

• Weave style (e.g. plain, twill, 4 shaft satin)
• Number of tows/cm in warp and weft directions
• Limits on deviations from an ideal 0.90 structure
• Whether any binder is applied and if it is:
  - The chemistry of the binder
  - The acceptable limits on binder content
  - The particle size range of the binder (if particulate)
  - How that binder is applied

Process critical properties such as permeability or drape limits are very unlikely to be on the specification
Material specifications resins

- Essentially about chemistry and formulation control rather than mechanical performance.
- Basic resin is covered by ASTM standard D1763-00
- Formulated resin specifications would also be expected to cover:
  - Rheology
  - Cure scheduling
  - Viscosity change with time and temperature
  - Resin density
  - Thermal expansion
  - Tg
  - Water absorption
  - Basic mechanical performance
Material specifications prepregs

Material specifications are in place for some of the prepregs covered by NCAMP such as NMS 128/2 for 8552/IM7 UD.

These give the requirement limits for:

- Resin content
- Fibre areal weight
- Volatiles content
- Flow
- Gel time
- Tack
- Drape
- HPLC, IR, DSC exotherm peak temperature
- Cured ply thickness
- Dry Tg

- In almost every case a standard test method is called up
- In addition minimum laminate mechanical property standards are set.
Material specifications prepregs

• NMS 128/2 does not apply directly to the IM7/8552 UD due to a different fibre areal weight and the NCAMP spec is very tightly drawn.

• The Certificates of Conformity do quite closely follow the NCAMP standard (apart from having no drape test reported).

• Tack is reported, but as the requirement is for tack from 1-5 where no units are noted the value of this for control or QA purposes is distinctly dubious.
Comments on prepreg specifications

• Wide ranges of individual measurements for resin content (+/-8.6%) and fibre areal weight (+/-3.7%)

• Wide acceptance ranges for Flow (+/-32%) and Gel time (+/-27%)

• Very poorly defined for Tack and Drape

• Loose acceptable limits for minimum UTS and UCS at 87% of average UTS and for modulus at +/-8.5% on the average (Average UTS values 15% higher than the minimum average value are used by Hexcel in their CoC)
Comments on prepreg specifications

• The most critical prepreg data for tolerancing.

• Recent delivered batches of IM7/8552 report significantly tighter distributions of fibre content.

• Any batches delivered at the specification limits are still contractually acceptable, so we need to be able to accommodate the breadth of the specification limits in process design and development.
Interpreting specifications

- Specification data for: Hexcel: 913C-HTA(12K)-5-34%.

- Nomenclature:
  - Manufacturer’s name: resin system - Fibre type (number of fibres in each tow) – nominal cured thickness in thousandth of an inch – resin wt%].

Shaded area represents all combinations of fibre, resin content and prepreg weight that would meet the specification.
Comparing actual and specification data

Acceptance testing data for 387 samples of another prepreg – individual samples have values up to and beyond the specification limits
Comparing actual and specification data

Critical issues to note for this dataset are:

• Distribution of gsm is not a nice symmetric Normal distribution

• Small number (~5%) of individual test points that fall outside the specification limits

• Ideally, in a six sigma environment all test results should be very well inside the specification limits

• For a single sided manufacturing process the variability in the gsm of the incoming materials sets the minimum variability in the moulded part thickness and there are multiple other sources of variability in the incoming materials

• The dataset shown here is a few years old but uses tighter specification limits than the NCAMP 128/2 standard

© University of Bristol 2018
Other sources of material variability

These include variability in:

- Tape width for slit tape
- Fibre straightness and alignment
- Angle between warp/weft for woven reinforcements
- Surface roughness distribution
- Surface topology distribution
- Toughener distribution
- Resin content, resin distribution, degree of impregnation
- Tack performance
- Drape properties and tow steering properties
- Resin rheology
- Consolidation response to pressure
- As delivered bulk factor

Most of these sources of variability are not generally covered in materials purchase specifications
Conclusions

• The number of different potential systems makes data collection an intractable problem.

• Ideally we need to move to a system similar to that used in metals where anyone can make 2024T3 aluminium alloy.

• There is not a single system for which all the material characterisation data needed for design is publically available.

• Purchase specifications only cover a small part of the requirement to understand and control variability in the incoming materials.
Learning Objectives

Learners will be able to:

• Identify sources of data for composites materials
• Understand how to read a material specification document
• Identify the sources of variability in the materials used in composites manufacture
• Distinguish between materials variability and process variability
Requirements for data

Reliable data is **critical** for the design of any product.

This data may be related to either:

- the performance of the manufactured part
- the manufacturing process

Data requirements may include:

- **obeying liability rules** – *high quality data required*
- **a strict regulatory framework** – *e.g. in aerospace*
Materials selection data issues

Some reasonable data bases exist (five or six) for resin systems used in aerospace.

Publicly available databases include the Composite Materials Handbook (CMH 17) and the National Center for Advanced Materials Performance (NCAMP) system:

- CMH Vol 1. Guidelines for Materials Characterization
- CMH Vol 2. Materials Properties
- CMH Vol 3. Materials Usage, Design and Analysis

This material is available in a more user-friendly formal from organisations like Granta.
Materials selection data issues

Data reliability is far worse outside of the aerospace industry

The Huntsman epoxy resins selector guide identifies:

- 25 basic resins
- 17 premium resins
- 25 tri/tetra-functional resins
- 11 reactive diluents
- 60 hardeners
- 6 accelerators

× Limitless formulations possible
× Impossible to fund data capture across entire range of systems
Materials selection data issues

**CMH17** contains data on *mechanical performance*.

Further performance data could be required, such as:

- Creep
- Fatigue
- Residual stresses
- Resin Cure shrinkage
- Thermal expansion
- Thermal/ electrical conductivity
- Surface energy
- Edgewise impact response
- Rain erosion
- Chemical resistance
- Fire performance
- Damping
- Etc.

Not collected in any database (including CMH17)
Materials selection data issues

No publicly available data set exists which covers all aspects of design and manufacture.

The design and manufacture of a structure subjected to long term fatigue loading cannot be optimized using a single dataset.

How do we make best use of the available information sources to manage risk in the design and development of critical composite structures?
Sources of data

We need to assess the reliability of the available data.

The order of reliability is arguably, **from worst to best:**

- Supplier data
- Textbooks
- Academic papers
- In-company test data
- CMH 17 or NCAMP data
Supplier data

Supplier data = marketing tool

Data limited to headline properties

Generally presented as single values/typical values, with no idea of variability.

Datasheets include a suppliers disclaim of any responsibility for use of data supplied
Textbook data

Textbooks are sources of understanding - **not** data repositories.

Textbook data tends to be normalized, or lack detail – i.e it is **indicative**, not definitive.

However, textbooks are written by experts with reputations to protect.

Used wisely, they can be of high value to piece together information required for optimising design.
Academic literature data

Academic papers are subjected to peer reviewing to ensure data is of high quality and sufficiently detailed.

Details on materials, processes, test methodology, and data variability ensures that results are replicable.

Top rated journals uphold these standards, however many lower-rated journals do not.
Academic literature data

Academic literature may represent the only open source of reliable data

Data may be extracted and by organisations like the ESDU and embedded into datasheets, design guides, and software

ESDU data is critically appraised – generally accepted as reliable data source
In-company test data

Data is controlled by the organization that will utilize it – ideal for the company

The organization must have the appropriate facilities, experience, and skills for manufacturing and testing

Procedures must be carried out to the highest standards for data to be reliable
NCAMP: the National Center for Advanced Materials Performance - started through FAA funding within the National Institute for Aviation Research (Wichita State Uni.), stemmed from NASA's 1995 Advanced General Aviation Transport Experiment (AGATE).

NCAMP works with the FAA (Federal Aviation Administration) and industrial partners to:
• qualify material systems
• populate publicly available material databases

FAA and EASA accept composite specification and design values developed using the NCAMP process

© University of Bristol 2018
NCAMP data is passed through multiple quality assurance steps – used with confidence in critical structure design

All raw data including:
- stress-strain curves, pictures of specimens and test setups, M&P specifications, and pedigree information

is held alongside the allowable property data extracted from that raw data.

The downside of all this level of control is a high cost, hence a limited range of composite systems are covered by this process.
Data Structure and gaps

**NCAMP has data for:**
- Quasi-static mechanical responses in/out of plane for UD and multidirectional laminates.
- Cure kinetics and rheology
- Density and $T_g$
- H&S, Toxicity and disposal requirements
- Purchase specifications

**NCAMP does not currently have data for:**
- Fatigue, creep, stress rupture or fracture toughness
- Consolidation, drape, cure shrinkage, resin expansion or any other aspects of manufacturing data
- Other non-mechanical aspects of materials performance
Data Conclusions

1. NCAMP is the only source of freely available validated and verified data.

2. No freely available dataset exists for any composite material that covers all performance aspects required for design of critical structures.

3. Design data needs to be drawn from multiple sources understanding the strengths and weaknesses of those sources is critical

4. Lower cost material systems outside aerospace are much less well characterised - good data is scarce at best
Manufacturing related properties

To design a reliable and robust manufacturing process we might need a range of manufacturing data properties such as:

- Cure kinetics
- Rheology and tack
- Consolidation behaviour
- Permeability
- Resin distribution
- Surface quality
- Thermal conductivity through thickness
- Steering limits for AFP tape
- Drape properties
- True resin cure shrinkage

None of the information in red is likely to be readily available or form part of any purchase specification.
Material specifications base fibre tows

**NCAMP NMS818** is an 18 page document that defines the specifications for PAN based carbon fibre tows, including:

- Whether tow is twisted, and twist details if it is
- Filament count
- Surface treatment and sizing
- Spool type and any respooling permitted
- Properties; *strength, stiffness strain to failure, density, mg/m, sizing content - all to specific test specs and procedures for data reduction, reported against specification limits*
- Part marking to guarantee traceability and storage life
Woven carbon cloth specifications start from the carbon fibre spec and are then built upon to include factors such as:

- **Weave style** (e.g. plain, twill, 4 shaft satin)
- **Number of tows/cm** in warp and weft directions
- **Limits** on deviations from an ideal 0.90 structure
- Whether any binder is applied, and if it is:
  - the chemistry of the binder
  - the acceptable limits on binder content
  - the particle size range of the binder (if particulate)
  - how that binder is applied

Process critical properties such as permeability or drape limits are very unlikely to be on the specification.
Resin specifications are related to chemistry and formulation control – not primarily mechanical performance.

ASTM standard D1763-00 covers the basic resin but not the formulated systems.

Formulated resin specifications should cover:
- rheology,
- cure scheduling
- changes in viscosity with time and temperature
- resin density
- thermal expansion,
- Tg,
- water absorption
- basic mechanical performance
Material specifications prepregs

Some prepreg material specifications are covered by NCAMP, such as NMS 128/2 for 8552/IM7 UD. These give the requirement limits for:

- Resin content
- Fibre areal weight
- Volatiles content
- Flow
- Gel time
- Tack
- Drape
- HPLC, IR, DSC exotherm peak temperature
- Cured ply thickness
- Dry $T_g$

In almost every case a standard test method is called up, the testing frequency is established and upper and lower bound limits for both individual tests and average values are established where required.

In addition minimum laminate, mechanical property standards are set.
Material specifications prepregs

- NMS 128/2 does not apply directly to the commercially available IM7/8552 UD as there are differences in fibral aerial weight - the NCAMP spec is strict.

- The Certificates of Conformity against the purchase specification issued by Hexcel closely follow the NCAMP standard – however no drape test reported.

- Tack is reported with a requirement from 1-5. No units are noted – the value of this for control or QA purposes is dubious.
Comments on prepreg specifications

• NCAMP 128/2 individual measurements have tight averages, but wide allowable ranges for:
  ➢ resin content (+/-8.6%)
  ➢ fibre aerial weight (+/-3.7%)

• Acceptance ranges are wide for Flow (+/-32%) and Gel time (+/-27%) and poorly defined for Tack and Drape.

• Lenient acceptable limits for minimum UTS and UCS at 87 % average UTS and for modulus at +/-8.5% on the average – note that Hexcel report average UTS values 15% higher than the minimum average value they use in their CoC.
Comments on prepreg specifications

• Most critical data for tolerancing, especially on thickness:
  - Resin content
  - Fibre areal weight

• Recently, batches of IM7/8552 report significantly tighter distributions of fibre content than permissible by CoC specifications.

• However, batches delivered at the specification limits are contractually acceptable
  
  the breadth of the specification limits should be accommodated in process design and development.
Interpreting specifications

Specification data for:
Hexcel: 913C-HTA(12K)-5-34%.

The nomenclature is as follows,
Manufacturer’s name: resin system - Fibre type (number of fibres in each tow) – nominal cured thickness in thousandth of an inch – resin wt%.

The shaded area represents all combinations of fibre, resin content and prepreg weight that would meet the specification.
Comparing actual and specification data

Acceptance testing data for 387 samples of another prepreg – individual samples have values up to and beyond the specification limits
Comparing actual and specification data

Critical issues to note for this dataset are:

• The distribution of gsm is not a symmetric Normal distribution
• There is a small but not insignificant (~5%) number of individual test points that fall outside the specification limits
• Ideally, in a six sigma environment all test results should be very well inside the specification limits
• For a single sided manufacturing process the variability in the gsm of the incoming materials sets the minimum variability in the moulded part thickness and there are multiple other sources of variability in the incoming materials
• The dataset shown here is a few years old but uses tighter specification limits than the NCAMP 128/2 standard
Other sources of material variability

These include variability in:
• tape width for slit tape
• fibre straightness and alignment
• angle between warp/weft for woven reinforcements
• surface roughness / surface topology / toughener distribution
• resin content, resin distribution, degree of impregnation
• tack performance
• drape properties and tow steering properties
• resin rheology
• consolidation response to pressure
• as delivered bulk factor

Most of these sources of variability are not generally covered in materials purchase specifications
Conclusions

The number of different potential systems makes data collection an intractable problem.

Ideally we need to move to a system similar to that used in metals where anyone can make 2024T3 aluminium alloy.

There is not a single system for which all the material characterisation data needed for design is publically available.

Purchase specifications only cover a small part of the requirement to understand and control variability in the incoming materials.
Page 2:
Learners will be able to:

• Identify sources of data for composites materials
• Understand how to read a material specification document
• Identify the sources of variability in the materials used in composites manufacture
• Distinguish between materials variability and process variability

Page 3:
Any product that we want to design raises a requirement for reliable data to do that design.
That data falls into two groups,

• data relating to performance of the manufactured part
• data relating to the manufacturing process

The data may have to be derived within a strict regulatory framework – e.g. in aerospace, but even when that is not required product liability rules mean that data quality is critical to the design process.

Page 4:
At any one time there are probably 5 or 6 current standard resin systems in aerospace for which a reasonable data base exists.
The publically available database sits largely within the Composite Materials Handbook (CMH 17) and NCAMP system

• CMH Vol 1. Guidelines for Materials Characterisation
• CMH Vol 2. Materials Properties
• CMH Vol 3. Materials Usage, Design and Analysis

Organisations like Granta make some of this material available in a more user friendly format.

Page 5:
Outside aerospace the situation is MUCH worse.
The Huntsman epoxy resins selector guide identifies 25 basic resins, 17 premium resins, 25 tri/tetra functional resins, 11 reactive diluents, 60 hardeners and 6 accelerators.

There is no practical limit to the number of formulations that can be derived from this list – and no way of funding even the lowest level of data capture across the range of systems that are commercially available.
Page 6:
In addition to the data on mechanical performance that sits in CMH17 there could be a requirement for other aspects of performance such as:

Creep, fatigue, residual stresses, resin cure shrinkage, thermal expansion, thermal and electrical conductivity, surface energy for bonding or painting, edgewise impact response, rain erosion, chemical resistance, fire performance, damping, and many others.

This sort of performance data is not collected in a database such as CMH17, and probably can not be.

Page 7:
There is no single publically available dataset for any composite system that could be used to support all aspects of the design and manufacture of a structure subjected to long term fatigue loading after the first initiation of damage.

So the issue is – “How do we best work with the available information sources to manage risk in the design and development of critical composite structures?”

Page 8:
We need to take a view on the reliability of the data available to us.

The order of reliability is arguably as follows from worst to best.

- Supplier data
- Textbooks
- Academic papers
- In-company test data
- CMH 17 or NCAMP data

Page 9:
Supplier data is best understood as a marketing tool.

Data is limited to a few headline properties, generally presented as single values, often described as typical values, very seldom is any idea of variability presented.

There will always be a caveat on the datasheet that the supplier disclaims any and all responsibility for the use of any data supplied.

The suppliers have no reason to supply bad data, but it is best to be a little skeptical when assessing supplier data.

Page 10:
Textbooks are not really data repositories, being rather sources of general understanding, so that data tends to be normalised or have the detail stripped out, so that the information is indicative rather than definitive.
On the positive side the textbooks will have been written by people with significant expertise and experience who are putting their personal reputation behind the information presented.

Used wisely to piece together the information needed for design they can be very valuable.

Page 11:
In principle academic papers will have been subject to peer review to ensure that the quality is high and the expectation is that sufficient detail on the materials, processes and test methodology, including variability in the data, will be presented to allow the results to be replicated.

In practice the top rated Journals will certainly try to uphold these standards, but there are certainly papers published that fall short of these standards.

Page 12:
Used with care academic literature sources can be very valuable and may in some cases represent the only open source of useful data – for example for true resin cure shrinkage.

Some literature data has been extracted by organisations such as ESDU and embedded into ESDU datasheets, design guides and software. These guides are generally accepted as reliable data sources as a level of critical appraisal will have been applied to the sources of the data.

Page 13:
In principle every detail of the generation of the data is under the direct control of the organisation that wishes to use the data – which is in many ways an ideal situation.

However, unless that organisation has the right facilities, systems, experience and skills to plan and carry out the manufacturing and test procedures to the highest standards the data can still be all but worthless.

Page 14:
NCAMP, the National Center for Advanced Materials Performance, works with the FAA and industry partners to qualify material systems and populate a shared materials database that can be viewed publicly.

NCAMP started as a FAA-funded program within the National Institute for Aviation Research at Wichita State University and stemmed from NASA's 1995 Advanced General Aviation Transport Experiment (AGATE).

Both the FAA and EASA accept composite specification and design values developed using the NCAMP process.

Page 15:
NCAMP operates an extremely rigorous process to ensure that the data available have passed multiple quality assurance steps and can be used with confidence in the design of mission critical structures.

All raw data including stress-strain curves, pictures of specimens and test setups, M&P specifications and pedigree information is held alongside the allowable property data extracted from that raw data.
The downside of all this level of control is a high cost, and as a result of that only a very limited range of composite systems are covered by this process.

Page 16:
NCAMP has data for:

• Quasi-static mechanical responses in/out of plane for UD and multidirectional laminates.
• Cure kinetics and rheology
• Density and Tg
• H&S, Toxicity and disposal requirements
• Purchase specifications

NCAMP does not currently have data for:

• Fatigue, creep, stress rupture or fracture toughness
• Consolidation, drape, cure shrinkage, resin expansion or any other aspects of manufacturing data
• Other non-mechanical aspects of materials performance

Page 17:
1. Unless the data you need is in NCAMP there is no validated and verified data freely available.
2. There is no freely available dataset for any composite material that covers all possible aspects of performance required for design of critical structures.
3. Design data will need to be drawn from multiple sources and understanding the strengths and weaknesses of those sources is critical
4. Outside aerospace the lower cost material systems are much less well characterised and good data is scarce at best

Page 18:
In order to design a reliable and robust manufacturing process we might need data on a range of manufacturing properties such as:

• Cure kinetics
• Rheology and tack
• Consolidation behaviour
• Permeability
• Resin distribution
• Surface quality
• Thermal conductivity through thickness
Page 19:
NCAMP NMS818 is an 18 page document that defines what needs to be in a specification for PAN based carbon fibre tow, it includes:

- Whether tow is twisted, and twist details if it is
- Filament count
- Surface treatment and sizing
- Spool type and any respooling permitted
- Properties; strength, stiffness strain to failure, density, mg/m, sizing content - all to specific test specs and procedures for data reduction, and reported against specification limits
- Part marking to guarantee traceability and storage life

Page 20:
Woven carbon cloth specifications will start from calling up the carbon fibre spec and build on that to include factors such as:

- Weave style (e.g. plain, twill, 4 shaft satin)
- Number of tows/cm in warp and weft directions
- Limits on deviations from an ideal 0.90 structure
- Whether any binder is applied and if it is:
  - the chemistry of the binder
  - the acceptable limits on binder content
  - the particle size range of the binder (if particulate)
  - how that binder is applied

Process critical properties such as permeability or drape limits are very unlikely to be on the specification

Page 21:
Resin specifications are essentially about chemistry and formulation control rather than primarily being about mechanical performance.

There is an ASTM standard D1763-00 that covers the basic resin but not the formulated systems.

Formulated resin specifications would also be expected to cover rheology, cure scheduling and changes in viscosity with time and temperature, resin density, thermal expansion, Tg, water absorption, and perhaps basic mechanical performance
Page 22:
Material specifications are in place for some of the prepregs covered by NCAMP such as NMS 128/2 for 8552/IM7 UD.

These give the requirement limits for:

- Resin content
- Fibre areal weight
- Volatiles content
- Flow
- Gel time
- Tack
- Drape
- HPLC, IR, DSC exotherm peak temperature
- Cured ply thickness
- Dry Tg

In addition minimum laminate mechanical property standards are set.

In almost every case a standard test method is called up, the testing frequency is established and upper and lower bound limits for both individual tests and average values are established where required.

Page 23:
Although NMS 128/2 is in place it does not apply directly to the IM7/8552 UD that we purchase as that has a different fibre areal weight and the NCAMP spec is very tightly drawn.

However the Certificates of Conformity against the purchase specification issued by Hexcel do quite closely follow the NCAMP standard (apart from having no drape test reported).

Tack is reported, but as the requirement is for tack from 1-5 where no units are noted the value of this for control or QA purposes is distinctly dubious.

Page 24:
NCAMP 128/2 allows quite wide ranges of individual measurements for resin content (+/-8.6%) and fibre areal weight (+/-3.7%), although averages are tighter.

Acceptance ranges are rather wide for Flow (+/-32%) and Gel time (+/-27%) and very poorly defined for Tack and Drape.

Acceptable limits for minimum UTS and UCS at 87% of average UTS and for modulus at +/-8.5% on the average seem rather loose, especially when Hexcel are reporting average UTS values 15% higher than the minimum average value they use in their CoC.
Page 25:
The most critical prepreg data for tolerancing, especially on thickness, is the resin content and fibre areal weight as they directly translate into CPT and part thickness.

Recently delivered batches of IM7/8552 report significantly tighter distributions of fibre content than are permissible by the specifications in the CoC.

However, any batches that are delivered at the specification limits are still contractually acceptable, so we need to be able to accommodate the breadth of the specification limits in process design and development.

Page 26:
Specification data for: Hexcel: 913C-HTA(12K)-5-34%.

The nomenclature is as follows, Manufacturer’s name: resin system - Fibre type (number of fibres in each tow) – nominal cured thickness in thousandth of an inch – resin wt%].

The shaded area represents all combinations of fibre, resin content and prepreg weight that would meet the specification.

Page 27:
Acceptance testing data for 387 samples of another prepreg – individual samples have values up to and beyond the specification limits.

Page 28:
Critical issues to note for this dataset are:

- The distribution of gsm is clearly not a nice symmetric Normal distribution
- There is a small but not insignificant (~5%) number of individual test points that fall outside the specification limits
- Ideally, in a six sigma environment all test results should be very well inside the specification limits
- For a single sided manufacturing process the variability in the gsm of the incoming materials sets the minimum variability in the moulded part thickness and there are multiple other sources of variability in the incoming materials
- The dataset shown here is a few years old but uses tighter specification limits than the NCAMP 128/2 standard

Page 29:
These include variability in:

- tape width for slit tape
- fibre straightness and alignment
- angle between warp/weft for woven reinforcements
• surface roughness / surface topology / toughener distribution
• resin content, resin distribution, degree of impregnation
• tack performance
• drape properties and tow steering properties
• resin rheology
• consolidation response to pressure
• as delivered bulk factor

Most of these sources of variability are not generally covered in materials purchase specifications.

Page 30:
The number of different potential systems makes data collection an intractable problem.

Ideally we need to move to a system similar to that used in metals where anyone can make 2024T3 aluminium alloy.

There is not a single system for which all the material characterisation data needed for design is publically available.

Purchase specifications only cover a small part of the requirement to understand and control variability in the incoming materials.
Thickness Variability, Drivers and Control

Kevin Potter

bristol.ac.uk/composites
Learning Objectives

Learners will be able to:

• Identify the causes of variability in part thickness from design and process perspectives

• Understand the underlying processes driving variability

• Demonstrate an understanding of how the level of variability can be predicted and controlled
Background

• All manufacturing processes are subject to variability.

• Composite materials differ from most metallic manufacturing methods in that the material, is generated at the same time as the geometry of the part.

• For this reason a lot more effort has to be put into understanding the sources of variability than would be the case for most metallic production.
Background

• These notes concentrate on the dominant aerospace process of autoclave / vac bag moulding of preimpregnated reinforcements.

• In this case the single most important factor is probably that of controlling the thickness dimensions and this will be considered here in some detail.

• We have been struggling with the control of thickness in parts made on single sided tooling since the birth of the composites industry and still do not have a complete answer.
To get the dimensions under control we need to be making parts to the correct mean thickness with a small variation on that thickness.

### Ideally

- The variability on thickness, expressed as a standard deviation should be 1/6th of the drawing tolerance
- That would give a thickness defect rate of $\sim 1$ in $1,000,000$

### In practice

- Current thickness defect rates are probably 5 orders of magnitude worse than that
- Defects may stem from part design, manufacturing design, the lay-up process or the autoclave process
Part design issues

Problems will arise:

- If the design calls up different ply counts in an area of nominally constant thickness

- If the nominal ply thickness is incorrect the position of the mean will be in error. This most commonly arises because of errors in the assumed fibre volume fraction (i.e. taking a nominal figure rather than what will actually be produced)

- If the part is geometrically complex and a fixed Cured Ply Thickness (CPT) has been assumed.

These issues really all relate to the mean rather than the variability as such but are controlled in the design process.
The Cured Ply Thickness Fallacy

• Assumption:
  – we can define a cured ply thickness (CPT) that is a fixed characteristic of the prepreg being used
  – this CPT can be used as a simple offset from the tool surface in calculating component thickness at any point.

• Even for flat laminates this is a dubious assumption

• For components of any complexity there are a range of factors that invalidate the fixed CPT assumption
Consolidation on single curvature corners

- If the plys can’t slip over each other as they consolidate on an inside radius then bridging will occur and the laminate will get thicker in the corner.

- Only a few % of unrelieved consolidation is needed for the local thickness to go out of tolerance.
Impacts of bridged fibres

- The fibres that bridge the radius must directly react the consolidation pressure. This leads to a reduced resin pressure immediately below the bridged fibre. Resin will, therefore, tend to flow towards the region of bridged fibre.

- The best result is that the resin pressure will equalise in the bridged zone.

- If this region does not completely fill with resin under some pressure a high local voidage will result, with very low through-thickness and shear strengths.
Consolidation on more complex features

Ideally:
internal and external radii are close the bridging and wrinkling effects cancel out.

In practice:
inaccuracy in lay-up may still lead to bridging on the internal radius and the induced tension in the ply can then lead to a thin region on the external radius.
Impacts on thickness away from corners

- Internal flows of resin will have the same effect as an external bleed.
- Bridging in corner radii can thus have an influence on thickness tolerances remote from the actual point of the defect.
- Other resin sinks might be seen at tool/laminate edges, or at the start of honeycomb or foam core ramps, etc.
Consolidation on external corners

- If the plies can’t slip over each other as they consolidate outside radii then wrinkling will occur.
- Wrinkling will not produce any great resin sink. The quality of the material in the wrinkle is obviously going to be very poor in terms of fibre orientation, and the wrinkled area may also be voidy.
- Locally, in the region of the wrinkles the thickness may be very high.
Eliminating quality problems

- It can sometimes be virtually impossible to lay up the reinforcement accurately enough to avoid significant defects, and these defects cannot usually be repaired.

- In this case slip zones can be built in to the laminate.

Note: this breaks the “Rule” that fibres must always be continuous, in order to allow an adequate laminate quality.
Effects of double curvatures - drape

- Woven cloth drapes by a process of rotation between warp and weft, which for a 0.90 weave always reduces the area of the cloth.
- A reduced area always equates to an increase in thickness.

For a woven cloth draped over a hemisphere the relative thickness in the deformed region rises very rapidly as the polar angle approaches 90deg.
Effects of double curvatures - drape

Draping a woven cloth over a faceted surface such as a honeycomb ramp also generates significant drape and thickness change.

Max drape angle is >20deg and the cloth is about 40% higher gsm and thus thicker in the heavily draped region.
Effects of double curvature in AFP

Section A-A Polar angle ~45deg

© University of Bristol 2019
Effects of double curvature in AFP

- For this part if $L = 2\text{m}$ and $W = 1\text{m}$ the excess width at the widest point = 11.1% = 55.5mm for tapes running in the 0deg direction.

- If the tape width = 6.35mm then 79 tapes will be across the region of double curvature at the widest point and there will be a gap of 0.71mm on average between each tape.

- In this case fibres running in 90 or +/-45 directions would have different excess widths and therefore average ply weight/unit area.
Effects of double curvature in AFP

As laid up there are gaps between tapes and straight fibres, as the lay-up is consolidated there are two limiting cases.

1. The resin flows to fill the gaps, the gaps remain and fibres from adjacent plies can be distorted in the gaps
2. The tape deforms to close up the gaps, fibres from adjacent plies remain straight

The local Cured Ply Thickness may be different in each ply in cases 1 and 2. Which case will dominate depends on factors such as the local resin viscosity, the initial size of the gap between tapes and any residual voidage
Defining the cured ply thickness

• Understanding the way that Cured Ply Thickness develops and its variability is central to any thickness tolerance control in composites manufacturing, apart from in rigid tool RTM

• For any prepreg the CPT depends on the fibre areal mass (gsm) after any drape, the resin content and any resin bleed, the applied pressure and packing fraction curve

• For AFP there are additional factors that need to be accommodated and the mapping strategy chosen for complex or doubly curved surfaces can have a major impact on these features and hence on the CPT

• Currently there is no industry-standard way of dealing with any of these issues, and little research to deliver such a standard
Linking voidage and thickness targets

• Autoclave heating and pressure cycle can influence the gelation point of the resin and the level of resin removal which impacts on voidage.

• The level of resin removal influences the final thickness for controlled bleed systems.

• For freely bleeding (or high flow) systems it is also the major factor in determining the quality of the laminates, as expressed by the voidage.

• The level of resin removal is influenced by the pressure in the resin, the time available for flow, the reinforcement’s permeability matrix and the instantaneous viscosity of the resin.
Linking voidage and thickness targets

• The point in the temperature cycle at which pressure is applied during the cure controls the time available for resin flow

• This control is exercised directly by controlling the start of the process of resin flow and the viscosity at that point

• Control is also exercised indirectly via the very strong influence that pressure has on the tool’s temperature (via increasing the heat transfer rate from air to tool)

• In this way there may be some control on the time to resin gelation, and the end of resin flow
Design of the manufacturing process

For this material:
- ‘normal’ autoclave pressure gives a target Vf% of 65%,
- a low pressure Vf% of 60%
- a vacuum-only pressure Vf% of 52%.

Note that there is variability in the consolidation response as well as in gsm. The actual achieved Vf% will also depend on the % resin in the prepreg and whether any resin is bled out.
Design of the manufacturing process

- Assuming resin bleed is uniform, there is still the possibility of variations in thickness due to variations in the weight/unit area of the prepreg.
- The weight/unit area tolerance limits for typical prepreg can be up to ±5% on both prepreg weight and fibre weight, and resin content is likely have a slightly wider tolerance band.
- It should not be assumed that all combinations of fibre weight, prepreg weight and resin content are possible as there may be conflicts between the various elements of the specifications.
- If specifications also quote cured ply thickness and cured fibre volume fraction or maximum void contents, then further internal conflicts in the specification are possible.
Interpreting specifications

Specification data for:
Hexcel: 913C-HTA(12K)-5-34%.

The nomenclature is as follows,
Manufacturer’s name: resin system - Fibre type (number of fibres in each tow) – nominal cured thickness in thousandth of an inch – resin wt%.

The shaded area represents all combinations of fibre, resin content and prepreg weight that would meet the specification.
34% by weight resin equates to a zero bleed Vf% of about 59%. If this prepreg had the consolidation characteristics as shown previously the minimum autoclave pressure (at the nominal resin content) would be about 3 Bar, and the material could not be used for vacuum moulding without the risk of generating very voidy laminates.
Design of the manufacturing process

- At the specification’s minimum limit for resin content of 31.5% the zero bleed Vf% becomes about 62% and a higher minimum autoclave pressure would be required to avoid voidage.

- Taking that into account the minimum acceptable cure pressure would be just over 4 Bar to give good properties across the prepreg specification range.
Taxonomy of sources of variability

Some sources of variability (65)

Materials (26)
- Reinforcement
  - Fibre Issues
    - Mass/unit area
    - Vacuums and effect of vacuum
    - Viscosity and effect of vacuum
    - Viscosity of fibre alignment
    - Quality of fibre alignment
    - Surface porosity
    - Trapped air in prepreg
  - Prepreg Issues
    - Surface smoothness
    - Tack level
    - Bond interface
    - Permeability
    - Waterability
  - RTM Issues
    - Locking angle for resin
    - Shear limit for RTM
    - Ease of resin impregnation
    - Load response to deformation
- Resin
  - Resin content
  - Honeycomb thickness
  - N/C condition & cleanliness
  - N/C resistance to cutting
  - Formicast strength
  - Foam level of open porosity
- Core
  - Honeycomb thickness
  - N/C condition & cleanliness
  - N/C resistance to cutting
  - Formicast strength
  - Foam level of open porosity

Moulding processes (22)
- General
  - Order of lay-up
  - Operator & other skills
  - Lay-up aids & tools
  - Tool preparation
  - Mold release issues
  - Changes in cooling type
  - Lay-up aids & tools
- Autoclave
  - Types of lay-up
  - Mold closure issues in RTM
  - Vacuum: Injection P
  - Vacuum: Injection T
  - Vacuum level at injection
  - Local resin flows
  - Action of P on bridged lay-up

Post-moulding (17)
- Resin
  - Mould closure issues in RTM
  - Vacuum: Injection P
  - Vacuum: Injection T
  - Vacuum level at injection
  - Local resin flows
  - Back face support
- Machining
  - Drilling
  - Machining and hole drill
- NDT
  - Inspector skills
  - Resolution of processes
  - False rea & ve issues
  - Interpreting outputs
- Assembly
  - Carriage methods
  - Surface prep for bonding
  - Adhesives, mix & application
  - Bonding cure cycle
  - Prep for paint & finishing
  - Application of finishes
  - Mechanical assembly

Limitations:
This chart is limited to conventional unidirectional and woven reinforcements, processed by conventional autoclave moulding or resin infusion processes.
It does not cover other processes such as filament winding, pultrusion or any out of autoclave processes.
It does not specifically address reinforcements such as NCFs, tow steered preforms, 3D woven materials etc.
It does not cover lay-up processes such as Automated Tape Laying or Automated Fibre Placement.
It does not cover machining processes in any detail.

THIS IS A MINIMUM SET OF SOURCES OF VARIABILITY

Overall the intent here is to set out a format that can be usefully followed when trying to establish causes of variability and their development into defective components even if those materials and processes are not specifically covered here.
<table>
<thead>
<tr>
<th>Additional sources of variability in layup</th>
<th>Variability in prepreg edge position in manual layup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variability in tape cutting position in AFP</td>
</tr>
<tr>
<td></td>
<td>Variability in tape edge position after cutting in AFP due to loss of steering in AFP after tow cutting</td>
</tr>
<tr>
<td></td>
<td>Gaps and laps due to design intent or AFP machine control limitations</td>
</tr>
<tr>
<td></td>
<td>Deposition roller properties, pressure, residence time in AFP</td>
</tr>
<tr>
<td></td>
<td>Temperature at tape surface and core at the nip point in AFP</td>
</tr>
<tr>
<td></td>
<td>Fibre waviness or wrinkling due to tow steering or drape.</td>
</tr>
</tbody>
</table>
Other process variability issues

- Regularity of debulking cycles
- Debulking to thickness target or a set process
- Accommodating developing thickness in AFP machine programming
- Uniformity of pressure across the nip point in AFP
- Surface undulations developing during layup
- Differences in compaction over different geometry features
- Resin bleed free or constrained
- Ply drop design practices can influence permability and resin flow
- Bagging materials and practices
Identifying route to a good quality

1. Identify thickness tolerance as % of nominal thickness
2. Is %T consistent with ply count, gsm, Vf%, Vv%, across the material specification range and P range?
3. If not then the quality cannot be reached and something has to change.
4. Can we ease geometry tolerances or accept finish machining?
5. If not then to improve quality we then need to:
   1. Tighten the material supply spec
   2. Modify the process, e.g. using a higher P
   3. Accommodate variability by adjusting the ply count on a part by part basis, which may also require path reprogramming in AFP
Identifying route to a good quality

• If %T is consistent with ply count, gsm, Vf%, Vv%, etc, then we do have a process window with ideal lay-up.

• The emphasis now changes from materials related issues to machinery/process related issues such as:
  1. Minimum coverage for any ply allowing for gaps from any source
  2. Do intermediate debulks close up any gaps?
  3. What is the maximum coverage for any ply due to any source including overlaps (which can’t be eliminated by debulks)

As an example 2mm +/- 0.01mm is very unlikely to be consistent with incoming materials variability. 2mm +/-0.1mm should be OK – but only if everything else is under control.
Worked example

Assumptions.
- Min T = 2mm, Max T = 25mm using a stiff but floating caul plate
- Max Voidage on any one ply 2% (practically zero overall)
- Minimum Vf = 60%
- Max Vf = 66%
- Nominal CPT = 0.25mm at 60% Vf
- Fibre SG = 1.78. Resin SG = 1.3

Definitions
- Gaps
- Laps
- Perfect ply drops
- Imperfect ply drops
Worked example

Calculations:

- 60% Vf at 0.25mm CPT = 267gsm fibre max
- 66% Vf at 0.25mm CPT = 293.7gsm fibre max
- Minimum resin weight at 60% Vf is 130gsm = 32.7wt%
- Minimum resin weight at 66% Vf is 110.5gsm = 27.3wt% but this is below the minimum wt% at 60% Vf so cannot be part of the materials spec
- We can set minimum fibre at 267gsm and resin at 130gsm
- We can set maximum fibre at 293.7gsm and resin at 140gsm
- Nominal then becomes 280.4 +/- 13.4 gsm fibre and a maximum 34.3wt% resin at minimum fibre gsm

- These figures must feed into the material purchase spec
Worked example - AFP

• Assuming a ply overlap – in the thinnest section this is likely to take T out of tolerance
• In AFP assuming a 0.5mm gap on 6mm wide tape the gsm loss is 8.3%/ply and could easily go well above 10% locally
• At this loss the fibre gsm is below minimum spec limit
• Best outcome is a CPT below spec, but with an acceptable Vf and a low voidage
• Worst outcome is a voidy ply - if there is insufficient local pressure to close up the gaps or consolidate the fibre pack to generate sufficient short range resin flow
• If there is globally enough resin in the preform then long range resin flow could fill up the voids – if the resin rheology is suitable, and this could lead to other problems.
Worked example - AFP

- In principle we need to understand the % area coverage of each part of each ply to estimate the effective local gsm
- Thus the nominal CPT of every part of each individual ply - so as to get the right overall thickness for the total ply stack.

This is a mixture of design input and the realities of manufacturing and tends to fall between those two stools in terms of responsibilities
Matched tooling issues.

• Truly fixed cavity tools such as RTM tools closed up against fixed seals don’t really have thickness variability problems.

• Two part compression moulds can have problems with both quality and thickness variability.

• In an ideal world the tool becomes fully closed with the resin under a significant hydrostatic pressure to eliminate porosity at the point of gelation – in the real world it’s a bit different.
Compression moulding issues

When the prepreg has been heated to the point where the resin is liquid the press force is reacted by:

- The fibre bed compaction
- The hydrostatic pressure in the resin which in turn has two phases
  - The liquid resin
  - Any entrapped air or volatiles

As the tool closes the fibre bed carries an increasing part of the press load as it consolidates and resin will also tend to flow both within the tool and out of any flash gaps.
**Compression moulding issues**

- Initially the resin will expand as it heats then start to shrink as it cures.
- As it shrinks and resin flows out of the system the resin pressure will fall.
- If the resin pressure falls below the vapour pressure of any volatiles voidage can be generated, and any entrapped air will also expand.
- If the resin gels prior to full tool closure the resin will almost certainly be under pressure throughout giving good quality with some variability in thickness.
- If the tool closes fully on liquid resin the thickness can be ideal but the quality can be degraded.
Conclusions

• Achieving a constant thickness within a tight tolerance band is a non-trivial target for any process using single sided tooling.

• Unless the details of the manufacturing processes are well understood and fully accommodated in the design process it is very unlikely that structures where the thickness is reliably in tolerance will be produced.

• Even if sources of as-designed variability are eliminated sources of as-purchased materials variability and as-manufactured variability need to be under tight control.
And Finally!

Using matched tooling can eliminate most if not all thickness variability issues but at the cost of a higher tooling bill and can introduce other quality critical issues.

Whichever route is followed the keys to success are understanding of the issues and a rigorous control of both design and manufacture.
Learners will be able to:

- Identify the causes of variability in part thickness from design and process perspectives
- Understand the underlying processes driving variability
- Demonstrate an understanding of how the level of variability can be predicted and controlled

All manufacturing processes are subject to variability.
- Composite materials differ from most metallic manufacturing methods in that the material, is generated at the same time as the geometry of the part.
- For this reason a lot more effort has to be put into understanding the sources of variability than would be the case for most metallic production.

These notes concentrate on the dominant aerospace process of autoclave / vac bag moulding of preimpregnated reinforcements.
- In this case the single most important factor is probably that of controlling the thickness dimensions and this will be considered here in some detail.
- We have been struggling with the control of thickness in parts made on single sided tooling since the birth of the composites industry and still do not have a complete answer.

To get the dimensions under control we need to be making parts to the correct mean thickness with a small variation on that thickness.
- In an ideal world the variability on thickness, expressed as a standard deviation should be 1/6th of the drawing tolerance - that would give a thickness defect rate of ~1 in 1,000,000.
- In production current thickness defect rates are probably 5 orders of magnitude worse than that.
- Defects may stem from part design, manufacturing design, the lay-up process or the autoclave process.

Problems will arise:
- If the design calls up different ply counts in an area of nominally constant thickness
- If the nominal ply thickness is incorrect the position of the mean will be in error. This most commonly arises because of errors in the assumed fibre volume fraction (i.e. taking a nominal figure rather than what will actually be produced)
- If the part is geometrically complex and a fixed Cured Ply Thickness (CPT) has been assumed.

These issues really all relate to the mean rather than the variability as such but are controlled
in the design process

Slide 7:

The assumption is that we can define a cured ply thickness (CPT) that is a fixed characteristic of the prepreg being used and that this CPT can be used as a simple offset from the tool surface in calculating component thickness at any point. Even for flat laminates this is a dubious assumption as edge bleed is very likely to lead to a reduced thickness at the part edge – which is why we routinely trim back laminate edges. For components of any complexity there are a range of factors that invalidate the fixed CPT assumption.

Slide 8:

If the plies can’t slip over each other as they consolidate on an inside radius then bridging will occur and the laminate will get thicker in the corner. Only a few % of unrelieved consolidation is needed for the local thickness to go out of tolerance.

Slide 9:

The fibres that bridge the radius must directly react the consolidation pressure. This leads to a reduced resin pressure immediately below the bridged fibre. Resin will, therefore, tend to flow towards the region of bridged fibre. The best result is that the resin pressure will equalise in the bridged zone. If this region does not completely fill with resin under some pressure a high local voidage will result, with very low through-thickness and shear strengths.

Slide 10:

In an ideal world, where internal and external radii are close the bridging and wrinkling effects cancel out. In the real world inaccuracy in lay-up may still lead to bridging on the internal radius and the induced tension in the ply can then lead to a thin region on the external radius.

Slide 11:

Internal flows of resin will have the same effect as an external bleed. Bridging in corner radii can thus have an influence on thickness tolerances remote from the actual point of the defect. Other resin sinks might be seen at tool/laminate edges, or at the start of honeycomb or foam core ramps, etc.

Slide 12:

If the plies can’t slip over each other as they consolidate outside radii then wrinkling will occur.
Unlike the case for bridging, wrinkling will not produce any great resin sink. The quality of the material in the wrinkle is obviously going to be very poor in terms of fibre orientation, and the wrinkled area may also be voidy. Locally, in the region of the wrinkles the thickness may be very high.

Slide 13:

It can sometimes be virtually impossible to lay up the reinforcement accurately enough to avoid significant defects, and these defects cannot usually be repaired. In this case slip zones can be built in to the laminate.

Note: this breaks the "Rule" that fibres must always be continuous, in order to allow an adequate laminate quality.

Slide 14:

Woven cloth drapes by a process of rotation between warp and weft, which for a 0.90 weave always reduces the area of the cloth.

A reduced area always equates to an increase in thickness.

For a woven cloth draped over a hemisphere the relative thickness in the deformed region rises very rapidly as the polar angle approaches 90deg.

Slide 15:

Draping a woven cloth over a faceted surface such as a honeycomb ramp also generates significant drape and thickness change. Max drape angle is >20deg and the cloth is about 40% higher gsm and thus thicker in the heavily draped region.

Slide 17:

For this part if $L = 2m$ and $W = 1m$ the excess width at the widest point = 11.1% = 55.5mm for tapes running in the 0deg direction.

If the tape width = 6.35mm then 79 tapes will be across the region of double curvature at the widest point and there will be a gap of 0.71mm on average between each tape.

In this case fibres running in 90 or +/-45 directions would have different excess widths and therefore average ply weight/unit area.

Slide 18:

As laid up there are gaps between tapes and straight fibres, as the lay-up is consolidated there are two limiting cases.

1. The resin flows to fill the gaps, the gaps remain and fibres from adjacent plies can be distorted in the gaps

2. The tape deforms to close up the gaps, fibres from adjacent plies remain straight

The local Cured Ply Thickness may be different in each ply in cases 1 and 2. Which case will
dominate depends on factors such as the local resin viscosity, the initial size of the gap between tapes and any residual voidage.

Slide 19:

Understanding the way that Cured Ply Thickness develops and its variability is central to any thickness tolerance control in composites manufacturing, apart from in rigid tool RTM. For any prepreg the CPT depends on the fibre areal mass (gsm) after any drape, the resin content and any resin bleed, the applied pressure and packing fraction curve. For AFP there are additional factors that need to be accommodated and the mapping strategy chosen for complex or doubly curved surfaces can have a major impact on these features and hence on the CPT. Currently there is to my knowledge no industry-standard way of dealing with any of these issues, and little research to deliver such a standard.

Slide 20:

In addition to consolidation issues, the autoclave heating and pressure cycle can influence the gelation point of the resin and the level of resin removal which impacts on voidage. The level of resin removal influences the final thickness, as discussed earlier for controlled bleed systems. For freely bleeding (or high flow) systems it is also the major factor in determining the quality of the laminates, as expressed by the voidage. The level of resin removal is influenced by the pressure in the resin, the time available for flow, the reinforcement’s permeability matrix and the instantaneous viscosity of the resin; which is in its turn influenced by the temperature and state of cure.

Slide 21:

The point in the temperature cycle at which pressure is applied during the cure controls the time available for resin flow. This control is exercised directly by controlling the start of the process of resin flow and the viscosity at that point. Control is also exercised indirectly via the very strong influence that pressure has on the tool’s temperature, as opposed to the vessel air’s temperature, (via increasing the heat transfer rate from air to tool). In this way there may be some control on the time to resin gelation, and the end of resin flow. Exercising this control with high flow systems has always been difficult, relying very largely on the characterisation of the resin’s viscosity/temperature/time characteristics.

Slide 23:

Assuming that everything has been done to ensure that resin bleed is uniform, there is still the possibility of variations in thickness due to variations in the weight/unit area of the prepreg. The weight/unit area tolerance limits for typical prepreg can be up to ±5% on both prepreg
weight and fibre weight, and resin content is likely have a slightly wider tolerance band. It should not be assumed that all combinations of fibre weight, prepreg weight and resin content are possible as there may be conflicts between the various elements of the specifications. If specifications also quote cured ply thickness and cured fibre volume fraction or maximum void contents, then further internal conflicts in the specification are possible.

Slide 24:

Specification data for: Hexcel: 913C-HTA(12K)-5-34%.
The nomenclature is as follows, Manufacturer’s name: resin system - Fibre type (number of fibres in each tow) – nominal cured thickness in thousandth of an inch – resin wt%].
The shaded area represents all combinations of fibre, resin content and prepreg weight that would meet the specification.

Slide 25:

34% by weight resin equates to a zero bleed Vf% of about 59%. If this prepreg had the consolidation characteristics as shown previously the minimum autoclave pressure (at the nominal resin content) would be about 3 Bar, and the material could not be used for vacuum moulding without the risk of generating very voidy laminates.

Slide 26:

At the specification’s minimum limit for resin content of 31.5% the zero bleed Vf% becomes about 62% and a higher minimum autoclave pressure would be required to avoid voidage. Taking that into account the minimum acceptable cure pressure would be just over 4 Bar to give good properties across the prepreg specification range.

Slide 28:

• Variability in prepreg edge position in manual layup
• Variability in tape cutting position in AFP
• Variability in tape edge position after cutting in AFP due to loss of steering in AFP after tow cutting
• Gaps and laps due to design intent or AFP machine control limitations
• Deposition roller properties, pressure, residence time in AFP
• Temperature at tape surface and core at the nip point in AFP
• Fibre waviness or wrinkling due to tow steering or drape.

Slide 29:

• Regularity of debulking cycles
• Debulking to thickness target or a set process
• Accommodating developing thickness in AFP machine programming
• Uniformity of pressure across the nip point in AFP
• Surface undulations developing during layup
• Differences in compaction over different geometry features
• Resin bleed free or constrained
• Ply drop design practices can influence permability and resin flow
• Bagging materials and practices

Slide 30:

1. Identify thickness tolerance as % of nominal thickness
2. Is %T consistent with ply count, gsm, Vf%, Vv%, across the material specification range and P range?
3. If not then the quality cannot be reached and something has to change.
4. Can we ease geometry tolerances or accept finish machining?
5. If not then to improve quality we then need to:
   1. Tighten the material supply spec
   2. Modify the process, e.g. using a higher P
   3. Accommodate variability by adjusting the ply count on a part by part basis, which may also require path reprogramming in AFP

Slide 31:

If %T is consistent with ply count, gsm, Vf%, Vv%, etc, then we do have a process window with ideal lay-up.
The emphasis now changes from materials related issues to machinery/process related issues such as:

1. Minimum coverage for any ply allowing for gaps from any source
2. Do intermediate debulks close up any gaps?
3. What is the maximum coverage for any ply due to any source including overlaps (which can’t be eliminated by debulks

As an example 2mm +/- 0.01mm is very unlikely to be consistent with incoming materials variability. 2mm +/-0.1mm should be OK – but only if everything else is under control.

Slide 32:

Assumptions.

• Min T = 2mm, Max T = 25mm using a stiff but floating caul plate
• Max Voidage on any one ply 2% (practically zero overall)
• Minimum Vf = 60%
• Max Vf = 66%
• Nominal CPT = 0.25mm at 60% Vf
• Fibre SG = 1.78. Resin SG = 1.3

Definitions
Slide 33:

Calculations:

• 60% Vf at 0.25mm CPT = 267gsm fibre max
• 66% Vf at 0.25mm CPT = 293.7gsm fibre max
• Minimum resin weight at 60% Vf is 130gsm = 32.7wt%
• Minimum resin weight at 66% Vf is 110.5gsm = 27.3wt% but this is below the minimum wt% at 60% Vf so cannot be part of the materials spec
• We can set minimum fibre at 267gsm and resin at 130gsm
• We can set maximum fibre at 293.7gsm and resin at 140gsm
• Nominal then becomes 280.4 +/- 13.4 gsm fibre and a maximum 34.3wt% resin at minimum fibre gsm
• These figures must feed into the materials purchase spec

Slide 34:

• Assuming a ply overlap – in the thinnest section this is likely to take T out of tolerance
• In AFP assuming a 0.5mm gap on 6mm wide tape the gsm loss is 8.3%/ply and could easily go well above 10% locally
• At this loss the fibre gsm is below minimum spec limit
• Best outcome is a CPT below spec, but with an acceptable Vf and a low voidage
• Worst outcome is a voidy ply - if there is insufficient local pressure to close up the gaps or consolidate the fibre pack to generate sufficient short range resin flow
• If there is globally enough resin in the preform then long range resin flow could fill up the voids – if the resin rheology is suitable, and this could lead to other problems.

Slide 35:

In principle we need to understand the % area coverage of each part of each ply to estimate the effective local gsm - and thus the nominal CPT of every part of each individual ply - so as to get the right overall thickness for the total ply stack.
This is a mixture of design input and the realities of manufacturing and tends to fall between those two stools in terms of responsibilities

Slide 36:

Truly fixed cavity tools such as RTM tools closed up against fixed seals don’t really have thickness variability problems.
Two part compression moulds can have problems with both quality and thickness variability. In an ideal world the tool becomes fully closed with the resin under a significant hydrostatic pressure to eliminate porosity at the point of gelation – in the real world it’s a bit different.
When the prepreg has been heated to the point where the resin is liquid the press force is reacted by:

- The fibre bed compaction
- The hydrostatic pressure in the resin which in turn has two phases
  - The liquid resin
  - Any entrapped air or volatiles

As the tool closes the fibre bed carries an increasing part of the press load as it consolidates and resin will also tend to flow both within the tool and out of any flash gaps.

Slide 38:

- Initially the resin will expand as it heats then start to shrink as it cures.
- As it shrinks and resin flows out of the system the resin pressure will fall.
- If the resin pressure falls below the vapour pressure of any volatiles voidage can be generated, and any entrapped air will also expand.
- If the resin gels prior to full tool closure the resin will almost certainly be under pressure throughout giving good quality with some variability in thickness.
- If the tool closes fully on liquid resin the thickness can be ideal but the quality can be degraded.

Slide 39:

Achieving a constant thickness within a tight tolerance band is a non-trivial target for any process using single sided tooling.

Unless the details of the manufacturing processes are well understood and fully accommodated in the design process it is very unlikely that structures where the thickness is reliably in tolerance will be produced.

Even if sources of as-designed variability are eliminated sources of as-purchased materials variability and as-manufactured variability need to be under tight control.

Slide 40:

Using matched tooling can eliminate most if not all thickness variability issues but at the cost of a higher tooling bill and can introduce other quality critical issues.

Whichever route is followed the keys to success are understanding of the issues and a rigorous control of both design and manufacture.
Geometrical fidelity and spring-in

Kevin Potter
Learning Objectives

Learners will be able to:

• Understand the basics of geometric tolerancing
• Understand the origins of residual stresses in composites
• Distinguish between thermo-elastic and non-thermo-elastic stresses
• Demonstrate an understanding of how problems with residual stresses can be minimised
Introduction

- Mechanisms of laminates significant geometry changes (e.g. warp, bow and twist).
- These effects have been a source of manufacturing problems and difficulties for as long as there has been a composites industry.
- Although the mechanisms are now becoming understood, good predictive models that could be applied during the design process for complex parts are still a little way off.
Tolerancing

• Ideally: composite structures should match the dimensions as shown on the drawings, or at least fit within the tolerance limits.

• In reality: it is commonplace for composite parts to be significantly in error.

Spring in

Twist

Bow
Datum set

- Baseline need to be defined to define the geometrical errors.
- Establish a set of datum planes that we can measure from is required.

Historically many composite parts were checked geometrically against a go/no go fixture which simplifies matters somewhat but with the use of CMMs for geometry check, having a clear datum becomes more critical.
Datum set

• For this part it would be next to impossible to define a datum set

• Everything that could act as a datum has been eliminated/machined away.

Ensuring that we have clarity on the datum faces is essentially then a design task rather than a manufacturing task, although ensuring that the datums are transferred into the component and that tolerances are met does fall into the manufacturing responsibility.
Datum set

• Generally the tooling has to provide the mechanism for transferring the design datum to the component.

• For some tools there are features that can be used to provide measurement datums, for others we need to build some features into the tool that can be used as datums for measurement and machining fixturing.
Problems

• The tool might have a different shape at the cure T and room T.

• For a 2m long tool curing at 180C the tool will expand in the length direction:
  – Al : about 7.7mm
  – Steel : about 3.8mm
  – QI CFRP : about 1.6mm
  – Invar : about 0.4mm

• For aluminium or steel we would really need to design the tool to accommodate the tool expansion in the tolerances
Residual stresses and distortion

- Ensuring that the tool is of the correct dimensions at the cure temperature is not the whole story.

- Residual stresses in composites manufacture may routinely result in the generation of distortions.

- Residual stresses can also have a significant impact on mechanical performance

Residual stresses need to be thoroughly understood and incorporated into the mould design practices
Residual stresses at the fibre level

There are multiple levels of thermally induced residual stresses in composite materials

- At the fibre level the CTE of the resin is higher than that of the carbon fibre both axially and radially
- As the material cools the fibre goes into compression and the resin into tension – but there is no out of plane distortion

Note: This is not the same for aramid fibre!
Residual stresses at the ply level

Single plies do not distort but connecting a 0 ply to a 90 ply will generate both residual stresses and distortions.
Hygrothermal effects

• As a resin picks up water from the environment that water causes the resin to swell.

• As the resin swells the level of residual thermal stresses in the plies decays.

• In the extreme the sign of the residual stress can be reversed with the resin under tension and the fibre under compression.

• We should really talk about hygrothermal stresses to take account of both deltaT and humidity effects.
Spring–in

- As the laminate cools down from cure it shrinks far more \((30\times10^{-6}/K)\) through thickness than in plane \((1-5\times10^{-6}/K)\).
- Angles close up to maintain continuity without residual stress generation.

If the angle is opened up to remove the distortion then transverse tension stresses are generated that can fail the laminate in the corner.
Multiple connected corner radii can lead to a lower level of distortion, but will have a residual stress even without opening up the corners.
Spring-in

As part complexity increases we will always be in a position where the shape of the part on the tool at the cure temperature will be different to the shape of the part off the tool at RT, and there will be a measure of residual stress in the structure.
Spring–in

On very simple models, the level of spring-in for a simple corner bend would be predicted to depend on the CTEs of the laminate in various directions.

\[
\Delta \varphi = \varphi (\alpha_t - \alpha_i) \Delta T / (1 + \alpha_r \Delta T)
\]

Where
- \(\Delta \varphi\) = change in corner angle
- \(\varphi\) = corner angle at cure temperature \(T\)
- \(\alpha_t\) = through thickness CTE
- \(\alpha_i\) = in-plane CTE
- \(\Delta T\) = cool down temperature range
Spring–in

• These models are said to capture the thermo-elastic elements of the spring-in. That is to say that they consider how the geometry will change as the temperature changes.

• A considerable level of variability can be seen in the thermoelastic spring-in from sample to sample if the geometry changes due to effects such as bridging, thinning, wrinkling and the presence of resin rich zones - which all impact on the various CTEs.
Spring in

For structures such as this where all corners are fully reversed there should in principle be no overall spring in, but the point to point variations in thickness, fibre and resin distribution introduce a distortion.

© University of Bristol 2018
• Unfortunately, if we take a simple ‘L’ shaped part and monitor the included angle in the ‘L’ as it is heated we see that even at the cure temperature there is a residual spring-in.

• That is to say that there are non-thermoelastic processes that contribute to the spring-in. In practise the thermoelastic and non-thermoelastic components seem to be roughly equal in magnitude for many systems.
Spring-in

The non-thermoelastic effects include

The effects of cure shrinkage in the resin after the resin has gelled – accommodated via an additional $\Delta T$

The effect of tensions being carried in the prepreg due to bridging

The effects of interaction between the tooling and the prepreg as the tool is heated

The effects of wrinkling in each ply as it is taken around a radius
True resin cure shrinkage

- True resin cure shrinkage will be much higher than apparent cure shrinkage.
- A proportion of that shrinkage occurs after gelation and directly impacts on the spring-in.
Tool-interaction effects

- Tool interaction effect is particularly important when metallic tools are used.
- This tool interaction effect can cause distortions even when flat tools are used.
- The effects are much greater when there are some features on the tooling that tend to increase the level of interaction, (e.g. joggles, steps and similar features).
- Friction between the prepreg and the tool as it expands can lead to measurable strains in the prepreg at the tool surface, the way those strains change through the laminate develop a range of possible outcomes.
Tool-interaction effects

What shapes would you predict to be made by these three laminates – all moulded against an aluminium tool surface?

a) 1 & 2 ply thick
b) 1 ply thick

© University of Bristol 2018
Tool interaction outcomes

Distortions shown here are to scale and not exaggerated. Having such thin laminates maximises the effects that we see.
Predicting spring-in

For simple bends the spring-in is relatively easily estimated.

- A box-like component the corners would be constrained and would be expected to take up a shape similar to that shown here on cool down, assuming that the edges were straight on the tooling.

![Diagram of a box-like component with spring-in at the corners](image)

- The modelling of the effect in this case would be more complex, and would require the use of FEA techniques that properly captured the various available mechanisms.
- The corollary of the reduced spring-in towards the corners of the box is that the residual stresses will be higher in these regions.
Predicting spring-in

A complex part need to include everything in the prediction

• Including things like the lightning strike protection and any insulation plies
• If we predict the geometry for just the reinforcement plies we will be in error
• FEA is the only tool that can cope with the complexity of the prediction
Conclusions

• It is critical to understand how the geometrical fidelity of a part will be measured and good datums are essential
• Any part processed at high T will be a different shape to the tool at RT
• Choosing a tooling material matched to the laminate CTE helps but does not solve all the problems
• For an arbitrary part there will be a mix of thermal distortions and residual stresses
• Getting it wrong can provoke premature failure
• We now understand thermal stresses and distortion pretty well in theory – but the practice still needs work
Learners will be able to:

- Understand the basics of geometric tolerancing
- Understand the origins of residual stresses in composites
- Distinguish between thermo-elastic and non-thermo-elastic stresses
- Demonstrate an understanding of how problems with residual stresses can be minimised

There are multiple mechanisms by which laminates may warp, bow and twist to give very significant geometry changes and these will be considered here. It should be noted here that these effects have been a source of manufacturing problems and difficulties for as long as there has been a composites industry. Although the mechanisms are now becoming understood, good predictive models that could be applied during the design process for complex parts are still a little way off.

Ideally: composite structures should match the dimensions as shown on the drawings, or at least fit within the tolerance limits.

In reality: it is commonplace for composite parts to be significantly in error.

We can't define the geometrical errors without being able to define the baseline and to do that we need to establish a set of datum planes that we can measure from. Historically many composite parts were checked geometrically against a go/no go fixture which simplifies matters somewhat but with the use of CMMs for geometry check having a clear datum becomes more critical.

For this part it would be next to impossible to define a datum set at this point as everything that could act as a datum has been eliminated/machined away. Ensuring that we have clarity on the datum faces is essentially then a design task rather than a manufacturing task, although ensuring that the datums are transferred into the component and that tolerances are met does fall into the manufacturing responsibility.

Generally the tooling has to provide the mechanism for transferring the design datum to the component. For some tools there are features that can be used to provide measurement datums, for others we need to build some features into the tool that can be used as datums for measurement and machining fixturing.

We will normally be checking the cured geometry at room temperature and curing the part typically at 180C, so the tool will be a different shape at the cure T and room T. For a 2m long tool curing at 180C the tool will expand in the length direction: For Al by about 7.7mm
For steel by about 3.8mm
For Q1 CFRP by about 1.6mm
For invar by about 0.4mm
For aluminium or steel we would really need to design the tool to accommodate the tool expansion in the tolerances

Slide 9
- Ensuring that the tool is of the correct dimensions at the cure temperature is not the whole story.
- Residual stresses in composites manufacture may routinely result in the generation of distortions.
- Residual stresses can also have a significant impact on mechanical performance

Residual stresses need to be thoroughly understood and incorporated into the mould design practices

Slide 10
There are multiple levels of thermally induced residual stresses in composite materials
At the fibre level the CTE of the resin is higher than that of the carbon fibre both axially and radially, so as the material cools the fibre goes into compression and the resin into tension – but there is no out of plane distortion
This is not the same for aramid fibre!

Slide 11
Single plies do not distort but connecting a 0 ply to a 90 ply will generate both residual stresses and distortions

Slide 12
As a resin picks up water from the environment that water causes the resin to swell.
As the resin swells the level of residual thermal stresses in the plies decays.
In the extreme the sign of the residual stress can be reversed with the resin under tension and the fibre under compression.
We should really talk about hygrothermal stresses to take account of both deltaT and humidity effects

Slide 13
As the laminate cools down from cure it shrinks far more (30E-6/K) through thickness than in plane (1-5E-6/K).
Angles close up to maintain continuity without residual stress generation
If the angle is opened up to remove the distortion then transverse tension stresses are generated that can fail the laminate in the corner

Slide 14
When we have multiple connected corner radii we will see a lower level of distortion, but will
have a residual stress even without opening up the corners

Slide 15
As part complexity increases we will always be in a position where the shape of the part on the tool at the cure temperature will be different to the shape of the part off the tool at RT, and there will be a measure of residual stress in the structure

Slide 16
On very simple models, the level of spring-in for a simple corner bend would be predicted to depend on the CTEs of the laminate in various directions.

\[ \Delta \varphi = \varphi (\alpha_t - \alpha_i) \Delta T / (1 + \alpha \Delta T) \]

Where
\[ \Delta \varphi = \text{change in corner angle} \]
\[ \varphi = \text{corner angle at cure T} \]
\[ \alpha_t = \text{through thickness CTE} \]
\[ \alpha_i = \text{in-plane CTE} \]
\[ \Delta T = \text{cool down temperature range} \]

Slide 17
These models are said to capture the thermo-elastic elements of the spring-in. That is to say that they consider how the geometry will change as the temperature changes.
A considerable level of variability can be seen in the thermoelastic spring-in from sample to sample if the geometry changes due to effects such as bridging, thinning, wrinkling and the presence of resin rich zones - which all impact on the various CTEs

Slide 18
For structures such as this where all corners are fully reversed there should in principle be no overall spring in, but the point to point variations in thickness, fibre and resin distribution introduce a distortion.

Slide 19
Unfortunately, if we take a simple ‘L’ shaped part and monitor the included angle in the ‘L’ as it is heated we see that even at the cure temperature there is a residual spring-in. That is to say that there are non-thermoelastic processes that contribute to the spring-in. In practise the thermoelastic and non-thermoelastic components seem to be roughly equal in magnitude for many systems.

Slide 20
The non-thermoelastic effects include
- The effects of cure shrinkage in the resin after the resin has gelled – accommodated via an additional \( \Delta T \)
- The effect of tensions being carried in the prepreg due to bridging
• The effects of interaction between the tooling and the prepreg as the tool is heated
• The effects of wrinkling in each ply as it is taken around a radius

Slide 21
The true resin cure shrinkage will be much higher than the apparent cure shrinkage. A proportion of that shrinkage occurs after gelation and directly impacts on the spring-in.

Slide 22
The tool interaction effect is particularly important when metallic tools are used in which the tool CTE differs from that of the reinforcement, e.g. for aluminium rather than invar or composite tools.
This tool interaction effect can cause distortions even when flat tools are used, although the effects are much greater when there are some features on the tooling that tend to increase the level of interaction, such as joggles, steps and similar features.
Friction between the prepreg and the tool as it expands can lead to measurable strains in the prepreg at the tool surface, the way those strains change through the laminate develop a range of possible outcomes.

Slide 25
For simple bends the spring-in is relatively easily estimated, for a box-like component the corners would be constrained and would be expected to take up a shape similar to that shown here on cool down, assuming that the edges were straight on the tooling. The modelling of the effect in this case would be more complex, and would require the use of FEA techniques that properly captured the various available mechanisms. The corollary of the reduced spring-in towards the corners of the box is, of course, that the residual stresses will be higher in these regions.

Slide 26
For a complex part we need to include everything in the prediction, including things like the lightning strike protection and any insulation plies.
If we predict the geometry for just the reinforcement plies we will be in error. FEA is the only tool that can cope with the complexity of the prediction.

Slide 27
• It is critical to understand how the geometrical fidelity of a part will be measured and good datums are essential
• Any part processed at high T will be a different shape to the tool at RT
• Choosing a tooling material matched to the laminate CTE helps but does not solve all the problems
• For an arbitrary part there will be a mix of thermal distortions and residual stresses
• Getting it wrong can provoke premature failure
• We now understand thermal stresses and distortion pretty well in theory – but the practice still needs work
Defect Taxonomy

Kevin Potter

bristol.ac.uk/composites
Learning Objectives

Learners will be able to:

1. Demonstrate how a defect taxonomy can be built

2. Understand how such a taxonomy can be of value in understanding sources of variability and defects

3. Distinguish between defects arising from design and manufacturing inputs
Why look at defect taxonomy?

**Problem:** Composites potentially contain hundreds of specific defects - trying to handle them on a one by one basis is like eating soup with a fork.

**Solution:** Defects can be described consistently using taxonomy.

A *taxonomy* is simply a way classifying things or concepts so that information can be easily communicated.

**Improved communication is the first step to defect reduction.**
Why is defect taxonomy important?

Defect taxonomy → structured understanding

Classified defects can be linked to their potential source and outcome → addition of layers to hierarchy
**Variability taxonomy**

**Some sources of variability (65)**

- **Reinforcement**
  - Mass/unit area
  - Vf% of Fibres
  - Vf% vs P
  - Vf% P
  - Quality of fibre alignment
  - Surface porosity
  - Degree of initial cure
  - Foam level of open porosity
  - Shell life

- **Resin**
  - H/C condition & cleanliness
  - H/C resistance to crushing
  - Foam crush strength

- **Core**
  - Honeycomb thickness

- **Fibre Issues**
  - Trapped air in prepreg
  - Surface smoothness
  - Tack level

- **Prepreg issues**
  - Slider content
  - Permeability
  - Wettablity

- **RTM Issues**
  - Locking angle for woven cloth
  - Shear limit for UD & NCF
  - Ease of wrinkle formation
  - Load response to deformation

- **Forming issues**
  - Core cycle var. T & P
  - T variations across part
  - Tool part CTS differences
  - T at demould
  - Demould procedures

- **Moulding processes (22)**
  - Order of lay-up
  - Operator & other skills
  - Lay-up aids and tools
  - Test preparation
  - Mold release issues
  - Changes in tooling type
  - Lay-up aids temp

- **General**
  - Types of bagging mat
  - Bagging methodology
  - Vacuum level in bag
  - Local resin flow
  - Action of P on bridged lay-

- **Auto clave**
  - Mold closure issues in RTM
  - Resin Injection P
  - Resin Injection T
  - Vacuum level at injection

- **Resin**
  - Bulk resin flow

- **Machining**
  - De-flashing process
  - Uncertainty of datum
  - Edge trimming
  - Jigging for machining
  - Machining and hole drill
  - Back face support

- **NDT**
  - Inspector skills
  - Resolution of processes
  - False +ve & -ve issues
  - Interpreting outputs

- **Assembly**
  - Carriage methods
  - Surface prep for bonding
  - Adhesive, mix & application
  - Bonding cure cycle
  - Prep for paint & finishing
  - Application of finishes
  - Mechanical assembly

**Limitations.**

This chart is limited to conventional unidirectional and woven reinforcements, processed by conventional autoclave moulding or resin infusion processes.

It does not cover other processes such as filament winding, pultrusion or any out of autoclave processes.

It does not specifically address reinforcements such as NCFs, tow steered preforms, 3D woven materials etc.

It does not cover lay-up processes such as Automated Tape Laying or Automated Fibre Placement.

It does not cover machining processes in any detail.

**THIS IS A MINIMUM SET OF SOURCES OF VARIABILITY**

Overall the intent here is to set out a format that can be usefully followed when trying to establish causes of variability and their development into defective components even if those materials and processes are not specifically covered here.
Is this taxonomy complete?

Definitely not.

Why?

- Limited to particular processes it was developed for.
  - i.e. manual lay-up/ autoclave moulding and pressed preform/ low pressure RTM.

- No account taken for defects produced by other methods.
  - i.e. contact moulding, filament winding, thermoplastic stamping, pultrusion, 3D weaving, patch placement, thin ply processes, etc…

- Complete exclusion of defects generated in-service.
Lay-up and cure - Voidage

- Resin selection is in design → resin shrinkage belongs to design.
Lay-up and cure - delamination

- Mostly simply caused & avoidable on shop floor.
Lay-up and cure – paperwork and travellers

Incorrect records  Loss of traceability  Travellers lost  Travellers inadequate  Traveller test failure

All of these errors can be fatal.

Avoid dependence on travellers.
### Lay-up and cure – layup errors

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrong prepreg</td>
<td>Incorrectly prepared material</td>
</tr>
<tr>
<td>Intensifier errors</td>
<td>Issues during curing process</td>
</tr>
<tr>
<td>Backing film laid in</td>
<td>Damage or defects in backing material</td>
</tr>
<tr>
<td>Inadequate debulking</td>
<td>Insufficient debulking leading to defects</td>
</tr>
<tr>
<td>Damaged tool</td>
<td>Physical damage to the tool</td>
</tr>
<tr>
<td>Poor tool prep</td>
<td>Improper preparation of the tool</td>
</tr>
<tr>
<td>Surface contamin</td>
<td>Contamination on the surface</td>
</tr>
<tr>
<td>Wrong layup order</td>
<td>Incorrect order of layup layers</td>
</tr>
<tr>
<td>Wrong bag materials</td>
<td>Incorrect materials for bagging</td>
</tr>
<tr>
<td>Misplaced cores</td>
<td>Cores placed incorrectly</td>
</tr>
<tr>
<td>Ply size errors</td>
<td>Incorrect ply size</td>
</tr>
<tr>
<td>Poor mould release</td>
<td>Problems with mould release</td>
</tr>
<tr>
<td>Wrong ply count</td>
<td>Incorrect ply count</td>
</tr>
<tr>
<td>Wrong RTM binder</td>
<td>RTM binder not applied correctly</td>
</tr>
<tr>
<td>Bridging in bagging</td>
<td>Excessive bridging during curing</td>
</tr>
<tr>
<td>Excess RTM binder</td>
<td>Excessive resin during curing</td>
</tr>
<tr>
<td>Overtreat RTM binder</td>
<td>Excessive resin application during curing</td>
</tr>
<tr>
<td>Bridging and wrinkling</td>
<td>Excessive bridging and wrinkling</td>
</tr>
<tr>
<td>Wrong cores</td>
<td>Incorrectly placed cores</td>
</tr>
<tr>
<td>Foreign objects</td>
<td>Foreign objects in the composite</td>
</tr>
</tbody>
</table>

Most of this looks like simple, readily avoidable, inexcusable carelessness.

**So why is it so common?**
Geometry – Spring-in and residual stress

- **Not** manufacturing defects
- Related to design processes
- Result in scrap parts
Geometry – Thickness & periphery errors

- Flanges too narrow
- Flanges too wide
- Loss of datum data
- Part too thin
- Part too thick

• All very common errors, especially part-thickness
### Geometry – HC sandwich panel errors

- Mostly occur in the Honeycomb prior to assembly and cure

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrong H/comb</td>
<td>Rough trim surfaces</td>
</tr>
<tr>
<td>H/comb under size</td>
<td>Dents and damage</td>
</tr>
<tr>
<td>H/comb over size</td>
<td>Separated nodes</td>
</tr>
<tr>
<td>Wrong ramp angle</td>
<td>Surface contamin</td>
</tr>
<tr>
<td>Poor HC bonding</td>
<td>Inadequate edge dip</td>
</tr>
<tr>
<td>Potted insert errors</td>
<td>Ramp collapse</td>
</tr>
<tr>
<td>Skin/core debonding</td>
<td>Skin Dimpling</td>
</tr>
<tr>
<td>Periphery and T errors</td>
<td></td>
</tr>
</tbody>
</table>

© University of Bristol 2018
Geometry – Fibre misalignment errors

- Consider improvements to the design process.
Machining, assembly and handling errors

• Note that poor datum definition results in machining errors.

• Predominantly, errors arise from simple manufacturing errors.
Adding detail

We can start to give more detailed descriptions of the defects that we see - using a common framework for comparison.

For example we might want to:

- Identify the cause or aetiology where possible
- Identify whether it is an error in Design, Manufacturing or both M/D
- Estimate the likely effects of the error
- Estimate the probability of occurrence in a well-run shop
- Assess the likely MRB review outcome e.g.:
  - Accept as is
  - Rework
  - Repair and Concess
  - Concess without repair
  - Scrap

Assess the costs of these outcomes
Example - In/out of plane wavy fibres good drape

**Aetiology:** Drape forces the reinforcement tows into in-and out-of plane curvatures to map to the tool surface.

*Mapping exactly follows design intent* - no manufacturing defect – although performance will be affected.

**Likely effect:** Changes in fibre direction & thickness, possible changes in laminate balance and symmetry, local minor fibre wrinkling

**Probability:** 100% occurrence, unavoidable

**Outcome:** A if the effects are accommodated in the design process and stress analysis
Example - In/out of plane wavy fibres bad drape

Aetiology: Drape forces the reinforcement tows into in-and out-of plane curvatures to map to the tool surface.

Mapping does not follow design intent, including for non-formable geometries and poor following of instructions - M/D

Likely effect: A range of very significant defects e.g. folds, heavy wrinkles, thickness changes, fibre wrinkling, balance, symmetry change.

Probability: Common (Unfortunately).

Outcome: C or S - these defects cannot be reworked and are unlikely to be repairable so total scrap is quite likely.
Defect databases

- Defect taxonomy is a **useful tool** to minimise costs of poor quality and defects, but not a sufficient guide alone.

- A suitable guide would include a defect database with the frequency and costs of specific defect types.

- Companies do have defect databases, however they often lack clarity.
Defect databases

Common errors are:

- Quality information captured at the end of the manufacturing process (many moulding issues are rooted in earlier processes).
- Allowing unstandardized or free form descriptions of defects.
- Ambiguously capturing the position of the defect.
- Not capturing the cost of MRB, other remedial action and scrappage.

- Standard non-compliance and defect codes should be used in a consistent manner.

- Machine learning/ data mining with an unstructured database could work.

- A well-structured database will certainly work.
Example - Honeycomb Cored sandwich panels

**Step 1.** Identify the stages in production at which defects can arise.

- Tool prep
- Honeycomb Prep
- Ply cutting
- Lay-up in clean room
- Cure
- Moulding trim and inspection
- NDE
- Test pieces
- Drill and machine
- Paint shop
- Final assembly
Step 2. Identify defect types at each stage (>100 found)

Step 3. Identify reporting methodology. The panel below is divided into 11 regions - it may well be advantageous to use more.

We need to be able to code the defects easily. For example:

**B9** defect could be bridged reinforcement in the region of the joggle.

**RC6** could be ramp collapse in the cut-out region.

**OT7** an over thickness tolerance condition on the outboard flange etc.
Step 4. Populate the database with quality and cost data and keep it under review.

Step 5. When the process has bedded in and we have confidence in our understanding of defect aetiologies, consider corrective actions for current and future products.

Corrective action includes ensuring that the defects sourced from the design process are eliminated by changing design practices and adopting Design for Manufacture principles.
Conclusions

**Problem:**

The cost of poor quality and moulding defects in composite manufacture is difficult to control.

**Solution:**

Taxonomy of defects and source variability coupled with good cost and quality database.
Acceptance Criteria, rework, repair and concessions

Kevin Potter
Learning Objectives

Learners will be able to:

• Understand the need for formal quality processes
• Distinguish between rework and repair procedures
• Demonstrate a basic understanding of how a quality system operates for composites
# Acceptance Criteria

<table>
<thead>
<tr>
<th>Definition</th>
<th>Standards applied as part of the quality assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Determine whether a part is fit for use</td>
</tr>
<tr>
<td></td>
<td>Include a range of dimensional and other quality parameters</td>
</tr>
</tbody>
</table>
# Rework

## Definition
- An action of correction to correct nonconformities
- Bring a product back into 100% conformance

## Example
- Open up an undersize drilled hole
- Trim back an edge been cut oversize
- Touch up a paint finish

Note: Rework does not generally generate a requirement to inform the customer or generate a concession action.
# Repair

## Definition
- An action of correction to make nonconformities fulfill the intended use or purpose
- May not meet the specified requirements

## Example
- Patch a damaged laminate surface
- Inject resin into a delamination
- Drill out a misplaced hole and fit a larger fastener

Note: A need to repair will generate a requirement to inform the customer of the defect and generate a concession action
Concession

Definition

- Permission to use or release a product that does not conform to the specified requirements

Example

- An admission of failure

Note: A concession is generally limited to the delivery of a specific item or items affected by a specific non-conformance rather than a complete class of products.
Concession

Concessions can be sought to repair the non-compliant part or to “Use as is”

Repair
- Must be done to a formally released and controlled repair procedure

Concessions
- As a supplier of composite parts you can request a concession - but not demand one
- A constant stream of such requests will not be endearing you to your customer as a supplier!
- May be appropriate if the defect can be demonstrated not to lead to the potential for premature failure
- An example: a honeycomb sandwich panel which is over thickness in the cored region

Use as is

© University of Bristol 2018
Decision making process & MRB

Formal process required to take control of the disposition of non-conforming parts - Materials Review Board (MRB).

- Nonconforming material, such as relifing out-of-life prepreg
- Nonconforming product, such as Use-as-is, Rework, Repair, or Scrap.
- Redesigning the part or manufacturing process.
MRB and Quality

- MRB activity sits between Quality and Engineering functions and both will be heavily involved.
- We need to have a look at the Quality Assurance / Quality Control functions to see how things fit together.
Quality Assurance / Control

• The word “Quality” can be used in two distinct senses:
  - as a measure of perfection
  - as a system for demonstrating that components have been made in an acceptable manner and can be documented to be acceptable

• The only useful definition: whether a component meets specifications or not

• A component that only just meets specifications is deemed to have the same quality as a part of perfect exhibition standard

• The design and development process has the greatest effect on quality defined in this way
The Quality Assurance task

Function of a quality system
- Demonstrate the products delivered are fit for purpose
- Level of detail depend on the function of the part and the consequences of product failure

Quality Assurance task
- Ensure that there is a fully documented design and manufacture process
- Each and every quality-limiting step is identified

Controls
- Ensure that uncontrolled, or worse unsuspected, defects do not find their way into flight hardware.
The Quality Control task

• Purpose: provide measurements that demonstrate the requirements of the QA procedures are being met.

• For example:
  - a specification on weight/unit area of reinforcements is a QA document
  - the actual measurements done to demonstrate compliance with the specification are QC
  - the regular calibration of the measurement tools used in QC falls under QA
The cornerstone of this QA/QC activity is the concept of **traceability**.

We want to know:

- the loading/operating envelope assumptions
  
- the methods and results of stressing
  
- materials of construction, their allowable properties and batch numbers *etc.*
  
- the names of the people who laid up the part or who operated the autoclave on the afternoon that the part was moulded, *etc.*
Traceability

- The traceability information gives a good feeling of comfort but of itself has rather less impact on reliability than might be imagined.

- The most likely causes of mechanical failure are operating outside the design envelope and poor maintenance, neither of which will be eliminated by the paper trail.

- If a failed part is well maintained and was operated within the design envelope then either the paperwork is in error with regard to the part quality, or the real quality issues are not being controlled.
Traceability

• The rigour of a full traceability approach is of very significant value in providing a disciplined approach to the design and manufacture process

• BUT there is a very real danger in the belief that it is the paper trail that ensures safety.

• Generating the right bits of paper is far less important than rigorously analysing the design and manufacturing operations.
Manufacturing documentation

• Only manufacturing documentation will be dealt with here.

• The master document for any component will be its drawing, which sets out materials, dimensions and tolerances, surface finish, laminate composition, etc.

• It is not always a trivial matter even to discern from the drawing exactly what is required in manufacturing and the drawing does not contain any manufacturing information as such.

• So in addition to the drawings there is a whole raft of other documentation that generally falls into a particular pattern
# Methods Manual typical contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Likely contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title page</td>
<td>Title, document number, issue, date and full sign off</td>
</tr>
<tr>
<td>List of amendments at current issue</td>
<td>Any changes since previous issue can be logged here</td>
</tr>
<tr>
<td>List of appendices</td>
<td>If appendices are used, rather than being called up as separate documents they must be listed</td>
</tr>
<tr>
<td>List of active pages</td>
<td>Can be used to track revisions to the document</td>
</tr>
<tr>
<td>List of revisions</td>
<td>Can be used to track revisions to the document</td>
</tr>
<tr>
<td>Scope</td>
<td>What sorts of parts are covered, e.g. leading edge wing panels, etc.</td>
</tr>
<tr>
<td>Limitations</td>
<td>If document only applies to specific parts</td>
</tr>
<tr>
<td>Applicable documents/references</td>
<td>e.g. process specifications</td>
</tr>
<tr>
<td>Health and Safety</td>
<td>Basic H&amp;S statement is commonly included</td>
</tr>
<tr>
<td>Quality Assurance</td>
<td>Basic QA philosophy statement</td>
</tr>
<tr>
<td>Manufacture, mould tools</td>
<td>Environment control limits / cleanliness</td>
</tr>
<tr>
<td>Manufacture, environment</td>
<td>Inspection, preparation, handling etc</td>
</tr>
<tr>
<td>Section</td>
<td>Likely contents</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Manufacture, honeycomb</td>
<td>Conditioning, reinforcing, trimming, filling etc</td>
</tr>
<tr>
<td>Manufacture, prepreg handling</td>
<td>Handling, cutting, labelling, storage, etc</td>
</tr>
<tr>
<td>Manufacture, part lay-up</td>
<td>Lay-up, consolidation, trimming, process aids, fibre alignment honeycomb lay-up, film adhesive, test specimens etc,</td>
</tr>
<tr>
<td>Manufacture, preparation for cure</td>
<td>Application of breather, bleeder and vacuum bag, vacuum leak checking etc</td>
</tr>
<tr>
<td>Manufacture, cure</td>
<td>Autoclave procedures and cure profile</td>
</tr>
<tr>
<td>Drill and trim</td>
<td>Standards, speeds and feeds, etc (or appendix)</td>
</tr>
<tr>
<td>Inspection</td>
<td>Procedures, part marking, acceptance criteria</td>
</tr>
<tr>
<td>Testing</td>
<td>NDT requirements</td>
</tr>
<tr>
<td>Rework / repair *</td>
<td>Review procedures for non compliant parts and rework / repair standards</td>
</tr>
<tr>
<td>Process verification</td>
<td>Handling of in-process testpieces</td>
</tr>
<tr>
<td>Painting</td>
<td>Methods and procedures</td>
</tr>
<tr>
<td>Appendices</td>
<td>Can use appendices or call up other documents</td>
</tr>
</tbody>
</table>
## Defects

<table>
<thead>
<tr>
<th>Defects</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defects</td>
<td>Dimensional and geometrical out of tolerance issues (most common defects)</td>
</tr>
<tr>
<td></td>
<td>Defects generated in the trimming of components to size and in drilling all the holes</td>
</tr>
<tr>
<td></td>
<td>Other defects of appearance or quality</td>
</tr>
</tbody>
</table>

In addition, errors in the process control or the paperwork will lead to parts being deemed non-compliant in an aerospace setting.
Defect assessment

• Non dimensional defects will be assessed against a set of part Quality Standards known as Acceptance Criteria.

• There may be two levels set:
  - “Accept as is” or fully compliant
  - “Correctable Limit”

• If the parts are not fully compliant a decision must be made as to whether the part can be reworked to bring it inside the quality standards.

• Rework implies that the part defects fall within the correctable limits, and after rework parts are fully compliant.
## Other defects

### Non-dimensional errors in Acceptance Criteria

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface scratches, depressions and dents</td>
<td>FOD/Material inclusions</td>
</tr>
<tr>
<td>Bridging and wrinkles</td>
<td>Honeycomb defects such as dimpling, core movement, splice gaps &amp; separated nodes</td>
</tr>
<tr>
<td>Delaminations and voids</td>
<td>Assembly warpage and faying (bolting or bonding) surface flatness</td>
</tr>
<tr>
<td>Surface resin richness</td>
<td>Very visible weave pattern with woven reinforcements due to a shortage of resin between the tows</td>
</tr>
</tbody>
</table>
Other defects

• The acceptable and correctable limits varied from component to component, and even from area to area within one part.

• Acceptance Criteria would be expected to be much tighter for flight critical parts than for simple fairings and similar parts.

• Some Acceptance Criteria are set very tight, but it has to be accepted that the production of composite parts often produces cosmetically poor parts, even if they are structurally sound.
Other defects

- This picture shows a part of the side frame for the BMWi3 life cell.

- Significant areas of wavy fibre is noticed which is unacceptable for aerospace application.

- However, parts with this defect pass the crash-test and other structural requirements – so are defined as within the Acceptance Criteria for this application.
Defect Assessment

- Repair can be applied on part quality falls outside the correctable limit. Some similar repairs may be applicable to in-service damage.

- The repair scheme must be subjected to a rigorous design, stress and manufacturing analysis process.

- It is usual for the repair schemes to be brought together into a company repair manual, which may also be made available to end users for in-service use.
Defect Assessment

Ideally

- Identify the root cause of each non-conformance
- Eliminate the problem

Practically

- An expensive approach when only making small numbers of any particular component
- Need to take a view on whether we can live with a particular level of non-conformant parts or must tackle the causes.

Requires

Good understanding of the costs of non-conformities:
- In terms of MRB activity, rework, repair and scrap
- Through inefficiencies as a result of the distortion to production flow
Defect Assessment

One approach used in some aerospace companies when there is uncertainty about structural adequacy:

• Quarantine non-conformant parts until a significant number has been reached

• Perform the test when the value of potentially releasing the parts is greater than the cost of test

• If the test is passed the quality standard can be updated to make this condition acceptable

• Previously non-conformant parts can be released alongside future parts with that feature.
Conclusions

• Currently the design and manufacturing processes used with composites do not achieve 100% right first time

• A structure of MRB, rework, repair procedures and concession processes is then required, which add significant costs to the manufacture of composite parts

• Good record keeping is essential to be able to identify and track those costs so as to be able to generate the business cases to support the research and development needed to improve design and manufacturing processes and avoid the costs in future.

• MRB should be used to drive improvements rather than just manage limitations in as-moulded quality
Page 2:
Learners will be able to:

- Understand the need for formal quality processes
- Distinguish between rework and repair procedures
- Demonstrate a basic understanding of how a quality system operates for composites

Page 3:
Acceptance criteria are the standards that are applied as part of the quality assessment carried out after moulding to determine whether a part is fit for use.
These could include a range of dimensional and other quality parameters

Page 4:
An action of correction to correct nonconformities that bring a product back into 100% conformance to the applicable requirements by application of the normal manufacturing processes.

Examples could be to open up a drilled hole that has been drilled undersize, trim back an edge that has been cut oversize or touch up a paint finish.

Rework does not generally generate a requirement to inform the customer or generate a concession action

Page 5:
An action of correction that renders the nonconforming product to a status that it fulfils the intended use or purpose but may not meet the specified requirements.

An action of correction to make a product functional, but not 100% conforming to requirements.

Examples might be to patch a damaged laminate surface, inject resin into a delamination or drill out a misplaced hole and fit a larger fastener.

A need to repair will generate a requirement to inform the customer of the defect and generate a concession action

Page 6:
A concession is the permission to use or release a product that does not conform to the specified requirements – i.e. an admission of failure!

Note: A concession is generally limited to the delivery of a specific item or items affected by a specific non-conformance rather than a complete class of products.

It is important to be clear that as a supplier of composite parts you can request a concession - but not demand one, and that a constant stream of such requests will not be endearing you to your customer as a supplier!
Page 7:
Concessions can be sought to repair the non-compliant part or to “Use as is”

Use as is may be appropriate if the defect can be demonstrated not to lead to the potential for premature failure of a component or structure – an example might be a honeycomb sandwich panel which is over thickness in the cored region.

If repair is required it must be done to a formally released and controlled repair procedure

Page 8:
There needs to be a formal process in place that takes control of the disposition of non-conforming parts this is often referred to as a Materials Review Board or MRB.

The MRB usually comprises a cross section of functions such as Design, Stress, M&P and Quality.

The MRB will make decisions on what to do with nonconforming material, such as relifing out-of-life prepreg; or nonconforming product, such as Use-as-is, Rework, Repair, or Scrap.

The MRB may also recommend redesigning the part or manufacturing process.

Page 9:
MRB activity sits between Quality and Engineering functions and both will be heavily involved

We need to have a look at the Quality Assurance / Quality Control functions to see how things fit together.

Page 10:
The word “Quality” can be used in two distinct senses -

- as a measure of perfection

- as a system for demonstrating that components have been made in an acceptable manner and can be documented to be acceptable.

The only useful definition of quality is whether a component meets specifications or not.

A component that only just meets specifications is deemed to have the same quality as a part of perfect exhibition standard.

The design and development process has the greatest effect on quality defined in this way.

Page 11:
The function of a quality system is to demonstrate to the customer or regulatory authority that the products delivered are fit for purpose.

The level of detail required to do this will depend largely on the function of the part, and critically on the consequences of product failure.

The Quality Assurance task is to ensure that there is a fully documented design and manufacture process; and that each and every quality-limiting step is identified.
Controls will then put into place to ensure that uncontrolled, or worse unsuspected, defects do not find their way into flight hardware.

Page 12:
The Quality Control task is to provide measurements that demonstrate that the requirements of the Quality Assurance procedures are being met.

For example:

- a specification on weight/unit area of reinforcements is a QA document,
- the actual measurements done to demonstrate compliance with the specification are QC,
- the regular calibration of the measurement tools used in QC falls under QA.

Page 13:
The cornerstone of this QA/QC activity is the concept of traceability.

We want to know:

- the loading/operating envelope assumptions,
- the methods and results of stressing,
- materials of construction, their allowable properties and batch numbers etc
- the names of the people who laid up the part or who operated the autoclave on the afternoon that the part was moulded, etc, etc.

Page 14:
The traceability information gives a good feeling of comfort but of itself has rather less impact on reliability than might be imagined.

The most likely causes of mechanical failure are operating outside the design envelope and poor maintenance, neither of which will be eliminated by the paper trail.

If a failed part is well maintained and was operated within the design envelope then either the paperwork is in error with regard to the part quality, or the real quality issues are not being controlled.

Page 15:
The rigour of a full traceability approach is of very significant value in providing a disciplined approach to the design and manufacture process,

**BUT** there is a very real danger in the belief that it is the paper trail that ensures safety.

Generating the right bits of paper is far less important than rigorously analysing the design and manufacturing operations.

Page 16:
This only relates to manufacturing documentation, the documentation of the design, stress analysis and validation processes will not be dealt with here.
The master document for any component will be its drawing, which sets out materials, dimensions and tolerances, surface finish, laminate composition, etc. It is not always a trivial matter even to discern from the drawing exactly what is required in manufacturing and the drawing does not contain any manufacturing information as such.

So in addition to the drawings there is a whole raft of other documentation that generally falls into a particular pattern

Page 20:
By far the most common defects in as-moulded composite parts made in an autoclave are dimensional and geometrical out of tolerance issues.

A very large number of defects are also generated in the trimming of components to size and in drilling all the holes that aerospace joint design practices seem to insist on.

Other defects of appearance or quality are, however, commonplace and need to be considered. In addition, errors in the process control or the paperwork will lead to parts being deemed non-compliant in an aerospace setting.

Page 21:
Non dimensional defects will be assessed against a set of part Quality Standards known as Acceptance Criteria. There may be two levels set.

The first would be the “Accept as is” or fully compliant limit, the second would be the “Correctable Limit”.

If the parts are not fully compliant a decision must be made as to whether the part can be reworked to bring it inside the quality standards. Rework implies that the part defects fall within the correctable limits, and after rework parts are fully compliant. The customer need not be informed of the rework applied.

Page 22:
The non-dimensional errors that would be included in Acceptance Criteria might be:

- Surface scratches, depressions and dents
- Bridging and wrinkles
- Delaminations and voids
- Surface resin richness/ resin ridges or resin dryness / very visible weave pattern with woven reinforcements due to a shortage of resin between the tows
- FOD/Material inclusions
- Honeycomb defects such as dimpling, core movement, splice gaps & separated nodes
- Assembly warpage and faying (bolting or bonding) surface flatness.

Page 23:
The acceptable and correctable limits will change from component to component, and even from area to area within one part depending on the local stresses and the consequences of failure.
Acceptance Criteria would be expected to be much tighter for flight critical parts than for simple fairings and similar parts.

Some Acceptance Criteria are set very tight, but it has to be accepted that the production of composite parts often produces cosmetically poor parts, even if they are structurally sound.

Page 24:
This is a picture of part of the side frame for the BMWi3 life cell. It shows significant areas of wavy fibre that would be expected to be unacceptable in an aerospace part.

However, parts with this defect pass the crash-test and other structural requirements – so are defined as within the Acceptance Criteria for this application.

Page 25:
If the part quality falls outside the correctable limit it may still be possible to generate a repair scheme, which can be applied to bring the part into an acceptable state. Some similar repairs may be applicable to in-service damage.

The repair scheme must be subjected to a rigorous design, stress and manufacturing analysis process to demonstrate that it is structurally sound and fit for purpose.

It is usual for the repair schemes to be brought together into a company repair manual, which may also be made available to end users for in-service use.

Page 26:
In an ideal world we might aim to investigate each non-conformance with a view to identifying the root cause and eliminating the problem.

In practice this can be a very expensive approach when we are only making small numbers of any particular component, so we need to take a view on whether we can live with a particular level of non-conformant parts or must tackle the causes.

This requires us to have a good understanding of the costs of non-conformities - both directly in terms of MRB activity, rework, repair and scrap and indirectly through inefficiencies as a result of the distortion to production flow

Page 27:
One approach that has been taken in some aerospace companies when there is uncertainty about structural adequacy (for example due to an occasional and localised voidage which is out of spec) is to simply quarantine non-conformant parts until a significant number has been reached - when the value of potentially releasing the parts is greater than the cost of testing one of them to destruction a structural test can be carried out.

If the test is passed the quality standard can be updated to make this condition acceptable and all the previously non-conformant parts can be released alongside future parts with that feature.
Currently the design and manufacturing processes used with composites do not achieve 100% right first time, we therefore need to have in place a structure of MRB, rework, repair procedures and concession processes that can add significant costs to the manufacture of composite parts.

Good record keeping is essential to be able to identify and track those costs so as to be able to generate the business cases to support the research and development needed to improve design and manufacturing processes and avoid the costs in future.

MRB should be used to drive improvements rather than just manage limitations in as-moulded quality.
Effects of defects

Kevin Potter
Effects of Defects - Learning Objectives

Learners will be able to:

• Demonstrate an appreciation of the impacts of defects in composite mouldings on structural performance
• Understand the importance of certification processes and testing in the development of composite structures
• Distinguish between design features and defects
• Demonstrate an appreciation of defect mitigation strategies
The most safety critical part of the design process:

Components and structures

Adequate lifetime under service load

No premature failure

To achieve

Processes and procedures to ensure design and manufacturing practices deliver a safe structure.
First principles 2

Processes and procedures to ensure design and manufacturing practices deliver a safe structure.

Framework used to certify:

- Appropriate tools have been used in design and stress analysis
- Appropriate manufacturing procedures have been adopted to ensure that the design intent has been properly achieve
- Any ambiguity or lack of clarity can have significant and very negative consequences
The pyramid of testing is at the heart of aircraft certification.

This approach allows us to:

- Build up from a knowledge of how simple flat laminates behave via a step by step process.
- Increasing the complexity and degree of "realism" at each test level.
- Reducing the number of tests to deliver a complete philosophy of validation and verification by a combination of test and analysis.
Design allowables: a statistically sound description of the mechanical performance of a specific grade and lay-up of a composite material laminate when subjected to a predetermined set of test procedures in simple loading modes.

### Design allowables

- Carried out on materials processed as they would be in industry and which have passed NDE checks
- Generally include the impacts of temperature and humidity on the measured properties
- Have been carried out in accredited laboratories using well defined and specified test procedures
- Have been measured on multiple batches of material to ensure properties are stable over time
“Allowables” testing 2

- Should be representative of acceptable production quality rather than of “Perfect Quality”

- Not all possible aspects of mechanical performance are likely to have been captured in “Allowables” testing:
  - some aspects may not have adequate test standards – for example for aspects of wear and abrasion
  - some may sensitive to the lay-up and other conditions – for example bolt bearing or impact

- These aspects of performance can be captured at the next level in the Pyramid – Element tests
Element testing

Unlike “Allowables” testing which should apply generically to any and all components Element testing is starting to:

Become application specific
  • For example, there is no point doing bolt strength tests on a structure to be bonded

Reflect the structural performance
  • Generally still in a simplified way
  • For example a bolt bearing test would be carried out on a flat test piece even if the component had some curvature.

We can think of combining a number of element tests together to generate a more realistic test – this represents the Component level in the Pyramid
Component testing

• Every feature of the structure is expected to be present including:
  - thickness variations
  - complex geometry fully representative of the final structure
  - any machining required
  - often involving an assembly of components

• Component is likely to be either a section of the full structure or a sub-scale structure.

• Hard to ensure the boundary conditions properly match those of the full structure, which is required to ensure that the testing is valid
A very small number of tests would be expected to be carried out at this level:

- “Allowables”: 1000s of tests
- “Element” : 100s of tests
- “Component”: 10s of tests
- “Full Structure”: 1 test

As for the Component testing, ensuring that the test loadings properly capture the in service loadings in the multiplicity of loading cases that can be seen in service can be a significant challenge.

Image courtesy of LM Wind Power, Denmark
Pyramid of Testing 2

**Assumption**

The Allowable properties of a flat laminate adequately describe the properties of a non-flat laminate

We have captured at Allowables and Elements levels all the sources of variability that we will experience at the higher levels

That we have properly captured all the sources of in-service degradation and accommodated them as required in the design of testing procedures at Allowables, Elements, Component and Structure levels
## Manufacturing in an ideal world

<table>
<thead>
<tr>
<th>Ideally</th>
<th>In reality</th>
</tr>
</thead>
<tbody>
<tr>
<td>The reinforcement lay-up and fibre directions on the tool exactly matches that on the part drawing</td>
<td>The reinforcement fibre directions on the drawing are generally not even clearly defined at all points on a complex surface</td>
</tr>
<tr>
<td>The as-cured part geometry exactly matches the part drawing</td>
<td>The as-cured part geometry will not perfectly match the part drawing</td>
</tr>
<tr>
<td>Variability is no greater than that found in laminates used for Allowables testing</td>
<td>Variability exists in all materials and processes and can be very significant</td>
</tr>
<tr>
<td>All fibres are locally straight without in-plane or out-of-plane distortions greater than those found in laminates used for Allowables testing</td>
<td>All fibres will be subject to in-plane or out-of-plane distortions</td>
</tr>
<tr>
<td>Voidage or Residual stresses are no greater than that found in laminates used for Allowables testing</td>
<td>Residual stresses are always present</td>
</tr>
<tr>
<td>Voidage can be significant</td>
<td></td>
</tr>
</tbody>
</table>

© University of Bristol 2018
Reality check 1

Parts with complex geometry are very difficult to generate a well defined set of fibre paths for – and it is impossible unless the manufacturing route is central to the design process.

In-plane fibre waviness will be caused by taking the fibres around a corner, or by draping to a doubly curved surface.

Out-of-plane waviness will be caused by ply drops or gaps and overlaps in AFP.
Reality check 2

• All the features shown will impact negatively on performance – BUT they are not defects as they arise directly from design decisions and CANNOT be “Fixed” by better manufacture

• Allowable properties as measured on flat laminates in simple stress states have almost no power to predict the properties of more complex real components

• Higher levels of the Pyramid of Testing required

• Any attempt to go directly from Allowables properties to a prediction of the responses of the Full Structure is fraught with difficulties
Pyramid of Testing is not a perfect vehicle for establishing the properties of composite structures:

• Allowables and Elements do not necessarily capture all the sources of variability in real components

• Component and Full Structure tests are not carried out in large enough numbers

• There is currently no realistic alternative to the Pyramid of Testing approach
What tests are needed 1

• The most critical question: what loads will be applied?

• There will generally be multiple load cases – any missing can lead to seriously overestimate the strength and reliability of structures.

• Requirements capture, right at the very start of the product design process is absolutely critical to the development of a safe and reliable structure.

• We will need to understand all the ways that our structure could fail.

• We are less likely to want to test failure modes with high Reserve Factors in the stress analysis than if the Reserve Factors are low.
What tests are needed 2

For example, a wing spar has to carry bending and torsional loads from wing bending, it has to:

- Pick up local loads from various mechanisms and systems
- React internal pressures in the wing due to fuel surge in an aborted take-off and over pressurisation during refuelling.

- Most of these loading cases would primarily drive stresses into fibre-dominated failure modes.
- The internal pressure cases would tend to lead to opening up of the corners of the spar, inducing a through thickness tensile stress in the corners.
- This is a matrix-dominated failure mode and likely to be more variable and sensitive to defects. A specific test of this failure mode might well be required even if the Reserve Factors were relatively high, to allow for the defect sensitivity.
Factors that can impact performance

- Deliberately designed-in features – including Residual stresses due to elevated T cure
- Incidentally designed in features
- Defects caused by a lack of control or understanding in the manufacturing processes
- Cosmetic issues – how can they impact on performance
Features arising from design decisions

- Residual stresses
- Gaps between plies or tape courses in AFP
- Fibre waviness in the reinforcement as delivered
- Ply drops
- Additional fibre waviness
- Consolidation induced bridging or fibre wrinkling

This level of fibre waviness/tow buckling was a consequence of local tow steering in AFP
Defects arising in Manufacture

Defects, arising during manufacture

- voidage
- dry spots and other wet-out issues
- delaminations
- bridging or fibre wrinkling due to faulty lay-up
- fibre waviness

Other defects will not be considered

- Inclusions
- ply contamination
- errors in ply count
- lay-up order or ply orientation
- honeycomb core collapse and other core related defects
- curing or vacuum errors or bag burst

© University of Bristol 2018
Impacts of geometry

In general terms:

• Complex geometry are more likely to contain the sort of features and defects.

• Complex geometry are likely to carry more complex stress fields, and it is more difficult to assess the quality through NDT.

**Take-home message 1.**

In seeking to eliminate strength reductions due to defects, at least as much emphasis needs to be placed on the design as on the manufacturing activity.
Impacts of residual stress and distortions

• All matrix resins shrink during the cure cycle due to a mixture of cure shrinkage and thermal shrinkage of the resin when cured at elevated temperature.

• For a laminate made from a 0.90 lay-up of an epoxy matrix UD prepreg cured at 180°C the transverse strain in each ply from this source can reach up to about 50MPa (≈0.5% strain) a significant proportion of the transverse ply strength.

• As parts become thicker or more geometrically complex (including geometrical complexity due to wrinkle defects) the importance of residual stresses increases and can become a critical issue.
Impacts of residual stress and distortions

• Shown here is a section through a thick block of orthogonally 3D woven composite illuminated by UV light.

• The sample had not been subjected to any external loads post manufacture.

• The bright lines are cracks which have been highlighted using a fluorescent dye penetrant.

• No errors were made in the manufacture of this part, the cracks are clearly a problem they essentially arise from the materials selection process.
Impacts of voidage and delaminations

- Voidage/porosity potentially leads to significant loss of those properties which have a major contribution from the resin.

- These include through-thickness strength, out-of-plane shear strength and compressive strength in 2D reinforced laminated composites.

- The property loss caused by voidage is not a simple matter of looking at the volume percentage of voids, as the distribution of voids can have a very great impact.

- The general consensus is that mechanical properties degrade as voidage increases, initially that reduction is slow, a few % drop in interlaminar shear strength for each % increase in voidage up to perhaps 4 or 5% voidage.
Impacts of voidage and delaminations

- Up to about 4-5% we generally see a more or less uniform distribution of small voids of roughly circular cross-section.
- As voidage increases beyond about 5% the voids tend to become more localised at ply interfaces, to become of more irregular cross-sections, and to have a more negative impact on strength.

In an aerospace environment we would probably set a maximum of 2% voidage as a general acceptance level.
Impacts of voidage and delaminations

Measurements of through-thickness strength by loading a corner piece as drawn here showed that a reduction in strength of more than 50% could be experienced due to a global void content of less than 0.5%.

In this case the general laminate quality was actually very good with almost no voidage being visible, apart from a series of small voids in a localised patch at a single ply interface. This series of voids coalesced and formed a delamination under load, leading to a very significant loss of strength.
Impact of misaligned reinforcements

This is a complex area and we need to start from first principles and work up from there. The first question is really “what do we mean by misaligned?”. For a flat laminate we can be completely unambiguous about the intended and actual fibre direction datum and thus about the accuracy of alignment.

For the components below there is no intuitively obvious fibre direction datum and we have to have local frames of reference against which we can define the correct fibre direction and thus give an indication of fibre misalignment.
Impact of misaligned reinforcements

• Fibre misalignment can be defined as a deviation between the nominal and actual fibre direction.

• This misalignment can be in-plane or a combination of out-of-plane and in-plane.

• There is no universally accepted terminology to describe this misalignment, but for the sake of clarity in-plane misalignment will be described as fibre waviness and out-of-plane misalignment as fibre wrinkling.

• Assuming that we can define an adequate fibre direction datum at any point it is next necessary to look at the mechanisms by which fibre misalignment can be generated.

• As before it is useful to consider both unavoidable features and avoidable defects separately.
## Impact of misaligned reinforcements

<table>
<thead>
<tr>
<th>Unavoidable features in continuous fibre composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐ As delivered dry UD tows may not be entirely straight</td>
</tr>
<tr>
<td>☐ UD prepreg usually contains in-plane wavy fibres</td>
</tr>
<tr>
<td>☐ Woven cloth always contains crimped (i.e. wrinkled fibres)</td>
</tr>
<tr>
<td>☐ Non-crimped fabrics normally exhibit some distortion of the tows due to the stitch or binder yarn fibres</td>
</tr>
<tr>
<td>☐ When forming any reinforcement around an out-of-plane radius additional in-plane waviness will be generated</td>
</tr>
<tr>
<td>☐ When forming any reinforcement around an in-plane radius additional waviness or wrinkling will be generated, e.g. Tow steering in AFP or woven cloth drape</td>
</tr>
<tr>
<td>☐ Ply drops will generate a localised fibre wrinkling</td>
</tr>
</tbody>
</table>
Impact of misaligned reinforcements

Avoidable defects in continuous fibre composites

- Lay-up errors
- Fibre wash in RTM
- Bridging in internal radii
- Consolidation defects on external radii
- Forming errors
- Mould closure effects
Unavoidable factors

• The key to understanding many of the unavoidable features is to examine the nature of the tows of fibre.

• A tow consists of many thousands of very thin (typically <10µm) fibres, which may be held lightly together with a small amount of size or binder, or be completely dry.

• To a first approximation the fibres individually have no resistance to bending or buckling under load.

• Bending the tows will tend to buckle the fibres and generate misalignment, which may not be fully recovered when the tow as a whole is straightened out.

• Any snagging of fibres in the tow during processing produces similar effects and handling dry fibre tows needs to be done with great care to avoid introducing defects.
Unavoidable factors

• As delivered UD tows have usually been wound onto a small (<100mm) diameter tube, leading to the sort of localised fibre misalignment noted above.

• Any localised misalignment introduced at this stage will tend to carry through to the next process step, whether that is the manufacture of UD prepreg or the weaving of a cloth.

In UD prepreg we see both generalised waviness (not generally assumed to be a defect) and also specific localised defects
Unavoidable factors

• The level of generalised fibre waviness for the prepreg shown is equivalent to what would be expected due to the prepreg being wound on to a 300mm D drum for delivery – leading to the compressive collapse of the fibres on the inner radius.

• The level of generalised, as delivered, misalignment in the 0.25mm thick prepreg shown is a maximum of about 3.8°, with a wavelength of a few mm.

• When this prepreg is laid up on to a curved surface the inner surface is once more put under a compressive stress and this has the effect of increasing the amplitude of the misalignment without significantly impacting on the wavelength.
Unavoidable factors

The misalignment can be visualised by polishing sections through corner regions as the reflectivity of the areas where the fibres are in the plane of the section is very different to that of the regions of more misaligned fibre.

Each of the 8 plies shows alternating light and dark regions which indicate the changing fibre direction due to the waviness in the fibres for this laminate moulded on a 10mm internal radius tool.
Unavoidable factors

If the tows are curved in the plane, as they might be in a tow steered laminate a greater impact on fibre alignment will be expected as the tow width is generally 10-20x the ply thickness and can be much more if the tows have been spread.

- The fibres in this tow-placed laminate show up as bright lines and the resin as dark areas.

- The inside surface of each tow can be seen to be very wavy, where the fibres in the tow have buckled to give both in-plane and out-of-plane misalignment.
Unavoidable factors

• For woven cloths and braids there will always be some out of plane misalignment due to the weaving process.

• This misalignment is innate to the material and is a feature rather than a defect.

• Woven cloth is principally used where there is a need to match the reinforcement to complex geometrical features by the process of distorting the cloth known as drape.

• The drape process will also generate curved fibre paths so the impact on tow level misalignment will also be seen in draped woven cloths where fibre paths are curved.
Unavoidable factors

Tows rotate out of plane to shed the excess length, under the cure pressure a local wrinkle will form.

In regions of high, but uniform, shear the tows remain flat and unwrinkled.
Unavoidable factors

- Ply drops will generate localised fibre wrinkling
- This can generate significant fibre misalignment and initiate delaminations under in-plane tensile loading
Unavoidable factors

• A typical laminate is made from tows of fibre that are not ideally straight, these are then transformed into semi-finished products such as cloths and prepregs which contain higher levels of misalignment and then converted into products which contain additional levels of local misalignment due to the part geometry and forming routes.

• These misalignments are largely unavoidable; as determined by the particular material and part geometry used.

• While they must be accommodated in test and analysis activities they cannot be assumed to be defects as they are the direct result of decisions made in the design process.
Avoidable defects

• The distinctions between features and defects are not always entirely clear, but in general defects involve a localisation of the misalignment and a deviation from the ideal as-designed geometry or internal laminate structure.

• When we lay a sheet of UD prepreg onto a curved surface a mismatch between the prepreg and the surface become apparent as the area that is in contact with the tool is increased.

• We can mimic this by laying down a ply with a very slight initial misalignment and look at how that misalignment propagates as the lay-up proceeds
Avoidable defects

If we lay down the ply so that the initially deviated (at the limit of acceptable practice) right hand edge is laid down straight an increasing level of misalignment is seen as lay-up proceeds.
Avoidable defects

- The level of fibre waviness that can be generated by an initial $2^\circ$ offset is shown here.

- A region of gross misalignment is formed (a $40^\circ$ fibre misalignment) from a minor lay-up misalignment of only $2^\circ$, which is inside lay-up accuracy standards.

- This is one reason that lay-up of UD reinforcements on curved surfaces is so difficult.
Avoidable defects

Large scale misalignments may also be formed as reinforcements are pressed into tools, especially by mould closure forces in RTM components, or by the way in which preforms are manufactured for RTM moulding.

Gross misalignment driven by mould loading forces

Out of plane waviness due to a poorly controlled preforming process

Out of plane wrinkling in the corner of an autoclave moulded part – probably driven by the action of the autoclave pressure
Impact of misalignment defects on strength

• It must be noted that all of the numerical values given here for the effects of misalignment on strength are related to the specific materials, lay-up and defects under consideration.

• While they may be typical for these sorts of materials and defects they cannot be used to predict the performance of other materials or processes.

• They are perhaps better used to identify the sorts of defects we must aim to avoid rather than the level of strength knockdown that may have to be tolerated.
Impact of misalignment defects on strength

Defects arising as shown here have been examined as follows. An 8 ply 2mm thick laminate was made up with 4 plies undeformed and 4 plies deformed as shown.

These samples were then tested in flexure, with the defect on both tensile and compressive surfaces.

The increase in thickness in the misoriented region was taken as a marker for the severity of the waviness/wrinkling (generally increasing from point 1 to 5 in) and plotted against the reduction in baseline strength for a nominally ideal laminate.
Impact of misalignment defects on strength

- The tolerance on the laminate thickness for this sort of laminate is likely to be ±5%.
- In principle a part with a more severe wrinkle could be identified and eliminated from the population through dimensional inspection.
- However, even very small thickness increases can be associated with significant losses of strength, making inspection more problematical.
Impact of misalignment defects on strength

• These L sections were cut from production parts and loaded as shown here to measure the through-thickness tensile strength.

• There were three distinct sets of results in this testing.

• The first were “good” samples where there was no localised voidage or deviation from the expected ply trajectory around the corner. These had strengths over 50MPa and failed by a single line of failure at a position close to the peak transverse tensile stress.

• The second group exhibited wrinkled plies and first failure occurred at the position of the wrinkle and remote from the position of peak transverse tensile stress as shown here.
Impact of misalignment defects on strength

- In addition to the change in the point at which failure initiates the failure propagation is also different from the baseline case.
- The failure propagates by multiple delaminations initiating and growing for short distances before another delamination is initiated at a different ply interface.
- There is a general decrease in strength as the misalignment increases, up to a 50% reduction in through-thickness strength above a 20° misalignment.
- For the third set of results, a similar or even greater level of strength reduction could be produced by the presence of voids tending to concentrate at one interface between plies even when the fibre alignment was ideal.
Impact of misalignment defects on strength

Goodman Diagram - Effect of mean stress on stress amplitude

Impact on Fatigue Loading of corners at 10,000 cycles
Cosmetic issues – uneven surfaces

Surface finish

• This RTMed component has a patchy surface finish, some areas are smooth and shiny (green) and some are rough (red).

• These sorts of issues would not be expected to significantly degrade the laminate strength, but could have an impact on the strength of a bonded joint.

• More generally an uneven surface can have an impact on strength in bolted flanges where the action of the bolts on uneven surfaces can generate interlaminar shear stresses and potentially delaminations.

These surfaces would need to be made smooth to avoid problems in bolted joints

© University of Bristol 2018
## Minimising the impact of defects

### Designing out “defects”

There are many features that can impact on mechanical performance that arise directly or indirectly from the design process.

As an example, a decision to use a 5mm internal corner radius on a tool to make a 5mm thick moulding would guarantee a defective part as the nominal geometry, whilst geometrically feasible, is simply not practically possible.

As the thickness drops in proportion to the radius a good quality will steadily become easier to achieve, however a 5mm internal radius is still quite small in absolute terms and rather difficult to lay prepreg into accurately.

To get a good reproducible quality by hand lay-up of unidirectional prepreg a minimum corner radius of perhaps 10mm would be a better design with regard to manufacturability and moulded quality.
Designing out "defects"

The larger corner radius will be less likely to be bridged, less likely to be seriously voided and will definitely have lower levels of fibre waviness induced by the curvature of the prepreg.

A part of the design process would be the selection of the specific grade of prepreg to be used. Selecting a heavier grade of prepreg would reduce the number of plies and thus positively impact on labour costs.

The level of fibre waviness induced by the curvature would be increased, and the difficulty of achieving a high quality lay-up may also be increased compared to that for the thinner prepreg.

Equally, for a part that has significant double curvature and requires the use of an extensively draped reinforcement the selection in the design process of a woven reinforcement with a wide tow rather than a narrow tow will increase the level of fibre wrinkling as those tows become more distorted in the drape process.
# Designing out defects

**Designing out “defects”**

For any geometry that can be draped with a single piece of woven cloth there are generally multiple pathways by which that drape can be achieved.

Even though the initial orientation of the cloth to the tool may be identical, each pathway to the final draped geometry will generate a different set of local fibre orientations and characteristic features and “defects”.

Different pathways will also require more or less skill from the operator, with some pathways being much more likely than others to generate defects.

A detailed examination of drape processes and the characteristics of different materials can be complicated, but in view of the potential impacts on quality and performance these details of lay-up and manufacture must form part of the design process.
Controlling out defects

Assuming that the design process has output a design that meets the sort of requirements noted above and that the impacts of those design features on mechanical performance have been properly accounted for in stress analysis the manufacturing task is “simply” to ensure that the design intent is carried through into production.

Take-Home message 2
There is a rather grey area between design and manufacture in much industrial practice, and the proper handover from design to manufacture is of paramount importance.
Controlling out defects

Generating unambiguous manufacturing instruction sets and validating the reliability and reproducibility of these in a production environment is a critical part of the product development process.

A logical design and manufacture cycle might position this activity as the final element of the design phase.

The manufacturing role would then be simply to implement those instruction sets with suitable inspection and control steps.

In this view of the design and development process, accommodating materials variability falls into the design area and accommodating process variability falls into the manufacturing area.
Controlling out defects

It is more common in an industrial setting to hand over from a design to a manufacturing lead prior to the generation of unambiguous manufacturing instruction sets, so that the responsibility for all aspects of quality, process control and variability can appear to fall into the manufacturing area.

The problem with this is that the unambiguous manufacturing instruction sets that are generated may not then be checked against all the details of the design intent.

The phrase “unambiguous manufacturing instruction sets” has been used repeatedly here. There can be no apologies for this - unless ambiguity is eliminated and validated processes are used throughout, the probability of the manufacturing process drifting away from the design intent and into a lack of control is unacceptably high.
Controlling out defects

• Probably the most critical (and often most poorly done) step in the whole product development cycle is the transfer between design and manufacturing responsibility.

• Ideally the transfer is gradual; as the details of the design are clarified and tested against materials and process capabilities and variability those details can move across into the manufacturing arena – until transfer is complete with a reliable production system in place.

• The steps at which control is required will emerge during the design process, during the process of generating unambiguous manufacturing instruction sets, during the manufacture of pre-production prototypes and in the manufacture of early production models.
Controlling out defects

It is good practice to capture quality information relating to both product variability and defects in a well structured and searchable database, from the very start of the transfer from design into production.

**Take-home message 3**

Design has the information on regions of importance from a structural viewpoint, and manufacture has the information on materials and process capability and regions of potential deviations from ideal manufacture.

Only by combining the two sorts of knowledge can the right controls be put in place.
Controlling out defects

There is a tendency to assume that going from manual lay-up to automated processes such as AFP will solve all the problems.

The rippled and wavy fibres shown here from an AFP lay-up will become significant defects as heat and pressure are applied to consolidate and cure.
Features vs Defects – a reassessment

We noted earlier that we need to clearly distinguish between features and defects, however changes in technology can change that boundary.

For example it has been shown that the typical ply drop stress concentration can be largely reduced or effectively eliminated by scarfing the ply rather than simply cutting through it.

A laminate with conventional ply drops develops delaminations well below the fibre strain to failure. With scarfed ply drops this brush failure mode develops at a much higher strain in the fibre.
Features vs Defects – a reassessment

- Taking fibrous reinforcements around a radius either in or out of plane will generate fibre waviness and/or wrinkles.
- This is not strictly true if the deformation is generated by shearing the reinforcement rather than bending it.
- A research machine has been developed that can apply this shear deformation to a strip of dry or prepregged reinforcement up to 100mm wide.
- If this approach is used to steer the reinforcement across a surface then the reinforcement remains substantially free of wrinkled fibres at a radius of curvature that would cause very damaging defects if it was achieved by bending the reinforcement.
Features vs Defects – a reassessment

- Ply drop terminations and reinforcement steering have been identified as two significant sources of strength reduction in composite structures.

- Recent research has demonstrated that there are potential technical solutions to avoiding both of these strength reductions by modifications to manufacturing practices and manufacturing machinery.

- Does this mean that we should now be reassessing these sources of strength reduction as defects rather than features as they are no longer unavoidable in principle?
Features vs Defects – a reassessment

Currently we would have to continue to treat these sources of strength reduction as design features rather than as manufacturing defects.

However:

• We do need to keep the distinction between features and defects under constant review as the technology develops
• When considering the importance of technology developments, or the design of research programmes in composites manufacture we need to use the potential to reduce or eliminate the impacts of sources of strength reductions as a major criterion in the assessment of the developments
• As academics we have to appreciate that until there is a COTS supply chain the research and development job is not finished
Future trends

Design of reinforcements and matrices that are less prone to/sensitive to defects

• In an ideal world the reinforcements used would be designed to be ideally suited to the manufacturing processes that are available to give robust processing.

• Current woven reinforcements are well aligned to manual lay-up processes but are not well suited to automated manufacturing processes such as stamp forming or vacuum forming.

• The principal reason for this lies in the cloth deformation mode. The single deformation mode available in woven cloth (scissoring shear) gives a fully reversible deformation mode that allows for manual handling and repositioning without major damage to the reinforcement.
Future trends

• If the fully versatile manual handling is replaced by simple mechanical forming then more deformation modes are required (c.f. sheet metal forming).

• Non Crimp fabrics can have more deformation modes (scissoring shear or transverse stretching + inter-tow shear, depending on fabric structure) as can unidirectional prepreg (transverse stretching + in-plane shear), and both perform better than conventional woven cloth in automated forming.

• However, both these reinforcements are generally made from inextensible continuous fibre tows. Extensibility needs to be incorporated into the tow to provide more deformation modes to permit forming of fully clamped sheets and open out the manufacturing options. Various options have been tried in this area and more work is needed to balance manufacturing and performance requirements.
Future trends

- Current matrices contribute to defects through cure shrinkage and high thermal expansion coefficients.

- It may well be that these properties are inherent in the chemistry used, but any improvements in these areas would be of significant benefit with regard to performance.

- Equally, the use of a single matrix at all points in the laminate is not ideal as the balance of say stiffness and fracture toughness should perhaps be different within the tow, between the tows and at ply drops and other discontinuities.

- However, the development of such complex matrices is perhaps a long-term aim and the short term targets should be to understand the current matrices to maximise process robustness.
Managing variability in materials and processing

- Studies of variability in unidirectional prepreg materials have shown that this variability can have a real impact on process reliability and on part performance.
- Other reinforcement forms may be less susceptible to variability, but the data available to support that assumption are insufficient.
- No realistic way for the average manufacturer of composite parts to limit this variability from their material suppliers.
- Some materials purchase specifications permit rather wide ranges of some properties of significant impact on manufacturing quality (such as initial warp/weft angle in woven cloth)
- Very little of value about manufacturing critical properties such as tack or drape.
Managing variability in materials and processing

- It is well worth while keeping track of the variability in incoming materials to identify any long-term trends and to trap any marginally compliant material that might cause production problems.
- The in-roll variability can be as high as the roll to roll variability making a material selection approach to narrowing the variability generally infeasible.
- The main impacts on in-process variability are probably in the lay-up stage, through issues such as tack and drape and the straightness of warp and weft in woven cloth.
- For RTM variability in the reinforcement permeability would potentially be critical – but I have never seen reinforcement permeability included in material specifications, it is essentially not controlled and could be subject to significant variability.
Managing variability in materials and processing

• Variability in the cure process seems not to be a major factor in product quality

• It is clearly preferable to have matrices with the latter characteristic

• The current status is that we are generally trying to manage the variability in materials and manufacturing processes without many of the tools needed to support this.
Managing variability in materials and processing

The history of advanced composites to date has largely been about the targeted development of material forms that focus on mechanical performance as measured on carefully selected and defect free flat laminates.

**Take-home message 4**

Mechanical performance can rapidly be degraded by deviations from the ideal composite structure arising from design decisions and manufacturing errors.

We need to rebalance material development targets to focus on improving the performance of real complex parts, and away from flat laminates.
Conclusions

Deviations from the design intent can have very significant impacts on the mechanical performance of composite structures.

In some cases what appear to be relatively minor defects can have a disproportionately strong impact.

Take-home message 5
The allowable properties as measured on flat laminates in simple stress states have almost no power to predict the properties of real components containing a range of defects.
Conclusions

• It is critically important to clearly distinguish what is in the design domain and what is in the manufacturing domain.

• Difficulties in achieving the highest manufacturing quality that arise as a result of design decisions (including choices of materials and processes) cannot be fixed in the manufacturing process. They can only be fixed in the design process.

• Understanding variability and defects is absolutely key to designing good composite components and structures.

• We’re getting better at it – but are still far from perfect.

• Constant interaction and feedback between design and manufacture is the only way to assure trouble free production and adequate in-service performance.
Hand out - Materials Variability and Materials Specifications

Page 2:
Learners will be able to:

- Demonstrate an appreciation of the impacts of defects in composite mouldings on structural performance
- Understand the importance of certification processes and testing in the development of composite structures
- Distinguish between design features and defects
- Demonstrate an appreciation of defect mitigation strategies

Page 3:
The most safety critical part of the design process is to ensure that the components and structures that are manufactured and assembled are going to have an adequate lifetime under service load conditions without premature failure.

To achieve this we put in place processes and procedures to ensure that the design and manufacturing practices will deliver a safe structure.

Page 4:
These processes and procedures are based on both theory and practical experience and form a framework that can be used to certify that:

- Appropriate tools have been used in design and stress analysis
- Appropriate manufacturing procedures have been adopted to ensure that the design intent has been properly achieved

Any ambiguity or lack of clarity can have significant and very negative consequences.

Page 5:
This approach allows us to:

- Build up from a knowledge of how simple flat laminates behave via a step by step process
- Increasing the complexity and degree of “realism” at each test level
- Reducing the number of tests to deliver a complete philosophy of validation and verification by a combination of test and analysis
Page 6:
Design allowables are a statistically sound description of the mechanical performance of a specific grade and lay-up of a composite material laminate when subjected to a predetermined set of test procedures in simple loading modes.

They will be carried out on materials processed as they would be in industry and which have passed NDE checks

They will generally include the impacts of temperature and humidity on the measured properties

They will have been carried out in accredited laboratories using well defined and specified test procedures

They will have been measured on multiple batches of material to ensure properties are stable over time

Page 7:
Should be representative of acceptable production quality rather than of “Perfect Quality”

Not all possible aspects of mechanical performance are likely to have been captured in “Allowables” testing:

- some aspects may not have adequate test standards – for example for aspects of wear and abrasion
- some may sensitive to the lay-up and other conditions – for example bolt bearing or impact

These aspects of performance can be captured at the next level in the Pyramid – Element tests

Page 8:
Unlike “Allowables” testing which should apply generically to any and all components Element testing is starting to become application specific – there is no point doing bolt strength tests on a structure to be bonded.

Element tests are starting to reflect the structural performance, but generally still in a simplified way – for example a bolt bearing test would be carried out on a flat test piece even if the component had some curvature.

We can think of combining a number of element tests together to generate a more realistic test – this represents the Component level in the Pyramid

Page 9:
Every feature of the structure is expected to be present including:

- thickness variations
- complex geometry fully representative of the final structure
- any machining required
- often involving an assembly of components

Component is likely to be either a section of the full structure or a sub-scale structure.
Hard to ensure the boundary conditions properly match those of the full structure, which is required to ensure that the testing is valid

**Page 10:**
A very small number of tests would be expected to be carried out at this level. We could have gone from 1000s of tests at “Allowables” to 100s at “Element” to 10s at “Component” to as few as 1 at the “Full Structure” level.

As for the Component testing, ensuring that the test loadings properly capture the in service loadings in the multiplicity of loading cases that can be seen in service can be a significant challenge

**Page 11:**
The Pyramid of Testing approach implicitly assumes that:

- The Allowable properties of a flat laminate adequately describe the properties of a non-flat laminate
- We have captured at Allowables and Elements levels all the sources of variability that we will experience at the higher levels
- That we have properly captured all the sources of in-service degradation and accommodated them as required in the design of testing procedures at Allowables, Elements, Component and Structure levels

**Page 12:**
To meet those assumptions exactly requires us to be able to say that:

- The reinforcement lay-up and fibre directions on the tool exactly matches that on the part drawing
- The as-cured part geometry exactly matches the part drawing
- Variability is no greater than that found in laminates used for Allowables testing
- All fibres are locally straight without in-plane or out-of-plane distortions greater than those found in laminates used for Allowables testing
- Voidage or Residual stresses are no greater than that found in laminates used for Allowables testing

The reality can be rather different, especially for structures of complex geometry:

- The reinforcement fibre directions on the drawing are generally not even clearly defined at all points on a complex surface
- The as-cured part geometry will not perfectly match the part drawing
- Variability exists in all materials and processes and can be very significant
All fibres will be subject to in-plane or out-of-plane distortions due to matching any geometry that is not a flat sheet.

Residual stresses are always present, will often be different to those seen in flat laminates, and can be critical in more complex parts.

Voidage can be significant, in some loading modes severe strength reductions can be seen at very low global voidage levels.

Page 13:

Page 14:
All the features shown will impact negatively on performance – BUT they are not defects as they arise directly from design decisions and CANNOT be “Fixed” by better manufacture.

Therefore we can reasonably state that the allowable properties as measured on flat laminates in simple stress states have almost no power to predict the properties of more complex real components containing a range of internal micro/mesostructural features.

This is why we need the higher levels of the Pyramid of Testing and any attempt to go directly from Allowables properties to a prediction of the responses of the Full Structure is fraught with difficulties.

Page 15:
It is clear that the Pyramid of Testing is not a perfect vehicle for establishing the properties of composite structures:

- Allowables and Elements do not necessarily capture all the sources of variability in real components arising from either design features or defects below a scale detectable in NDE
- Component and Full Structure tests are not carried out in large enough numbers to establish statistical reliability at this level
- There is currently no realistic alternative to the Pyramid of Testing approach, so we need to maximise the value that we can take from it by understanding the effects that the defects that we see can have on performance

Page 16:
The most critical question that has to be answered is what loads will be applied?

There will generally be multiple load cases and if we miss any we can seriously overestimate the strength and reliability of our structures.

Requirements capture, right at the very start of the product design process is absolutely critical to the development of a safe and reliable structure.
We will need to understand all the ways that our structure could fail – but we only have to test the structure in the loading cases that are safety critical and are above some agreed threshold probability of happening in service.

We are less likely to want to test failure modes with high Reserve Factors in the stress analysis than if the Reserve Factors are low.

Page 17:
For example a wing spar has to carry bending and torsional loads from wing bending, it has to:

• Pick up local loads from various mechanisms and systems
• React internal pressures in the wing due to fuel surge in an aborted take-off and over pressurisation during refuelling.

Most of these loading cases would primarily drive stresses into fibre-dominated failure modes.

The internal pressure cases would tend to lead to opening up of the corners of the spar, inducing a through thickness tensile stress in the corners.

This is a matrix-dominated failure mode and likely to be more variable and sensitive to defects. A specific test of this failure mode might well be required even if the Reserve Factors were relatively high, to allow for the defect sensitivity

Page 18:

• Deliberately designed-in features – including Residual stresses due to elevated T cure
• Incidentally designed in features
• Defects caused by a lack of control or understanding in the manufacturing processes
• Cosmetic issues – how can they impact on performance

Page 19:
Features, arising from design decisions, may include:

• residual stresses
• ply drops
• gaps between plies or tape courses in AFP
• fibre waviness in the reinforcement as delivered
• additional fibre waviness caused by mapping the chosen reinforcement to the tool
• consolidation induced bridging or fibre wrinkling
Page 20:
Defects, arising during manufacture, may include:

• voidage
• dry spots and other wet-out issues
• delaminations
• bridging or fibre wrinkling due to faulty lay-up
• fibre waviness due to errors in draping the reinforcement to the tool or due to fibre wash in RI processes

Other defects such as inclusions; ply contamination; errors in ply count, lay-up order or ply orientation; honeycomb core collapse and a range of other core related defects; curing or vacuum errors or bag burst, will not be considered here as they tend to lead to catastrophic losses of properties and the mouldings being total scrap, and must simply be avoided.

Page 21:
Non dimensional defects will be assessed against a set of part Quality Standards known as Acceptance Criteria. There may be two levels set.

The first would be the “Accept as is” or fully compliant limit, the second would be the “Correctable Limit”.

If the parts are not fully compliant a decision must be made as to whether the part can be reworked to bring it inside the quality standards. Rework implies that the part defects fall within the correctable limits, and after rework parts are fully compliant. The customer need not be informed of the rework applied.

Page 22:
The non-dimensional errors that would be included in Acceptance Criteria might be:

• Surface scratches, depressions and dents
• Bridging and wrinkles
• Delaminations and voids
• Surface resin richness/ resin ridges or resin dryness / very visible weave pattern with woven reinforcements due to a shortage of resin between the tows
• FOD/Material inclusions
• Honeycomb defects such as dimpling, core movement, splice gaps & separated nodes
• Assembly warpage and faying (bolting or bonding) surface flatness.
Page 23:
The acceptable and correctable limits will change from component to component, and even from area to area within one part depending on the local stresses and the consequences of failure.

Acceptance Criteria would be expected to be much tighter for flight critical parts than for simple fairings and similar parts.

Some Acceptance Criteria are set very tight, but it has to be accepted that the production of composite parts often produces cosmetically poor parts, even if they are structurally sound.

Page 24:
This is a picture of part of the side frame for the BMWi3 life cell. It shows significant areas of wavy fibre that would be expected to be unacceptable in an aerospace part.

However, parts with this defect pass the crash-test and other structural requirements – so are defined as within the Acceptance Criteria for this application.

Page 25:
If the part quality falls outside the correctable limit it may still be possible to generate a repair scheme, which can be applied to bring the part into an acceptable state. Some similar repairs may be applicable to in-service damage.

The repair scheme must be subjected to a rigorous design, stress and manufacturing analysis process to demonstrate that it is structurally sound and fit for purpose.

It is usual for the repair schemes to be brought together into a company repair manual, which may also be made available to end users for in-service use.

Page 26:
In an ideal world we might aim to investigate each non-conformance with a view to identifying the root cause and eliminating the problem.

In practice this can be a very expensive approach when we are only making small numbers of any particular component, so we need to take a view on whether we can live with a particular level of non-conformant parts or must tackle the causes.

This requires us to have a good understanding of the costs of non-conformities - both directly in terms of MRB activity, rework, repair and scrap and indirectly through inefficiencies as a result of the distortion to production flow.

Page 27:
One approach that has been taken in some aerospace companies when there is uncertainty about structural adequacy (for example due to an occasional and localised voidage which is out of spec) is to simply quarantine non-conformant parts until a significant number has been reached - when the value of potentially releasing the parts is greater than the cost of testing one of them to destruction a structural test can be carried out.
If the test is passed the quality standard can be updated to make this condition acceptable and all the previously non-conformant parts can be released alongside future parts with that feature.

**Page 28:**
Currently the design and manufacturing processes used with composites do not achieve 100% right first time, we therefore need to have in place a structure of MRB, rework, repair procedures and concession processes that can add significant costs to the manufacture of composite parts.

Good record keeping is essential to be able to identify and track those costs so as to be able to generate the business cases to support the research and development needed to improve design and manufacturing processes and avoid the costs in future.

MRB should be used to drive improvements rather than just manage limitations in as-moulded quality

**Page 29.**
Fibre misalignment can be defined as a deviation between the nominal and actual fibre direction.

This misalignment can be in-plane or a combination of out-of-plane and in-plane.

There is no universally accepted terminology to describe this misalignment, but for the sake of clarity in-plane misalignment will be described as fibre waviness and out-of-plane misalignment as fibre wrinkling.

Assuming that we can define an adequate fibre direction datum at any point it is next necessary to look at the mechanisms by which fibre misalignment can be generated.

As before it is useful to consider both unavoidable features and avoidable defects separately.

**Page 30.**
Unavoidable features in continuous fibre composites

- As delivered dry UD tows may not be entirely straight
- UD prepreg usually contains in-plane wavy fibres
- Woven cloth always contains crimped (i.e. wrinkled fibres)
- Non-crimped fabrics normally exhibit some distortion of the tows due to the stitch or binder yarn fibres
- When forming any reinforcement around an out-of-plane radius additional in-plane waviness will be generated
- When forming any reinforcement around an in-plane radius additional waviness or wrinkling will be generated, e.g. Tow steering in AFP or woven cloth drape
- Ply drops will generate a localised fibre wrinkling

**Page 31.**
Avoidable defects in continuous fibre composites
- Lay-up errors
- Fibre wash in RTM
- Bridging in internal radii
- Consolidation defects on external radii
- Forming errors
- Mould closure effects

Page 32.

The key to understanding many of the unavoidable features is to examine the nature of the tows of fibre.

A tow consists of many thousands of very thin (typically <10µm) fibres, which may be held lightly together with a small amount of size or binder, or be completely dry.

To a first approximation the fibres individually have no resistance to bending or buckling under load. Bending the tows will tend to buckle the fibres and generate misalignment, which may not be fully recovered when the tow as a whole is straightened out.

Any snagging of fibres in the tow during processing produces similar effects and handling dry fibre tows needs to be done with great care to avoid introducing defects.

Page 33.

As delivered UD tows have usually been wound onto a small (<100mm) diameter tube, leading to the sort of localised fibre misalignment noted above.

Any localised misalignment introduced at this stage will tend to carry through to the next process step, whether that is the manufacture of UD prepreg or the weaving of a cloth.

In UD prepreg we see both generalised waviness (not generally assumed to be a defect) and also specific localised defects

Page 34.

The level of generalised fibre waviness for the prepreg shown is equivalent to what would be expected due to the prepreg being wound on to a 300mm D drum for delivery – leading to the compressive collapse of the fibres on the inner radius.

The level of generalised, as delivered, misalignment in the 0.25mm thick prepreg shown is a maximum of about 3.8°, with a wavelength of a few mm.

When this prepreg is laid up on to a curved surface the inner surface is once more put under a compressive stress and this has the effect of increasing the amplitude of the misalignment without significantly impacting on the wavelength.

Page 35.
The misalignment can be visualised by polishing sections through corner regions as the reflectivity of the areas where the fibres are in the plane of the section is very different to that of the regions of more misaligned fibre.

Each of the 8 plies shows alternating light and dark regions which indicate the changing fibre direction due to the waviness in the fibres for this laminate moulded on a 10mm internal radius tool.

**Page 36.**

If the tows are curved in the plane, as they might be in a tow steered laminate a greater impact on fibre alignment will be expected as the tow width is generally 10-20x the ply thickness and can be much more if the tows have been spread.

The fibres in this tow-placed laminate show up as bright lines and the resin as dark areas.

The inside surface of each tow can be seen to be very wavy, where the fibres in the tow have buckled to give both in-plane and out-of-plane misalignment.

**Page 37.**

For woven cloths and braids there will always be some out of plane misalignment due to the weaving process.

This misalignment is innate to the material and is a feature rather than a defect.

Woven cloth is principally used where there is a need to match the reinforcement to complex geometrical features by the process of distorting the cloth known as drape.

The drape process will also generate curved fibre paths so the impact on tow level misalignment will also be seen in draped woven cloths where fibre paths are curved.

**Page 38.**

**Page 39.**

Ply drops will generate localised fibre wrinkling as the fibres are deformed out of plane to match the ply edges of the dropped plies.

This can generate significant – if highly localised - fibre misalignment and initiate delaminations under in-plane tensile loading, having a significant impact on fatigue performance.

**Page 40.**

It should be clear that a typical laminate is made from tows of fibre that are not ideally straight, these are then transformed into semi-finished products such as cloths and prepregs which contain higher levels of misalignment and then converted into products which contain additional levels of local misalignment due to the part geometry and forming routes.
It must be stressed that these misalignments are largely unavoidable; as determined by the particular material and part geometry used.

While they must be accommodated in test and analysis activities they cannot be assumed to be defects as they are the direct result of decisions made in the design process.

Page 41.

The distinctions between features and defects are not always entirely clear, but in general defects involve a localisation of the misalignment and a deviation from the ideal as-designed geometry or internal laminate structure.

When we lay a sheet of UD prepreg onto a curved surface a mismatch between the prepreg and the surface become apparent as the area that is in contact with the tool is increased.

We can mimic this by laying down a ply with a very slight initial misalignment and look at how that misalignment propagates as the lay-up proceeds.

Page 42.

If we lay down the ply so that the initially deviated (at the limit of acceptable practice) right hand edge is laid down straight an increasing level of misalignment is seen as lay-up proceeds.

Page 43.

The level of fibre waviness that can be generated by an initial 2°offset is shown here.

A region of gross misalignment is formed (a 40°fibre misalignment) from a minor lay-up misalignment of only 2°, which is inside lay-up accuracy standards.

This is one reason that lay-up of UD reinforcements on curved surfaces is so difficult.

Page 44.

Large scale misalignments may also be formed as reinforcements are pressed into tools, especially by mould closure forces in RTM components, or by the way in which preforms are manufactured for RTM moulding.

Gross misalignment driven by mould loading forces

Out of plane waviness due to a poorly controlled preforming process

Out of plane wrinkling in the corner of an autoclave moulded part – probably driven by the action of the autoclave pressure

Page 45.

It must be noted that all of the numerical values given here for the effects of misalignment on strength are related to the specific materials, lay-up and defects under consideration.
While they may be typical for these sorts of materials and defects they cannot be used to predict the performance of other materials or processes.

They are perhaps better used to identify the sorts of defects we must aim to avoid rather than the level of strength knockdown that may have to be tolerated.

**Page 46.**

Defects arising as shown here have been examined as follows. An 8 ply 2mm thick laminate was made up with 4 plies undeformed and 4 plies deformed as shown.

These samples were then tested in flexure, with the defect on both tensile and compressive surfaces.

The increase in thickness in the misoriented region was taken as a marker for the severity of the waviness/wrinkling (generally increasing from point 1 to 5 in) and plotted against the reduction in baseline strength for a nominally ideal laminate.

**Page 47.**

The tolerance on the laminate thickness for this sort of laminate is likely to be ±5%, so that in principle a part with a more severe wrinkle could be identified and eliminated from the population through dimensional inspection.

However, an inspection of the data shows that even very small thickness increases can be associated with significant losses of strength, making inspection more problematical.

**Page 48.**

These L sections were cut from production parts and loaded as shown here to measure the through-thickness tensile strength.

There were three distinct sets of results in this testing.

The first were “good” samples where there was no localised voidage or deviation from the expected ply trajectory around the corner. These had strengths over 50MPa and failed by a single line of failure at a position close to the peak transverse tensile stress.

The second group exhibited wrinkled plies and first failure occurred at the position of the wrinkle and remote from the position of peak transverse tensile stress as shown here.

**Page 49.**

These L sections were cut from production parts and loaded as shown here to measure the through-thickness tensile strength.

There were three distinct sets of results in this testing.

The first were “good” samples where there was no localised voidage or deviation from the expected ply trajectory around the corner. These had strengths over 50MPa and failed by a single line of failure at a position close to the peak transverse tensile stress.

The second group exhibited wrinkled plies and first failure occurred at the position of the wrinkle and remote from the position of peak transverse tensile stress as shown here.
Page 50.

Page 51.

Surface finish

This RTMed component has a patchy surface finish, some areas are smooth and shiny (green) and some are rough (red).

These sorts of issues would not be expected to significantly degrade the laminate strength, but could have an impact on the strength of a bonded joint.

More generally an uneven surface can have an impact on strength in bolted flanges where the action of the bolts on uneven surfaces can generate interlaminar shear stresses and potentially delaminations.

Page 52.

Designing out “defects”

There are many features that can impact on mechanical performance that arise directly or indirectly from the design process.

As an example, a decision to use a 5mm internal corner radius on a tool to make a 5mm thick moulding would guarantee a defective part as the nominal geometry, whilst geometrically feasible, is simply not practically possible.

As the thickness drops in proportion to the radius a good quality will steadily become easier to achieve, however a 5mm internal radius is still quite small in absolute terms and rather difficult to lay prepreg into accurately.

To get a good reproducible quality by hand lay-up of unidirectional prepreg a minimum corner radius of perhaps 10mm would be a better design with regard to manufacturability and moulded quality.

Page 53.

The larger corner radius will be less likely to be bridged, less likely to be seriously voided and will definitely have lower levels of fibre waviness induced by the curvature of the prepreg.

A part of the design process would be the selection of the specific grade of prepreg to be used. Selecting a heavier grade of prepreg would reduce the number of plies and thus positively impact on labour costs; but the level of fibre waviness induced by the curvature would be increased, and the difficulty of achieving a high quality lay-up may also be increased compared to that for the thinner prepreg.

Equally, for a part that has significant double curvature and requires the use of an extensively draped reinforcement the selection in the design process of a woven reinforcement with a wide tow rather
than a narrow tow will increase the level of fibre wrinkling as those tows become more distorted in the drape process.

Page 54.

For any geometry that can be draped with a single piece of woven cloth there are generally multiple pathways by which that drape can be achieved.

Even though the initial orientation of the cloth to the tool may be identical, each pathway to the final draped geometry will generate a different set of local fibre orientations and characteristic features and “defects”.

Different pathways will also require more or less skill from the operator, with some pathways being much more likely than others to generate defects.

A detailed examination of drape processes and the characteristics of different materials can be complicated, but in view of the potential impacts on quality and performance these details of lay-up and manufacture must form part of the design process.

Page 55.

Assuming that the design process has output a design that meets the sort of requirements noted above and that the impacts of those design features on mechanical performance have been properly accounted for in stress analysis the manufacturing task is “simply” to ensure that the design intent is carried through into production.

Take-Home message 2

There is a rather grey area between design and manufacture in much industrial practice, and the proper handover from design to manufacture is of paramount importance.

Page 56.

Generating unambiguous manufacturing instruction sets and validating the reliability and reproducibility of these in a production environment is a critical part of the product development process.

A logical design and manufacture cycle might position this activity as the final element of the design phase.

The manufacturing role would then be simply to implement those instruction sets with suitable inspection and control steps.

In this view of the design and development process, accommodating materials variability falls into the design area and accommodating process variability falls into the manufacturing area.

Page 57.
It is more common in an industrial setting to hand over from a design to a manufacturing lead prior to the generation of unambiguous manufacturing instruction sets, so that the responsibility for all aspects of quality, process control and variability can appear to fall into the manufacturing area.

The problem with this is that the unambiguous manufacturing instruction sets that are generated may not then be checked against all the details of the design intent.

The phrase “unambiguous manufacturing instruction sets” has been used repeatedly here. There can be no apologies for this - unless ambiguity is eliminated and validated processes are used throughout, the probability of the manufacturing process drifting away from the design intent and into a lack of control is unacceptably high.

Page 58.

Probably the most critical (and often most poorly done) step in the whole product development cycle is the transfer between design and manufacturing responsibility.

Ideally the transfer is gradual; as the details of the design are clarified and tested against materials and process capabilities and variability those details can move across into the manufacturing arena – until transfer is complete with a reliable production system in place.

The steps at which control is required will emerge during the design process, during the process of generating unambiguous manufacturing instruction sets, during the manufacture of pre-production prototypes and in the manufacture of early production models.

Page 59.

It is good practice to capture quality information relating to both product variability and defects in a well structured and searchable database, from the very start of the transfer from design into production.

Take-home message 3

Design has the information on regions of importance from a structural viewpoint, and manufacture has the information on materials and process capability and regions of potential deviations from ideal manufacture.

Only by combining the two sorts of knowledge can the right controls be put in place.

Page 60.

There is a tendency to assume that going from manual lay-up to automated processes such as AFP will solve all the problems.

The rippled and wavy fibres shown here from an AFP lay-up will become significant defects as heat and pressure are applied to consolidate and cure

Page 61.

We noted earlier that we need to clearly distinguish between features and defects, however changes in technology can change that boundary.

For example it has been shown that the typical ply drop stress concentration can be largely reduced or effectively eliminated by scarfing the ply rather than simply cutting through it.
A laminate with conventional ply drops develops delaminations well below the fibre strain to failure. With scarfed ply drops this brush failure mode develops at a much higher strain in the fibre.

**Page 62.**

It has repeatedly been stated in these notes that taking fibrous reinforcements around a radius either in or out of plane will generate fibre waviness and/or wrinkles. This is not strictly true if the deformation is generated by shearing the reinforcement rather than bending it. A research machine has been developed that can apply this shear deformation to a strip of dry or prepregged reinforcement up to 100mm wide. If this approach is used to steer the reinforcement across a surface then the reinforcement remains substantially free of wrinkled fibres at a radius of curvature that would cause very damaging defects if it was achieved by bending the reinforcement.

**Page 63.**

Ply drop terminations and reinforcement steering have been identified as two significant sources of strength reduction in composite structures.

Recent research has demonstrated that there are potential technical solutions to avoiding both of these strength reductions by modifications to manufacturing practices and manufacturing machinery.

Does this mean that we should now be reassessing these sources of strength reduction as defects rather than features as they are no longer unavoidable in principle?

**Page 64.**

As of today, neither technology is available as a Commercial-Off-The-Shelf technology in the supply chain, so currently we would have to continue to treat these sources of strength reduction as design features rather than as manufacturing defects.

However:

We do need to keep the distinction between features and defects under constant review as the technology develops.

When considering the importance of technology developments, or the design of research programmes in composites manufacture we need to use the potential to reduce or eliminate the impacts of sources of strength reductions as a major criterion in the assessment of the developments.

As academics we have to appreciate that until there is a COTS supply chain the research and development job is not finished.

**Page 65.**

Design of reinforcements and matrices that are less prone to/sensitive to defects.
In an ideal world the reinforcements used would be designed to be ideally suited to the manufacturing processes that are available to give robust processing.

Current woven reinforcements are well aligned to manual lay-up processes but are not well suited to automated manufacturing processes such as stamp forming or vacuum forming.

The principal reason for this lies in the cloth deformation mode. The single deformation mode available in woven cloth (scissoring shear) gives a fully reversible deformation mode that allows for manual handling and repositioning without major damage to the reinforcement.

Page 66.

If the fully versatile manual handling is replaced by simple mechanical forming then more deformation modes are required (c.f. sheet metal forming).

Non Crimp fabrics can have more deformation modes (scissoring shear or transverse stretching + inter-tow shear, depending on fabric structure) as can unidirectional prepreg (transverse stretching + in-plane shear), and both perform better than conventional woven cloth in automated forming.

However, both these reinforcements are generally made from inextensible continuous fibre tows. Extensibility needs to be incorporated into the tow to provide more deformation modes to permit forming of fully clamped sheets and open out the manufacturing options. Various options have been tried in this area and more work is needed to balance manufacturing and performance requirements.

Page 67.

Current matrices contribute to defects through cure shrinkage and high thermal expansion coefficients.

It may well be that these properties are inherent in the chemistry used, but any improvements in these areas would be of significant benefit with regard to performance.

Equally, the use of a single matrix at all points in the laminate is not ideal as the balance of say stiffness and fracture toughness should perhaps be different within the tow, between the tows and at ply drops and other discontinuities.

However, the development of such complex matrices is perhaps a long-term aim and the short term targets should be to understand the current matrices to maximise process robustness.

Page 68.

Studies of variability in unidirectional prepreg materials have shown that this variability can have a real impact on process reliability and on part performance.

Other reinforcement forms may be less susceptible to variability, but the data available to support that assumption are insufficient.

Unfortunately, there is no realistic way for the average manufacturer of composite parts to limit this variability from their material suppliers.

Some materials purchase specifications permit rather wide ranges of some properties of significant impact on manufacturing quality (such as initial warp/weft angle in woven cloth) and say very little of value about manufacturing critical properties such as tack or drape.
It is well worth while keeping track of the variability in incoming materials to identify any long-term trends and to trap any marginally compliant material that might cause production problems.

The in-roll variability can be as high as the roll to roll variability making a material selection approach to narrowing the variability generally infeasible.

The main impacts on in-process variability are probably in the lay-up stage, through issues such as tack and drape and the straightness of warp and weft in woven cloth.

For RTM variability in the reinforcement permeability would potentially be critical – but I have never seen reinforcement permeability included in material specifications, it is essentially not controlled and could be subject to significant variability.

Variability in the cure process seems not to be a major factor in product quality, although the impact of variability in out-time can be quite different from one resin system to the next, with some resins being very sensitive to storage life and others having very wide process windows over a very long storage life.

It is clearly preferable to have matrices with the latter characteristic, although this will only be one factor among many in the selection of a matrix, and unfortunately is seldom taken as a critical factor.

The current status is that we are generally trying to manage the variability in materials and manufacturing processes without many of the tools needed to support this.

The history of advanced composites to date has largely been about the targeted development of material forms that focus on mechanical performance as measured on carefully selected and defect free flat laminates.

Take-home message 4

Mechanical performance can rapidly be degraded by deviations from the ideal composite structure arising from design decisions and manufacturing errors.

We need to rebalance material development targets to focus on improving the performance of real complex parts, and away from flat laminates.

Deviations from the design intent can have very significant impacts on the mechanical performance of composite structures

In some cases what appear to be relatively minor defects can have a disproportionately strong impact
Take-home message 5

The allowable properties as measured on flat laminates in simple stress states have almost no power to predict the properties of real components containing a range of defects.

Page 73.

It is critically important to clearly distinguish what is in the design domain and what is in the manufacturing domain.

Difficulties in achieving the highest manufacturing quality that arise as a result of design decisions (including choices of materials and processes) cannot be fixed in the manufacturing process. They can only be fixed in the design process.

Understanding variability and defects is absolutely key to designing good composite components and structures.

We’re getting better at it – but are still far from perfect.

Constant interaction and feedback between design and manufacture is the only way to assure trouble free production and adequate in-service performance.
Defect root cause exercise
Defect route cause exercise

• Please examine the sample provided and attempt to identify the most likely root causes for the defects

• You’ll have to do this in three steps
  1. Identify the manufacturing process that was used
  2. Identify the possible sources of variability in that process
  3. Identify which of those sources of variability contributed to the generation of the defects
Defect root cause exercise

Roadside utility poles can be designed to fail when impacted by a vehicle so as to limit the loads transferred back to the vehicle.

• However, in this case the pole failed on the night of installation due to a fairly high wind.

• The pole had a plastic cover, and when this was stripped off the laminate quality was seen to be very poor.
Describing the defects

- Defects decorated with red dye penetrant
- Transverse cracking in hoop winding
- Delamination between base laminate and hoop winding
- Significant local misalignment of longitudinal fibres
- Transverse microcracking of longitudinal fibres
How was this part made?
Understanding the origins of the defects

- To understand the defect origins we need to understand the manufacturing process.
- We can reverse engineer from the pole internal fibre geometry to the probable manufacturing process.
- We have a number of layers of axially aligned and hoop aligned fibres (axial layers are thicker than hoop layers) that run through the thickness from the tool surface to the outside and above that we have a separate hoop wound layer.
- There are a number of voids between the hoop and axial layers in the main wall.
Understanding the origins of the defects

The structure we see is consistent with this sort of manufacturing process, which could be carried out on a semicontinuous basis.

A band of UD reinforcement with the fibres arranged in the long direction of the pole is wet out with a liquid resin and wrapped around the mandrel using a web of hoop fibres.

This layer is then consolidated with a wet wound hoop layer (at about 85deg) to consolidate the primarily longitudinally aligned layer.

A plastic layer is then applied to the surface to complete the pole.

This is drawn as overshot for clarity but would need to operate as an undershot system.
What are the sources of variability?
## Sources of variability in the longitudinal layer

<table>
<thead>
<tr>
<th>Sources of Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre alignment on the web of hoop fibres</td>
</tr>
<tr>
<td>Fibre mass/unit area</td>
</tr>
<tr>
<td>Resin content and wetout quality, sizing and coupling agent effects</td>
</tr>
<tr>
<td>Resin viscosity</td>
</tr>
<tr>
<td>Tension in the hoop fibres</td>
</tr>
<tr>
<td>Air entrapment in the fibre/resin layer at the hoop/axial interface and at the tool surface</td>
</tr>
<tr>
<td>Friction at the tool surface in a semi-continuous process</td>
</tr>
<tr>
<td>Fibre waviness as supplied in the axial fibres</td>
</tr>
</tbody>
</table>
Sources of variability in the outer hoop wound layer

- Fibre mass/unit area
- Resin content and wetout quality
- Resin viscosity
- Air entrapment in the fibre/resin layer and at the interface between hoop and axial layers
- Thickness of the hoop layer
- Tension in the hoop wound fibres
Other sources of variability in the process

- Consistency of fibre sizing.
- Temperature at point of lay-up
- Temperature profile through cure
- Resin shrinkage in cure and on cooldown
- Variability in age or composition of resin / cure kinetics
- Temperature in the application of the plastic layer
- Handling damage during manufacture and transport to site
How were defects caused?
Look again at the defects

- Now we have an idea of the potential sources of variability we can look with fresh eyes at the quality of the different parts of the structure.
- The outermost hoop wound layer shows many cracks but has the level of transparency that would be expected from a well wet-out glass laminate.
- The thickness of the hoop layer is rather variable from about 1mm to just under 2mm, and the transverse cracking seems to be more frequent in the thicker areas.
- We would expect to see a significant transverse tensile stress arising from cure/thermal shrinkage in the hoop layer (constrained by the axial fibres) which could lead to the sort of cracking that we see and this would be expected to be more frequent in the thick regions. The use of high temperature cures or very reactive resins would tend to make these issues worse.
Look again at the defects

• We do not have access to a nominally good pole so can’t actually say that the transverse cracking is a defect rather than a feature of the design, but it would certainly tend to reduce the structural integrity of the beam.

• The areas of debonding between primarily longitudinal and outermost hoop layers seems largely to be associated with the transverse cracking propagating into a delamination at the ply interface, which would be in line with expectations.

• The primarily longitudinal layer is of the most concern as this layer will be carrying most of the structural loads in the intended application.

• Unusually, the longitudinal layer is not comprised of continuous fibres, but of a stack of 300mm long layers at a slight angle to the pole surface, this makes the ply to ply interface of more importance than in a conventionally made pole.

• The slight taper would also be expected to lead to some ply waviness which is apparent in the pipe wall.
Look again at the defects

- The longitudinal layers are not nearly as transparent as the hoop layer being characterised by a whiteness that suggests some limitations with wetout at the fibre level and fibre to resin bonding and possibly sizing or coupling.
- The intermediate hoop wound layers are of a similar quality to the outermost hoop layer.
- Each longitudinal layer is thick for a single ply and is severely distorted at the point where it is laid down on the mandrel, in the worst cases the fibres are closer to the hoop direction than the axial direction and there are multiple points at which incipient delamination can be seen at the ply terminations.
- In the severely distorted regions there is once more a significant amount of transverse cracking. We would not expect to see this in a pure UD tube, but the constraint from the hoop layer below the distorted region is probably driving this cracking.
Look again at the defects

- It is not immediately obvious how the severely distorted fibres are being caused.
- The consolidation of each longitudinal laminate will be driven by the tension in the hoop layer immediately above it, it seems very likely that a lack of control over that tension could lead to the sorts of distorted fibre defect seen.
- The structural weakness of the poles has to arise primarily from the longitudinal laminate and the combination of relatively thick plies, heavily distorted ply terminations, relatively poor fibre wetout, intra ply voidage and incipient delaminations at ply ends would be expected to give rise to a very much reduced strength.
How can we make improvements?
Improving matters

Production improvements could focus on:

• Guaranteeing good fibre wetout, which may well be a materials rather than a process issue as none of the hoop fibre layers show this problem
• A change in sizing on the axial fibres could be worthwhile to ensure full wetout, or the process could be run slower to allow more time for wetout
• Ensuring a constant and uniform winding tension in the intermediate hoop layers
• Ensuring a uniform thickness in the outermost hoop wound layer
• Reducing the cure temperature as much as possible to reduce thermal stresses
• Inspection of the pipe after manufacture – especially on the inside surface as the external surface is covered by a layer of polymer and not available

However the poles are designed to fail so cannot be too strong but need to perform reliably – it may be necessary to redesign the pole to get the right balance of performance.
Conclusions

Even when we are presented with a structure made by an unknown process we can use reverse engineering to identify the probable process – then apply an understanding of the sources of variability and defects in that process to suggest improvements.
Defect root cause, investigations and corrections

Kevin Potter

bristol.ac.uk/composites
Learning Objectives

Learners will be able to:

- Demonstrate an understanding of the factors that can contribute to premature failure
- Understand how to structure an investigation into the origin of defects
- Distinguish between correlation and causation in composites manufacturing
Introduction

- Taxonomies of defects and sources of variability have been produced
- Useful for capturing some of the complexity but do not focus on cause and effect.
- Identify a process to drill down root causes
What is a defect?

• Definition: A defect is something that takes the part outside its specifications and renders it not fit for purpose

• A part can be rendered unfit for purpose through:
  – localised or generalised loss of strength or stiffness
  – loss of temperature or other environmental resistance
  – loss of specified electrical or thermal conductivity performance
  – exceeding geometrical or mass tolerance limits

• In principle: any deviation from the part specification generates a defect.

• In practice: it is probably fit and strength related defects that dominate the defect spectrum and strength related defects that have the most importance in safety and operational terms.
Scaling the problem level 1

In order to scale the problems we can track a few defect types back from the identified defect back through to the root cause, or at least as close as we can get.

At the as-moulded state we can identify 7 defect classes

- Geometrical defects
- Voidage
- Delaminations
- Fibre architecture defects (wrinkling etc)
- Cure/thermal process errors
- Inclusions, contamination and FOD
- Simple lay-up errors such as wrong ply sequence
Scaling the problem level 2

For geometrical defects we might have

- Thickness errors
- Edge of part errors
- Dimensional infidelity due to twist, warpage and spring-in
- Core or stringer position errors
- Loss of datum
- Surface finish/surface quality issues
- Core crush or displacement
- Bridging and wrinkling
Scaling the problem level 3

For Thickness errors we might have

- Closed mould tooling not fully closed
- Prepreg out of thickness tolerance (or incompatibility between part and prepreg thickness tolerances)
- Wrong choice of cured ply thickness (CPT) or drape impacts on thickness not accommodated in the design
- Inadequate or excessive applied pressure in bag moulding causing deviations from expected resin flow
- Poor design practices such as overlapping at ply splices
- Bridging or overconsolidation in complex features
- Core thickness out of tolerance (where used)
- Excessive or inadequate bleed, including use of badly designed "intensifiers"
Scaling the problem level 4

for closed mould tooling not fully closed could be related to

- premature gelation/inadequate rate of resin bleed
- inadequate closing force available
- fibres trapped in sealing faces
- overloaded tool
- in addition to these factors some of the factors at the higher level (such as prepreg tolerances etc) will also impact here.
The influences giving rise to premature gelation/inadequate rate of resin bleed

- Wrong thermal history
- Resin flow restrictions from tightly sealed tooling
- High resin viscosity
- Fibre bed permeability inadequate
Scaling the problem level 6

Wrong thermal history may be due to:

- Prepreg out of life
- Prepreg incorrectly stored
- Errors in the tool temperature
- Errors in the time and temperature schedule
Scaling the problem

• We could of course dig further into why those events happened (e.g. due to human error, poor training or supervision, inadequate maintenance, defective process equipment or controllers)

• But this is probably a convenient place to stop as these sorts of errors are essentially outside the process.
Scaling the problem

We have identified:

• 7 generic defect types
• 8 sub-types of one generic defect type
• 8 areas of variability underpinning one of those sub-types
• 4 factors giving rise to one of those areas
• 4 influences on those factors
• 4 “root causes”.
Scaling the problem

• If the same level of detail were replicated across the full range of defects we would end up with $7 \times 8 \times 8 \times 4 \times 4 \times 4 = 28672$ elements of the root causes in total.

• Even allowing for many defects having simpler causation and that some factors will be at the root of multiple defects we are likely to have thousands of root causes.
Digging down to root causes

Generic defect types

Geometry

Voidage

Cure errors

Simple errors

Delaminations

Misalignment

Inclusions

Thickness errors

Tool not closed

Premature gel

Wrong T history

Out of life

EOP* errors

Prepreg oot*

Force too low

Incorrect storage

Dim Infidelity

"CPT wrong"

Fibres trapped

Too thin

Core pos* errors

Wrong bag P

Overloaded tool

High viscosity resin

Low permeability

Core displacement

Design practices

Seeded tool

Bridging etc

Bridging/wrinkling

Core T oot

Wrong bleed

Incorrect storage

Defects Root Causes

In addition to these generic thickness errors, these might include resin pooling, geodesy issues in the trim around regions and fibre tension effects in non-round PW; gaps, laps, steering errors, twisted tow effects in AFP and so on.

oot = out of tolerance *EOP = Edge of part *CPT = cured ply thick

© University of Bristol 2018
Digging down to root causes

Generic defect types

Geometry
- Delaminations
  - Thickness errors
  - EOP* errors
  - Dim Infidelity
  - Core pos* errors
  - Loss of datum
  - Surface quality
  - Core displacement
  - Bridging/wrinkling

Voidage
- Drape errors
  - Tow curvature
  - Lay-up errors
  - Core crush
  - Skin dimpling
  - Fibre wash
  - Ply drops/gaps
  - Consolidation*

Cure errors
- Poor ply/ply slip
  - Tool face shearing
  - Geometry lock out
  - Excess bulk factor
  - Radii too tight
  - Material issues*
  - Inadequate debulk
  - Temp too low
  - P too low
  - Time too short
  - Bad bagging
  - Inconsistency

Simple errors

Inclusions

Defects

Root Causes

* Consolidation during cure process
* e.g. the use of unbound reinforcements
Digging down to root causes

Generic defect types

Geometry
- Delaminations
  - Thickness errors
  - EOP* errors
  - Dim Infidelity
  - Core pos* errors
  - Loss of datum
  - Surface quality
  - Core displacement
  - Bridging/wrinkling

Voidage
- Misalignment
  - Radius spring-in
  - Twist
  - Flange bowing
  - Flanges too wide
  - Flanges narrow

Cure errors
- Thermo-Elastic
  - Rosin shrinkage
  - Tool Interaction
  - Pressure reaction

Simple errors
- Tool CTE
- Reinforcement CTE
- Cure T
- Tool-ply friction
- Ply-ply friction
- Tool surface finish
- Ply drops
- Tool feature effects
- Ply wrinkling in radii
- Locked tool effects

Defects

Root Causes
Where to start?

- We need to use a step by step process as shown above
  - Clearly and unambiguously define the defect type
  - Describe the number of ways that defect can arise
  - Rule out the defect generation processes that are not active
  - Identify the next level causes of the possible mechanisms
  - Repeat as required to get to the level of root causes
  - Make evidence based modifications at the level of root causes and monitor the results

- Experience has repeatedly shown that attempts to go straight to route causes seldom deliver robust improvements.
Defect Root cause exercise

Following part structural failure, how do we find the defects in design or manufacture that led to that failure?
Failure Investigation

- This follows the same sort of process as defect investigation, but generally after things have gone badly wrong.
- Failure to be investigated is that of a large (1m diam) predominantly carbon fibre centrifugal fan.
- Failure was total, all that was left was a large box of bits
Structure of fan

Centre plate, foam cored CFRP

End plate, ‘C’ Section CFRP

Longitudinal-section blade.

Blade root tapered at plate and bonded to in features in the ‘C’ end plates

Fan vanes aerofoil profile, foam core/CFRP skin

© University of Bristol 2018
Reasons for failure 1

• Fan blades are subjected to bending stresses as a result of centrifugal loading, failure initiates in blades

• Stress analysis shows that peak stresses in both foam and skin occurs at trailing edge

• Low but just adequate margin against allowable properties

• Assumed that the fan blades act as beams built in to the end plates

• Stresses roughly double if the beam is simply supported

• Stress analysis of the bonded joints was not carried out – shear stresses in the joints were very low leading to enough confidence in the design to avoid the analysis
Reasons for failure 2

- Peel stresses (direct tension across the joint) in the bonded joints were not considered.
- Strength in peel mode is very low and sensitive to defects – therefore we needed to look hard at this failure mode in the failure investigation.
- None of the joints subjected to peel stresses survived the failure.
- The quality of many of the joints was found to be very poor.
- Failure of the bonded joints leads to instant failure of the blade.
- Failure of one blade destroys the others.
- The smoking gun had been found – it is not always so clear.
Failure process

As made, unloaded, many adhesive fillets of defective geometry

Assumed loading case, well supported by end plates

Real case, bonds fail, unsupported, overloaded to failure
Can the design be saved?

• In addition to the strength problems the quality of the end plate mouldings was rather poor and the mouldings were very complex and expensive to make.

• It is very hard to design for peel as the peel stresses rise very rapidly towards the free edges.

• A large external fillet will help.

• We need to look at the stress analysis and deduce the maximum acceptable defect size using the joint’s fracture toughness.
Can the design be saved?

Peel stress MPa

Distance from free edge mm

© University of Bristol 2018
Can the design be saved?

Critical crack size – edge crack

Peel stress MPa

G \approx 1100 \text{ J/m}^2

E \approx 5 \text{ GPa}

© University of Bristol 2018
Can the design be saved?

- Close to the free edge we would need to guarantee to avoid any defect above about 3mm long.
- There is no NDT method that could reliably detect such flaws in such a complex structure.
- Even if we could detect the flaws there is no realistic rework option.
- The design therefore can not be saved and a complete redesign is required.
- That redesign needs to focus on a much reduced cost as well as a greatly improved reliability.
Requirements for successful failure investigation

To succeed in failure investigation and redesign we need

- Adequate time
- No external pressure
- No attempt at a witch-hunt
- Adequate resources
- Access to all relevant information
- Clear lines of responsibility
Requirements for successful failure investigation

In my experience we usually have this situation

- Very tight timescales
- A lot of external pressure
- Lawyers involved
- Limited resources
- May be obstructed in seeking information
- Responsibility may be unclear
Conclusions

• Whether we are investigating defects caused by failures in manufacturing or failures in service due to defects in structures the process has to be driven by a chain of evidence that is structured around an understanding of the causes and effects of defects.

• Adopting a structured approach to the investigation so as to move one step at a time on an assured basis avoids a great deal of the misunderstandings that can easily cause difficulties in reaching a robust solution.
Slide 2:

Learners will be able to:

- Demonstrate an understanding of the factors that can contribute to premature failure
- Understand how to structure an investigation into the origin of defects
- Distinguish between correlation and causation in composites manufacturing

Slide 3:

Taxonomies of defects and sources of variability have been produced and are useful for capturing some of the complexity but don’t focus on cause and effect. What we are going to do here is to identify a process that helps us to drill down to root causes.

Slide 4:

- A defect is something that takes the part outside its specifications and renders it not fit for purpose and thus requires it to be reworked, repaired or scrapped and probably also triggers a concession process.
- A part can be rendered unfit for purpose through localised or generalised loss of strength or stiffness, through loss of temperature or other environmental resistance, through loss of specified electrical or thermal conductivity performance, or by exceeding geometrical or mass tolerance limits and so on.
- In principle any deviation from the part specification generates a defect.
- In practice it is probably fit and strength related defects that dominate the defect spectrum and strength related defects that have the most importance in safety and operational terms.

Slide 5:

In order to scale the problems we can track a few defect types back from the identified defect back through to the root cause, or at least as close as we can get.

At the as-moulded state we can identify 7 defect classes:

- Geometrical defects
- Voidage
- Delaminations
- Fibre architecture defects (wringling etc)
- Cure/thermal process errors
- Inclusions, contamination and FOD
- Simple lay-up errors such as wrong ply sequence

Slide 6:

For geometrical defects we might have –

- Thickness errors
- Edge of part errors
- Dimensional infidelity due to twist, warpage and spring-in
- Core or stringer position errors
• Loss of datum
• Surface finish/surface quality issues
• Core crush or displacement
• Bridging and wrinkling

Slide 7:

For Thickness errors we might have:

- Closed mould tooling not fully closed
- Prepreg out of thickness tolerance (or incompatibility between part and prepreg thickness tolerances)
- Wrong choice of cured ply thickness (CPT) or drape impacts on thickness not accommodated in the design
- Inadequate or excessive applied pressure in bag moulding causing deviations from expected resin flow
- Poor design practices such as overlapping at ply splices
- Bridging or overconsolidation in complex features
- Core thickness out of tolerance (where used)
- Excessive or inadequate bleed, including use of badly designed “intensifiers”

Slide 8:

We can keep working down to try to bottom out the issues, e.g. for closed mould tooling not fully closed this could be related to -

- Premature gelation/inadequate rate of resin bleed
- Inadequate closing force available
- Fibres trapped in sealing faces
- Overloaded tool
- In addition to these factors some of the factors at the higher level (such as prepreg tolerances etc) will also impact here.

Slide 9:

To continue the process we can identify the influences giving rise to premature gelation/inadequate rate of resin bleed -

- Wrong thermal history
- High resin viscosity
- Fibre bed permeability inadequate
- Resin flow restrictions from tightly sealed tooling

Slide 10:

We can perhaps then get close to the root causes of, for example, wrong thermal history may be due to:

- Prepreg out of life
- Prepreg incorrectly stored
- Errors in the tool temperature
- Errors in the time and temperature schedule
Slide 11:
- We could of course dig further into why those events happened, due to human error, poor training or supervision, inadequate maintenance, defective process equipment or controllers and so on but this is probably a convenient place to stop as these sorts of errors are essentially outside the process.

Slide 12:
- We have identified 7 generic defect types, 8 sub-types of one generic defect type, 8 areas of variability underpinning one of those sub-types, 4 factors giving rise to one of those areas, 4 influences on those factors and 4 “root causes”.

Slide 13:
If the same level of detail were replicated across the full range of defects we would end up with $7 \times 8 \times 8 \times 4 \times 4 \times 4 = 28672$ elements of the root causes in total. Even allowing for many defects having simpler causation and that some factors will be at the root of multiple defects we are likely to have thousands of root causes.

Slide 17:
- We need to use a step by step process as shown above.
  - Clearly and unambiguously define the defect type
  - Describe the number of ways that defect can arise
  - Rule out the defect generation processes that are not active
  - Identify the next level causes of the possible mechanisms
  - Repeat as required to get to the level of root causes
  - Make evidence based modifications at the level of root causes and monitor the results
- Experience has repeatedly shown that attempts to go straight to route causes seldom deliver robust improvements.

Slide 19:
This follows the same sort of process as defect investigation, but generally after things have gone badly wrong.
Failure to be investigated is that of a large (1m diam) predominantly carbon fibre centrifugal fan.
Failure was total, all that was left was a large box of bits

Slide 21:
- Fan blades are subjected to bending stresses as a result of centrifugal loading, failure initiates in blades
- Stress analysis shows that peak stresses in both foam and skin occurs at trailing edge
- Low but just adequate margin against allowable properties
- Assumed that the fan blades act as beams built in to the end plates
- Stresses roughly double if the beam is simply supported
- Stress analysis of the bonded joints was not carried out – shear stresses in the joints
were very low leading to enough confidence in the design to avoid the analysis

Slide 22:

- Peel stresses (direct tension across the joint) in the bonded joints were not considered
- Strength in peel mode is very low and sensitive to defects – therefore we needed to look hard at this failure mode in the failure investigation
- None of the joints subjected to peel stresses survived the failure
- The quality of many of the joints was found to be very poor
- Failure of the bonded joints leads to instant failure of the blade
- Failure of one blade destroys the others
- The smoking gun had been found – it is not always so clear

Slide 24:

- In addition to the strength problems the quality of the end plate mouldings was rather poor and the mouldings were very complex and expensive to make.
- It is very hard to design for peel as the peel stresses rise very rapidly towards the free edges
- A large external fillet will help
- We need to look at the stress analysis and deduce the maximum acceptable defect size using the joint’s fracture toughness

Slide 27:

- Close to the free edge we would need to guarantee to avoid any defect above about 3mm long
- There is no NDT method that could reliably detect such flaws in such a complex structure
- Even if we could detect the flaws there is no realistic rework option
- The design therefore can not be saved and a complete redesign is required
- That redesign needs to focus on a much reduced cost as well as a greatly improved reliability

Slide 28:

**To succeed in failure investigation and redesign we need**

- Adequate time
- No external pressure
- No attempt at a witch-hunt
- Adequate resources
- Access to all relevant information
- Clear lines of responsibility

Slide 29:

**In my experience we usually have this situation**

- Very tight timescales
- A lot of external pressure
- Lawyers involved – they want to know “who made the mistake?” and not “How did this happen?”
- Limited resources
- May be obstructed in seeking information
- Responsibility may be unclear.

Slide 30:

Whether we are investigating defects caused by failures in manufacturing or failures in service due to defects in structures the process has to be driven by a chain of evidence that is structured around an understanding of the causes and effects of defects. Adopting a structured approach to the investigation so as to move one step at a time on an assured basis avoids a great deal of the misunderstandings that can easily cause difficulties in reaching a robust solution.
Variability and tolerancing workshop
March 26^{th} NCC

Task 1
Participant number ........................

Place a 150 x 150 mm ply against the lines shown below:
Task 2: 0.125mm Challenge

Participant number ................................

1. Try and place a 150mm x 150mm ply to within 0.125mm?
2. Hand cut a 150mm x 150mm ply down to 120mm x 120mm.
3. Place this ply 17mm from the Bottom and left edges of the first ply
4. Measure the placement accuracy and size with the callipers.
5. What tolerance would be appropriate for this task?
Task 3A

Step 1:
- 2 participants each layup a 620mm x 410mm ply onto either of the U-shaped moulds in a 0°/90° configuration: (do NOT use the provided instructions)
- Assess the quality (wrinkles/bridges/symmetry etc) and compare with your partners work:
  - Ply position?
  - Shear angle?
  - Shear location (e.g. which bits of the ply are sheared)

Step 2:
- The other two participants not repeat the layup but DO use the instruction booklet provided.
- Quality check and asses the layups, are they more similar?
Task 3B(1)

For plies placed onto flat moulds, defining the position of the ply can be straightforward.

For curved moulds with no angular features this can be more difficult:

This mould of a face has a single glass ply placed mid-layup.

Task:

- Two of the group have to illustrate and/or describe how the location of this ply could be defined and communicated. (Ply template is provided)
- Once completed, remove the ply.
- The remaining two will try to replicate the ply.
- The next group will work from this new ply, and the end of the session we will compare the original ply with a final version.
Task 3B(2)

Ply placement in awkward locations:

- Place a 200mm x 200mm ply, following the datums (taped lines) on the rear of the large aluminium tool.
- Do NOT move the tool (Unless you can’t actually reach the back!)
- Once complete, rotate the tool and check the ply:
  - Alignment to the datums
  - Bridging/ply-tool contact
Task 3C

Double curvature

- There are two sets of interchangeable moulds, each with an ‘Easy’, ‘Medium’ and ‘Difficult’ version, with increasing ramp angles from 20-73 degrees.
- Each laminator should do all three mould from either set, work in order of ‘easy’ to ‘difficult’.
- Align the ply as best as possible to the datum’s provided:
- After each ply is laid down, quality inspect the ply:
  - Alignment to datums
  - Bridging (non-contact in corners)
  - Wrinkling
  - Symmetry
- Compare the ply quality and the ramp angle increases.
Task 3D
Layup speed vs tolerance.

- This exercise is a demonstration of this effect. Two sets of templates are provided, one with a very tight tolerance, and another with a wider tolerance.
- Before layup each person removes the backing film from 4 plies (60mm x 60mm), ready for layup.
- In a ‘team relay’ style (e.g. only one layup at a time) Starting with the ‘tight tolerance’ templates, each person lays down 4 plies each (each one on a fresh template). The edge of the plies must all be within the template lines as shown below:
- Time how long it takes to layup 4 plies.

Repeat the trial but this time using the ‘Wide tolerance’ template, again timing the layup.
- Compare the times taken
- Would there be a serious aesthetic/structural consequence of a wider tolerance?
Tight tolerance template (2 plies)
Wide tolerance template (2 plies)
Learners will be able to:

• Understand the basics of costing in a production environment

• Understand company structures and cost centres

• Distinguish between different cost types
Why do costing?

- Without it, no idea what to charge
  - Overestimate: lose business
  - Underestimate: lose money
  - No costing is a lose-lose situation!

- How detailed?
  - Can we trust our costing?
  - To what extent?
  - Can they guide critical business decisions?
Estimation vs analysis

- Employees who look at part loads/structure to ensure they don’t fail – Stress Analysts

- Employees who look at costs to ensure the company doesn’t fail – Cost Estimators

- Why the difference in title?

- Both are critical to the survival of the business
Estimation

• Wikipedia:

Estimation is the process of finding an estimate, or approximation, which is a value that is usable for some purpose even if input data may be incomplete, uncertain, or unstable. The value is nonetheless usable because it is derived from the best information available.

• Need the best outcome at every step, despite uncertainty

• Also applies to structural ‘analysis’
  • Utilises and advanced estimation model!
Cost estimation in design

• Focus here is on cost estimation in production, however, impact of design cannot be ignored.

• Product design directly determines a significant amount of production cost

• Identifying costs at the design stage can save a lot of money!
Impacts of design on manufacturing costs

<table>
<thead>
<tr>
<th>Direct contribution to manufacturing costs</th>
<th>Influence on manufacturing costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td></td>
</tr>
<tr>
<td>Labour</td>
<td></td>
</tr>
<tr>
<td>Overheads</td>
<td></td>
</tr>
</tbody>
</table>
Impacts of design on manufacturing costs

- Outline design
- Detailed design and verification
- Assessment

100\% of final costs committed

Time from start of design process

© University of Bristol 2018
Lessons learned in other industries

- Design changes as % of the total

- Company 1
- Company 2

- End of outline design
- End of detail design
- Start of production

50% total
Basics of costing

- At its simplest we can start with an estimate of:
  - How much material we will need
  - How much labour will be directly involved in converting that material into product
  - What we need in terms of energy inputs
  - What we need in terms of equipment, facilities and factory floor space

All of which need to be assessed in £, € or $ terms – and then we may have to worry about exchange rates risks!
Basics of costing

• Manufacturing cost ≠ sale price
  • Realistically, there’s no relationship

• Just taking an overview is not enough
  • Need to get into details to be even approximately close
Basics of costing - Materials

- Should be the easy part
  - Know what’s going into the part
  - Know what’s getting sold to the customer
  - “Buy to fly ratio”

- Waste disposal costs can be high
  - Things that are mixed on demand can have very poor utilisation
  - The cost of ‘cheaper’ consumables such as release film still stacks up significantly
Basics of costing – Bought in

- In principle should be simple too
  - Know what we need
  - Know what we have ordered

- Can have complications
  - Minimum order quantities
  - Delivery schedules

- What’s missing?
Basics of Costing – Direct labour

- Directly involved in adding value
  - Moving parts along the value stream
  - "touch labour"

- Good estimates are not easy
  - Minor changes can mean a large difference in touch labour time

- Currently no accurate way to account for this
  - Significant differences between estimated and actual costs
Lay-up labour - Geometry Impacts

- Experienced laminators given a series of timed lay-up tasks over a graded set of tools
- Increasing ramp angles from 20° to 70°
- Instructed to focus on a “high quality” result.
- Clear trend: Lay-up time increases with difficulty
- Small changes in angle = big impact!
Lay-up labour - Materials impacts

- Material differences
  - 5 slightly different materials
  - ‘Standard tool’
  - Experienced laminators
  - How different is lay-up time?

- All the materials were similar carbon fibre woven cloths with an epoxy matrix
- Lay-up times could still vary by a factor of two!
Lay-up labour – quality issues

• Differences in the ease of work of the material chosen lead to quality differences too
  • More likely to have issues with material that is harder to work with
  • Higher rates of defects, rework, repair, and concessions.

• Differences are hard to predict
  • Not easy to build into a cost model
Basics of costing – Indirect labour

- Activity associated with the supervision and quality control of the production.

- Historically, not to ascribed directly to a specific product
  - Carried in overhead costs

- Can cause significant problems
  - Quality costs related to MRB/rework/repair and concessions can be higher than predicted in the proposal cost estimations
Basics of costing – overhead

• “The cost of doing business”
  • Power
  • Spares and maintenance
  • Amortisation of capital sums
  • Business rates
  • Etc.

• Generally not split on a product by product basis
  • Carried as a cost at the factory level
  • Split among product lines by an agreed scheme
  • These schemes can seem almost arbitrary
Basics of costing – Margins

- Normally accounted at the factory level rather than the product level

- Difference between income and manufacturing costs
  - Must accommodate the costs of doing business today and developing a business for tomorrow

- Costs are not split out on a product by product basis
  - Carried at the factory level
  - Distributed to product lines according to some agreed scheme
Basics of costing – Margins

• Worthwhile to try to delve into the margins a bit deeper
  • Understand how costs develop through the life of a product

• Need to look at the structure of the business as a whole
  • Understand the relationships between the various activities
Structure has been deliberately kept functional rather than hierarchical as it's more important to identify all the tasks/roles than ascribe them to the correct thread at this stage.

Clearly some functions have been expanded much more than others at this stage.
Structure has been deliberately kept functional rather than hierarchical as it’s more important to identify all the tasks/roles than ascribe them to the correct thread at this stage.

Clearly some functions have been expanded much more than others at this stage.
Company structure

• Almost everything that was in the first organisation chart is now in the little blue box

• In a small company many of these functions could be carried by one or two people
  • The issue is then capturing this
  • They still generate a cost!

• Tendency is for the manufacturing people to see their part as generating all the money and everyone else as spending (or wasting) it
  • Whilst I have some sympathy for that viewpoint it is at best an oversimplification and should be resisted.
Non-Recurring costs (NRC)

• So far, have only discussed recurring costs
  • Costs that are incurred by an ongoing project to manufacture and supply components or structures.

• Non-Recurring Costs (NRC)
  • Costs incurred in getting to the point of switching on a production line
  • In the context of low volume manufacture these costs can be a substantial part of the total project costs
Non-Recurring costs (NRC)

• NRC can include:
  • Design costs;
  • Materials allowables programmes,
  • Prototype and production tooling costs;
  • Prototype manufacture costs;
  • Prototype testing and qualification costs including first article cut-up etc;
  • Production line set-up costs;
  • Component specific equipment costs;
  • Development of acceptance criteria,
  • Part specific inspection, NDT and QC/QA costs etc, and the costs of financing all the above.

The actual design part of this can be an almost trivial part of the total in terms of direct cost, however the design will have a very strong influence on every other aspect of the NRC.
Non-Recurring costs (NRC)

• NRC costs can vary greatly between two different designs for the same component

• An example:
  • Design 1: mechanically fastened assembly of three autoclave moulded parts using a well understood carbon cloth/epoxy system
  • Design 2: a one shot, very complex moulding using materials for which no allowables exist; a novel process
  • The difference in the NRC could be huge
  • The novel approach can be assumed to give lower recurring costs
  • How does this develop through the project?
The new technology is much more profitable/unit.

Only improves on the old technology in the last 10% of the project lifetime.

This is common.
Through-project costs

• NRC could be seen as a one off charge for the technology as a whole
  • Makes more sense to take that cost out of being project specific
  • Re-use the technology the NRC has given us

• NRC are a very important factor
  • Tend to work against the introduction of new technology
  • Important to recognise that these are very real costs
  • Using tried and tested technology can be the most sensible course of action
Other technology & development costs

- There are other significant costs associated with just maintaining and developing technical competence and competitiveness such as:
  - Training
  - IT investments
  - Manufacturing equipment upgrades
  - Technology development/acquisition
  - Partnership development
  - Supply chain development
  - Acquisition of market and leads data
Conclusions

• Understanding costing requires us to understand the structure of the manufacturing organisation and how that fits into the wider structure of the company organisation.

• We need to recognise that generating a good cost estimate is critical to the future prosperity of any company.

• But generating a good cost estimate is of itself generating a cost, so we need to be very clear about the assumptions that we make.
Costing Fundamentals

Introduction
This lecture will give an initial introduction to the concept of costing within a production environment and provide an overview as to why this is so important.

Learning objectives:
- Understand the basics of costing in a production environment
- Understand company structures and cost centres
- Distinguish between different cost types

Why do costing?
Without an effective approach to costing we have essentially no idea how much to charge for what we do. This means we could very easily overestimate costs and fail to win any business, or underestimate costs and lose money on everything we sell.

A better question, really, is how detailed do we need our costing to be – or to what extent can we trust our costings and make critical operational and strategic decisions based on them?

Estimation vs analysis
In most organisations we have people looking at the loads on the parts we design to ensure that they don’t fail in service – we call them Stress Analysts.

In the same organisation we will have people whose job it is to make sure that we understand the costs of what we are doing and thus that the company doesn’t fail – we call them Cost Estimators.

Why the difference when both are mission critical activities?

Estimation
Estimation is the process of finding an estimate, or approximation, which is a value that is usable for some purpose even if input data may be incomplete, uncertain, or unstable. The value is nonetheless usable because it is derived from the best information available.

This definition is from Wikipedia, it captures very well what we are doing in cost estimation where we have to get the best outcome despite uncertainty at every step of the process.

To be honest it probably also applies to the structural analysis side of things – both activities are really estimations

Cost estimation in design
Our focus here is on cost estimation for production but we need to take a very brief look at the earlier steps in the product development process to get the context right.

The costs of the design and wider product development activities need to be recovered by the income from sales of the developed products – but there is also a very direct impact of the design activity on the product costs.
Impacts of design on manufacturing costs

Figure 1: Direct contribution of aspects to the manufacturing costs vs influence on the overall cost

Figure 1 shows that, whilst the design process itself contributes very little to the overall costs directly (in comparison to materials, labour, and overheads), poor decisions made at this stage can cascade enormous costs through the entire production process.

Figure 2: Demonstration of the influence that early stage decisions have to the final cost

The assessment phase tends to tell us what we’re going to make, what we’re going to make it out of, and what process we’re going to use. By the end of the outline design phase, we tend to know what
our Bill of Materials (BoM) looks like, what our work breakdown structure looks like, and a general overall view of the process. By the end of the first phase, we have committed to around 30% of the total project costs. By the end of second phase, we will have committed to around 70% of the total costs already. However, the curve showing when the actual cost itself will be incurred will have roughly the opposite shape to that shown in Figure 2. The costs will be very low during the first two phases shown, and will rapidly scale up towards the end of the third phase as set-up and production begin.

![Figure 3: Comparison of different companies and where in the total process their design changes lay](image)

In Figure 3, Company 1 have made all the changes in design they will need to make before production begins. However, Company 2 are still making design changes long after the production has begun. During the initial design stage, these changes essentially amount to changing lines on paper, which is very cheap. During the detail design phase, this begins to become more expensive, with analysis being re-done etc., but this is still not requiring physical changes to made. However, by the time we reach the start of production, all the tooling has been purchased and production lines set-up etc. At this stage, the cost of change becomes enormous, and can be prohibitively expensive. In this example, Company 1 is Toyota and Company 2 is General Motors… the financial history of the two companies demonstrates the importance of getting the early stages of design correct!

**Basics of costing**

At its simplest we can start with an estimate of:

- How much material will we need?
- How much labour will be directly involved in converting that material into product?
- What we need in terms of energy inputs
- What we need in terms of equipment, facilities and factory floor space
All of which need to be assessed in £, € or $ terms – and then we may have to worry about exchange rates risks! Just take Brexit as an example – decisions made on the basis of £/$ or £/€ exchange rates 3 years ago could be significantly affecting a company’s production profits now.

A total breakdown of the sales price is given in the Appendix (Figure A1). Take note of some of the aspects that may lead to surprisingly large costs – e.g. scrap. Scrap can account for a surprisingly large amount of the material, up to 30-40% of the roll initially put onto the ply cutter. This is not only wasted material, but needs to be disposed of in a special way, costing even more!

A key thing to note is that the manufacturing cost and the sale price are not the same thing.

While we can write down what we want to do in a few lines, the moment we start to dig into the detail it becomes quite clear that to get to the Profit point is not quite so simple and that we really need to dig into the detail with a fair bit of rigour to be sure that we end up in the right place.

**Basics of Costing – Materials**

In many ways, the materials should be easy to handle as we should know what’s going into the part, and what proportion of what we buy in ends up being sold to the customer. This is known as the buy to fly ratio and can be much lower than we might imagine.

Equally, waste and disposal costs can be very high and must not be neglected – especially for consumables and for things like paste adhesives, sealants and paint that may get mixed on demand and thus have poor utilisation. A good analogy for this comes from Coleman’s Mustard who say they make all their profit from what gets left on the plate. As it’s taken out and used on demand, the utilisation is poor, and so more gets thrown away than actually eaten!

**Basics of Costing – Bought in**

Again, in principle we know exactly what we need and what we have ordered in so there should be no ambiguity about these costs at all. However, things like minimum order quantities and delivery schedules can complicate matters a bit.

If we look at the diagram, we can see that there is actually a big hole in the bought in costs – tooling. Very few companies make all of their own tools in house, and as such the cost for (often very expensive) bespoke tools can be a significant bought in expense.

**Basics of Costing – Direct Labour**

Direct labour, sometimes referred to as “touch labour”, is that directly involved in adding value to the parts being manufactured and moving them along the value stream.

Getting good estimates for this labour is not always easy, as for manual lay-up composites apparently minor differences in the design details can generate large differences in touch labour times for lay-up.

There is currently no very good way of accounting for this prior to preproduction manufacture; which can lead to significant differences between actual lay-up times and the estimated times that may have been used in proposals. Despite our knowledge of this effect, no software exists that can accurately track and predict this, and thus the associated costs.

An example of this is effect is shown with Airbus, who at one point decided to use 10 5 prepreg as it would require only half the number of plies. In principle, this appears to be an immediate saving in
lay-up time. However, this is only the case if the plies are as easy to lay-down, don’t cause problems elsewhere, and don’t cause problems structurally which must be paid for with more material. This shows than none of these problems are actually as simple and straight forward as they may initially appear!

**Lay-up labour - Geometry Impacts**

There is a prevalent debate in the composite industry as to the future of composites manufacture. Whilst the automation of manufacture using AFP is promising, there are some shapes this simply cannot capture with any degree of accuracy (e.g. a tabletop-sized hemispherical dome). As such, the cost of hand-laminating shapes should still be investigated.

Experienced laminators were given a series of timed lay-up tasks over a graded set of tools with increasing ramp angles from 20° to 70°. They were instructed to focus on achieving a “high quality” result.

![Figure 4: Results of a task given to three experience laminators to lay-up over a range of ramp angles, as shown.](image)

There is a very clear trend of significantly increased lay-up time as the ramp geometry increases in difficulty. From a 20° angle to a 70° angle, of what is nominally the same shape, lay-up time can be seen to increase by up to 5 times!

Even a small change in ramp angle has a big impact on lay-up time!

**Lay-up labour – Materials Impact**

Five slightly different materials have been laid down on a “standard” tool surface and the time taken to achieve the layup by experienced laminators has been measured. All the materials were similar carbon fibre woven cloths with an epoxy matrix.
Despite the materials being very similar the lay-up times could vary by a factor of two. This issue with the manufacturability of nominally the same cloth prepregs is rarely (if ever) taken into account at the design stage. Often, in an aerospace environment, you have no choice.

Lay-up labour – quality issues
It should be noted that these issues of large potential differences in lay-up labour due to “minor” design differences will also be very likely to be reflected in significantly different rates of defects, rework, repair, and concessions. If something is ‘harder’ to do, it’s more likely to contain a defect, or be of lower quality.

Again, these differences are real but not at all easy to predict the effects of so as to build them into a cost model.

Basics of costing – Indirect Labour
Indirect labour is that activity associated with the supervision and quality control of the production.

There has historically been a tendency not to ascribe this directly to a specific product but to carry it as part of the overhead costs.

This approach can cause significant problems if quality costs related to MRB/rework/repair and concessions are higher than predicted in the proposal cost estimations. For example, if you have issues with control of quality in one product run, then to improve this next time you may wish to add more supervision to that particular line.

A current trend is to try to reduce line/direct supervision (and the associated costs), and introduce self-monitoring and self-certification for quality control. This can work, but can also lead to a decrease in quality, and that cost of quality will be picked up elsewhere.

Basics of costing – Overhead
The overhead includes things like power, spares and maintenance of production equipment, amortisation of the capital sums related to that equipment and the facilities and factory as well as business rates etc. ‘The cost of doing business’.

Generally, these costs are not split out on a product by product basis but are carried as a cost at the factory level and then distributed to product lines according to some agreed scheme. This tends to be decided simply on a cultural basis of how a specific company operates, rather than weighing up the specific pros and cons of each method and making a reasoned judgement.

Basics of costing – Margins
The margin would normally be accounted at the factory level rather than the product level. It is simply the difference between income and manufacturing costs and has to accommodate all the costs of doing business today and developing a business for tomorrow.

Again, these costs are not split out on a product by product basis but are carried at the factory level and then distributed to product lines according to some agreed scheme.

It is worthwhile to try to delve into the margins a bit deeper so as to understand how costs develop through the life of a product.

To do that we need to look at the structure of the business as a whole to understand the relationships between the various activities.
Company Structure

Figure A.2 in the appendix shows a breakdown of the overall company structure. Almost everything that was in the first organisation chart is now in the little blue box within this company structure breakdown, with this shown in more detail in Figure 5.

![Company Structure Diagram](image)

**Figure 5: Demonstration of how most of what we have looked at so far fits into a small section of the overall company structure**

In a small company many of these functions could be carried by one or two people, but they all do need doing to some extent – and generate a cost that has to be covered. Thus, we must capture all the activities that the company must undertake, understand the cost of those activities, and what contribution these activities make to the bigger picture of the company’s success.

The different groups within the company must talk to each other properly to understand what is happening. If sales and marketing go to roadshows and begin promising things in a timescale and to a cost that production can’t deliver, then the company will not succeed.

There is a tendency for the manufacturing people to see their part as generating all the money and everyone else as spending (or even wasting) it. Whilst there is some sympathy for that viewpoint it is at best an oversimplification and should be resisted.

Non-Recurring Costs (NRC)

All the discussion so far has related to recurring costs. These are the costs that are incurred as a result of an ongoing project to manufacture and supply components or structures.

There are also costs that are incurred in getting to the point of switching on a production line and these are referred to as non-recurring costs. In the context of low volume manufacture these costs can be a substantial part of the total project costs. For example, BMW setting up a new manufacturing line for over 200,000 cars a year will have a significantly higher cost than an aircraft manufacturer looking at a production run of approximately 150 shipsets of components a year.

However, as a percentage of the total costs over the lifetime of the production run, the NRCs will work out to be significantly less important to the higher production environment, despite the substantially larger cost.
NRC can include:

- Design costs
- Materials allowables programmes
- Prototype and production tooling costs
- Prototype manufacture costs
- Prototype testing and qualification costs including first article cut-ups etc
- Production line set-up costs
- Component specific equipment costs
- Development of acceptance criteria
- Part specific inspection, NDT and QC/QA costs etc, and the costs of financing all the above

The actual design part of this can be an almost trivial part of the total in terms of direct cost, however the design will have a very strong influence on every other aspect of the NRC. This shows that we should really utilise the entire design space we have when considering these aspects, especially given the pay-off this could entail.

*Figure 6: An NRC structure chart*
Again, the specific structure of this chart is less important than ensuring everything which needs to be on it is, and it can be used to ensure that a cost has been accounted for in every aspect.

A common problem is for the design stage to be delayed and stretch, but a fixed deadline to remain unmoving. As such those on the right-hand side of the chart receive significantly less time than desired to fulfil their requirements. Often, it’s much more sensible to start this earlier on in the development stage.

NRC costs can vary greatly between two different designs for the same component.

For example, if one design calls for a mechanically fastened assembly of three autoclave moulded parts using a well understood carbon cloth/epoxy system; and another calls for a one shot, very complex moulding using materials for which no allowables exist, and a novel process, the difference in the NRC could be huge.

If we assume a much lower recurring costs for each unit of the novel approach compared to the old technology case we can look at how the costs vary throughout the project.

*Through-project costs*

![Figure 7: Demonstration of cost/profit throughout the life of different products](image)

The new technology shown in Figure 7 is much more profitable/unit than the old technology. BUT, for the whole project the new technology only improves on the old technology in the last 10% of the project lifetime.

In the case of the new technology the NRC contains some elements that could be one-off charges for the introduction of that technology, rather than for that specific programme and it would probably be better to strip out those costs if that technology could then be used on other projects.

Overall the NRC are a very important factor in many composite development projects and tend to work against the introduction of new technology, but it is important to recognise that these are very real costs and that the use of tried and tested technology can often be the most sensible course of action.

*Other technology & development costs*

In addition to the non-recurring costs associated with getting a specific product into service there will be significant costs associated with just maintaining and developing technical competence and
competitiveness. Figure A.3 in the appendix shows some of the other long-term capital investments that need to be made, and how the NRCs discussed previously fit in to this.

Some examples of the costs associated with maintaining and developing technical competence and competitiveness are:

- Training
- IT investments
- Manufacturing Equipment upgrades
- Technology development/acquisition
- Partnership development
- Supply chain development
- Acquisition of market and leads data

Each of the investment strands shown on the diagram take significant money. For example, contrary to popular belief, a successful supply chain does not grow organically and maintain itself, it must be carefully controlled and invested in in order to flourish.

A lot of training also seems to suffer from this lack of understanding of where investment of cost should go and at what point. A lot of training will tend to be done on the fly/on the shop floor.

Conclusions
Understanding costing requires us to understand the structure of the manufacturing organisation and how that fits into the wider structure of the company organisation.

We need to recognise that generating a good cost estimate is critical to the future prosperity of any company.

But generating a good cost estimate is of itself generating a cost, so we need to be very clear about the assumptions that we make.
Appendix

Figure A.1: Total breakdown of the sales price
Figure A.2: Breakdown of the structure of a company

Structure has been deliberately kept functional rather than hierarchal as it's more important to identify all the tasks/roles than ascribe them to the correct thread at this stage. Clearly some functions have been expanded much more than others at this stage.
Figure A.3: Long-term capital investment costs, with the NRC discussed highlighted
Costing Methodologies

Kevin Potter
Learners will be able to:

• Understand the different approaches to production costing
• Understand when to use different approaches
• Describe the underlying concepts of Life Cycle costing
Possible approaches to costing

• Can estimate material, jig and tool costs

• Estimating labour costs can be hard
  • As can scrap/rework rates etc.

• Need to accommodate all the operations
  • Ensure each project pays “fair share”

• Historically, questionable methods have been used to do this
Burdened or built-up labour rate

• Simplest method:
  • Take all costs (apart from shop-floor labour)
  • Divide through by number of shop floor hours
  • Gives cost of each hour of shop floor production labour
  • Add to materials and direct labour to give total production cost

• Could include everything in company turnover
  • Often does not include production material
Burdened or built-up labour rate

- An example: Typical medium sized UK company
  - Annual revenue ~ £160k/FTE at breakeven
  - Assuming:
    - Materials and other bought in have a cost at 25% of the revenue
    - 80% of the workforce is chargeable direct labour at 1600 available hours/year

- Calculation of direct labour FTE to be charged out to manufacturing projects
  - \((160k-40k)/(0.8\times1600) = £94/hr\)
  - This just covers costs, not profit!

- For reference, UK median annual income of about £29k
  - Hourly rate (including NI, pension etc.) ~ £24
  - Chargeout rate here ~ 4x wage rate!
Costing on a burdened labour rate

• Now have a very simple system

• Can simply multiply direct labour hours by 94 and add material costs
  • Reach a breakeven sale point
  • Use this and NRC to negotiate a sale price

• Can be arguably all the costing required
  • Company with single product and process
  • Experience of NRC cost and labour hours interpolation from real data
  • Using just this will minimise direct cost of costing
Reality check!

- There are problems with this approach!

- Low cost job:
  - Room temperature cure contact moulding
  - Home-made plaster tooling
  - One person with no oversight
  - Minimal quality requirements
  - This would be enormously overcosted, and likely never be accepted (but potentially extremely profitable)

- High Cost Job:
  - 100% use of AFP to make a primary structure
  - Company would lose substantial amounts of money
Breaking down costs - Fixed vs Variable

• Need a more realistic approach
  • Start by breaking the costs up into different categories
• Can begin with fixed vs variable costs

• Fixed Costs: don’t vary with production volume
  • Management
  • Rent, utilities, insurance etc.
  • Investment costs/NRCs can also but here (if product lifetime is known)

• Variable Costs: increase as output increases
  • Labour
  • Materials, consumables etc.
Breaking down costs – Quality costs

• Can be where complexity begins

• Some aspects of quality are *fixed costs*
  • Specific quality documentation
  • Other NRCs to confirm quality

• Some are *variable costs*
  • In process/product inspection
  • Rework, repair and concessions
  • Non-conformances due to design/training etc.
Breaking down costs – Production Machinery

• Some machinery will be needed

• Many organisations have standard machine cost tariffs
  • Can be a total £/hr charge
  • Can be broken down to separate costs

• This is company confidential data
Estimating machinery costs

• Step-by-step process:
  1. Cost of purchase
     • Includes requirements capture, specification development, any bidding costs
  2. Costs of installation
     • Includes any civil works such as pits and running services to the equipment
  3. Costs of any ancillary equipment needed
     • e.g. A liquid nitrogen plant or specialist software
  4. Costs of commissioning,
     • Writing H&S/Risk Assessments and SOPs
     • Initially reduced efficiency in a learning phase etc
  5. Gives us cost of the machinery installed and ready to use in production = £XXX
Estimating machinery costs

• What’s the useful life of the machinery?
  • Large press – Likely >10 years
  • Laptop – Likely < 2 years

• How to use this estimation
  • Take £XXX and divide through by the assumed life
  • Need to generate enough for a replacement at the end of the assumed life
Estimating machinery costs

• Just capital costs so far

• Look at the other costs of ownership
  • Regular maintenance/annual service
  • Periodic minor upgrades/occasional major upgrade
  • Dedicated software/end user technical support

• Having considered all this, let’s use a numerical example
Estimating machinery costs

• AFP with laser heating (Purely fictitious costs!):
  1. Purchase cost £2M
  2. Installation costs £0.5M
  3. Ancillary equipment costs £0.25M
  4. Costs of initial learning phase £0.4M
  5. Total procurement to usage cost = £3.15

• AFP technology is constantly updating so 5 year life assumed - Annual charge of £0.63M

• The lesson: cost of the machine itself is just the beginning!
Estimating machinery costs – Annual costs

• Annual capital cost - £0.66M
  • Assuming a small opportunity cost
• Supplier maintenance contract - £0.2M
  • 10% of purchase price
• User maintenance costs - £0.1M
• Software support costs - £0.1M
• Dedicated technician support - £0.1M

• Giving a total annualised cost of £1.16M/year to recover
Estimating machinery costs – Hourly costs

• Need to convert annual costs to hourly costs

• Most identify what basis the cost will be apportioned on

• 24/7 factory
  • 8,760 hours available, take 8,000 as a reasonable estimate
  • This gives £145/hr (assuming constant workflow)

• RTO operating a 12 hour working day
  • £290/hr to cover costs
Estimating machinery costs – sensitivity

- Hourly costs are sensitive to assumptions
  - Especially utilisation

- Less sensitive to lifetime assumptions
  - Start from a 5 year lifetime assumption
  - Change to a 10 year lifetime assumption
  - Estimated hourly cost reduced by <30%

- Could critique the sensitivity of your own companies costing process
Estimating machinery costs – sensitivity

• These calculations become more complicated when applied to reality

• Bidding on a job using an AFP, but in reality the AFP won’t be in constant use
  • Should cost at a rate to fully cover costs then
  • However, this could lead to being too expensive to win bids
  • May have to accept a lower cost
  • Then need to find more work to increase the utilisation!
Using machinery costs

• For hourly machinery costing, time devoted to one task is what’s important
  • *Not* the time carrying out effective work

• For example, regular debulks on a tool occupying an AFP
  • Still using AFP time
  • Could add extra cost to allow AFP to carry two tools
  • This way, could always be laying down prepreg
  • Machine hourly cost provides this simple business case
Using machinery/facility costs

- Start with simple work breakdown structure
  - Assign relevant machinery or costs as we go
  - Give quick indication of where costs are

- Can group these into cost bands for simplicity
  - Can use real facility data in a spreadsheet for ease also
Approximate cost levels

• Very High – Probably >£100/hr
  • E.g., AFP, Large Autoclave, Automation cell, Large area NDE, Heavy or fast acting press.

• High – probably £60 - £100/hr
  • E.g. CT scanning, Large area CMM, Large HDF, Heavy duty robot.

• Moderate – probably £30 - £60/hr
  • E.g. Specialised materials characterisation kit, 3D scanning, small autoclave or press, ply cutter, waterjet cutter.

• Low – probably < £30/hr
  • E.g. basic materials characterisation kit, small ovens, smaller press, hand scanners, resin injectors, clean room space.
Approximate cost levels

- Need to decide on right level to itemise costing
- Surprising if AFP rolled into overhead/fully built up labour rate
- Smallest cost elements usually built into overhead
  - Cost of itemising them becomes significant in itself
Cost estimating

- Begin with material cost
  - From design drawings or even sketches, size and shape plies can be found
  - These can be nested for the most efficient use of material
  - Allows us to establish material usage and waste

- Can usually get educated guess at material cost very early
  - Even before formal design drawings
Cost estimating

• Can assess manufacturing hours using historical records
  • Use suitable reduction factors (e.g. learning curve)
  • Based on real experience of similar projects

• Complementary approach: break production into small blocks
  • Use if less historical data available
  • Assess each small block to reasonable accuracy
  • E.g. cutting rolls of prepreg into kits can be broken into subtasks
Activity listing for prepreg kitting

1. Withdraw prepreg from stores, check and record stock level, transfer batch numbers to process sheets.
2. Leave prepreg to reach room temperature before opening bags.
3. Obtain templates, check against process sheet requirements.
4. Open bag, roll out 5m of prepreg onto cutting bench.
5. Cut out prepreg to templates; at an average speed of 1m/minute.
6. Label prepreg plies, with template and batch number.
7. Bag up, seal and identify kit.
8. Bag up, seal and record remaining length of prepreg.
9. Place prepreg roll in shop floor freezer, transferring batch details to freezer record book.
10. Transfer kit to holding freezer or shop-floor, with all paperwork filled in.
11. Return templates to storage.
Indirect costs

• Need to identify as many of the indirect costs as possible
  • Especially those that are variable with production volume.

• Some areas should be known
  • Number of supervisors, inspectors, production controllers, production engineers etc.
  • Power requirements for curing components etc.

• Some costs may be more difficult
  • Stores costs, sales department costs, overall administration and management costs, rent and rates etc
  • Some attempt needs to be made.
Example

- Floor beams for a single aisle aircraft: seven different manufacturing approaches

- Looked at materials cost

- Activity list for the total process gives a labour cost

- Overheads costs (including a constant NRC):
  - Assessed as a lump sum on the project
  - Added a notional 5% scrap and rework cost
  - Added 10% profit to arrive at a suitable potential sales price.
Labour and inspection hours vs the number of activities for 7 different designs of aircraft floor beam; each dot represents a different design and manufacturing route.
Labour costs is not the whole story, the best outcome comes when labour and materials are in balance.

Note - the profit as shown in the columns is calculated on the traditional cost-plus method and clearly bears no relationship to reality.
Example

• Outline costings for each design type took only a few hours to generate
  • Were able to discriminate very well between options
  • Allowed the rapid elimination of the four designs not capable of meeting the cost targets.

• Must then consider other cost requirements to decide between the remaining three.
Setting a Price

• Have looked at how much it will cost us to make a product

• Now have to decide how much to ask for the products.

• Should have a reasonable estimate of the production volume
  • Both annualised and total

• Allows us to generate revenue predictions for multiple scenarios
  • Try to understand the impacts of different scenarios
Scenario planning

• Generally the case that there will be a cost of getting into production
  • The first stage of any project is burning money today to develop business later

• Any overspends, overruns or inadequacies in preparation at this stage will have serious implications at later stages in the project.
Scenario planning

• Have to make assumptions about the volume of parts to be manufactured and delivered

• Think through the implications of those assumptions!

• Expect deliveries to start at a lower level and ramp up over time

• If we make the wrong assumptions about that ramp rate:
  • Unable to meet demand – annoying the customer
  • Or with a much higher cost base than we have planned – annoying the shareholders
Scenario planning

- Development costs will typically rise through the development process
  - Tooling, prototypes or certification costs mount

- Production rates:
  - Start low
  - Rise to a constant rate
  - Eventually dwindling to close to zero as the project starts to close

- Worst case is an overrun on costs and an overestimate on production volume
  - Best case is an increase in volume or reduction in costs
Scenario planning

• Tendency to take a very bullish approach to production costing
  • E.g. assuming that sales volume will increase and production costs will fall
  • And that the customer will still pay the same!

• Recent issues at both Airbus and Boeing show how dangerous those assumptions can be

• The same is true in other industries
  • Demonstrated by the Dieselgate issues in automotive
Life cycle costing

• There are really two versions of life cycle costing that have been used.

• The first is what might be thought of as a narrowly defined business model
  • Total cost of an asset or production capability over its entire life cycle from procurement to disposal

• We have largely covered that activity under Estimating Machinery Costs
  • Apart from issues of end of life disposal and reclamation of brown field factory sites
  • Massive for nuclear power but not for a composites factory
Life cycle costing

• The other approach: Go beyond the factory floor

• Look at the costs in operation of the manufactured components and structures
  • E.g. look at the total energy usage/CO2 emissions in a carbon fibre aircraft structure
  • Compare to an aluminium

• Composite structure has a higher environmental footprint in its manufacture, much lower one in use
  • Why we went down the composites road for aircraft in the first place
Life cycle assessment

- Examine the broader costs of extracting the materials that have gone into the manufacturing process
  - Critically, the costs of environmental harms remote from our factory operations

- Attempt to cost the harm done in use
  - E.g. the current issue of air pollution.

- Forces us to look at our waste streams
  - Drives a lot of the desire to develop more recyclable composites and bio based fibres and resins
Life cycle assessment methodology

- Life cycle assessment (LCA) identifies environmental impacts of product:
  - From extraction of raw materials
  - Through use/re-use
  - To eventual disposal.

- Holistic approach
  - Avoids shifting burdens from one part of system to another.

- Standardised (uniform application of LCA)
  - Goal and scope definition (ISO 14041)
  - Inventory analysis (ISO 14041)
  - Impact assessment (ISO 14042)
  - Interpretation (ISO 14043)
Life cycle assessment

• Little doubt that life cycle assessment is here to stay
  • Regulatory framework is likely to become tighter rather than looser

• Much better to work with the grain and expand our cost horizons
  • Enables us to maintain that increasing composites use is a public good
  • Especially when plastics are being viewed as a public enemy!
Conclusions

• We live in an uncertain world and the best we can hope to do is to identify the risks and plan for them as best we can.

• To do that we need an honest appraisal of our cost structures and a transparent system for assessing the costs of both doing business in general and of the specific products that we are making – and we increasingly need to be able to do that in a global context.
Costing Methodologies

Introduction
This lecture will give demonstrate different approaches than can be used for production costing and how these should be used, along with defining Life Cycle Costing.

Learning objectives:

- Understand the different approaches to production costing
- Understand when to use different approaches
- Describe the underlying concepts of Life Cycle costing

Possible approaches to costing
We have seen that, within limits, we can estimate the materials costs, and product specific jig and tool costs, but that estimating labour contents can be problematic, as can estimating scrap and rework rates.

Even when we have those costs identified we need a way to accommodate the costs of all the rest of the operations to ensure that any project pays its “fair share”.

Historically, the apportioning of this fair share has led to some very questionable practices.

Burdened or built-up labour rate
The simplest system is to take all the costs apart from shop-floor labour directly involved in production and divide through by the number of shop floor hours. This then produces a figure for the cost to the company of each hour of shop floor production labour and all the support that this requires. This can then be added to the materials and direct labour costs to get a total production cost.

Costs could in principle include everything that sits within the turnover of the company, but would more usually not include the production materials.

A typical medium sized engineering/manufacturing company in the UK might have an annual revenue in the region of £160k/FTE at breakeven.

Assuming that materials and other bought in have a cost at 25% of the revenue and that 80% of the workforce is chargeable direct labour at 1600 available hours/year.

Then each direct labour FTE needs to be charged out to manufacturing projects at \( \frac{(160k-40k)}{(0.8 \times 1600)} = £94/hr \) to cover all the costs, or a bit higher to include a notional profit.

For comparison at the UK median annual income of about £29k the hourly rate taking NI and pension costs etc gives an equivalent cost of about £24/hr so the chargeout rate here is about 4 times the wage rate.

Costing on a burdened labour rate
We now have an extremely simple system to operate.
Once we know the direct labour hours, we simply multiply by 94 and add on the materials costs to reach a sales price at which the company breaks even. Armed with this information and the NRC we can negotiate a price.

In a company making a single product type, with a single process type where there is good experience of interpolating NRC and labour hours from prior real tracked production data this is arguably all the costing you need and minimises the cost to the company of doing cost estimation.

**Reality Check!**

However, a moment’s thought is all it takes to show the problem with this approach.

A room temperature cure contact moulding job being done on home-made plaster tooling by one person with no need for supervision, oversight or NDE and minimal quality requirements will be ludicrously overcosted – but astonishingly profitable if the customer were stupid enough to agree to the costing.

On the other hand, a job needing 100% use of an AFP machine to make primary structure will be losing buckets of money if costed on this basis.

**Breaking down costs**

*Fixed vs Variable*

If we want to have a more realistic approach to costing, we have to start breaking out the costs into different boxes.

One place to start is with fixed and variable costs.

Fixed costs don’t vary with production volume, so management overhead, rent, rates, utility bills (apart from production water, energy etc), insurance and so on are fixed costs. Investment costs such as the NRC for product development should really be taken as one-off costs but can be held inside the fixed costs if we know the product lifetime.

Variable costs increase as the outputs increase, so include labour, materials, consumables, inspection and NDE.

*Quality Costs*

In some ways this is where some complexity starts to come in.

Aspects of Quality such as generating product specific quality documentation belong in the NRC and are thus fixed or one-off costs.

Aspects of quality such as in-process and product inspection, NDE, MRB, Rework, Repair and Concessions are clearly variable with both the production volume and the level of non-conformances which will be related to design details, training, production line supervision and so on.

*Production Machinery*

Whatever we are making some production machinery will be needed and in many organisations there will be a standard tariff of costs for various pieces of equipment. These may be expressed as a total £/hr charge, or as separate costs for the machine capital cost, power usage and the machine consumables or operating costs.
Such costs will definitely be regarded as company confidential giving us no generic data to work with, so to get to a reasonable figure we’ll have to start from the ground up.

**Estimating Machinery Costs**

We need to do this step by step.

1. Cost of purchase – including the costs of requirements capture, specification development, any bidding costs
2. Costs of installation including any civil works such as pits and running services to the equipment
3. Costs of any ancillary equipment needed – might be a liquid nitrogen plant or specialist software for example
4. Costs of commissioning, writing H&S documents, Risk Assessments and SOPs and an initially reduced efficiency in a learning phase etc
5. This then gets us to the cost of the machinery installed and ready to use in production = £XXX

The next thing to do is to take a view on the useful life of the equipment.

Will it last >ten years as might a hydraulic press or an Instron testing frame – or two years as might a laptop. We need then to take £XXX and divide through by the assumed life, as by the end of that life we need it to have generated the cash flow to replace it.

So far, we have just looked at the capital costs of the equipment, we now need to look at the other costs of ownership. Most equipment will need annual servicing, regular maintenance and periodic minor upgrades. In the case of the long-life items, more occasional but more expensive upgrading will also be needed. Some high value equipment will have dedicated software and end user technical support, which again might have to be taken as a charge on the equipment.

At this point we need to drop in some numbers and see where we get to.

We can base some estimates on an AFP machine using laser heating, although it must be emphasized that these are purely fictitious costs.

1. Purchase cost £2M
2. Installation costs £0.5M
3. Ancillary equipment costs £0.25M
4. Costs of initial learning phase £0.4M
5. Total procurement to usage cost = £3.15

An AFP Machine would be something expected to be constantly updating so a 5-year life will be assumed, and the annual charge becomes £0.63M.

So, the first message here is that the cost of the machine itself is not even close to being the end of it.

**Annual Costs**

- Annual capital cost £0.66M (assuming a small opportunity cost)
- Supplier maintenance contract £0.2M (10% of purchase price)
- User maintenance costs £0.1M
- Software support costs £0.1M
- Dedicated technician support £0.1M
Giving a total annualised cost of £1.16M/year to recover.

**Hourly Costs**  
An annual cost is OK at one level, but we really need to convert it into an hourly cost when looking at costing for specific tasks. The critical thing then is to identify what basis the costs will be apportioned on.

A factory might run 24/7 generating a potential 8760 hours available and 8000 hours might be a reasonable estimating point giving £145/hr – assuming that we have the workload to keep feeding the machine.

In an RTO operating a maximum 12 hour working day the hourly cost would have to be £290/hr to cover the costs.

**Sensitivity**  
The hourly cost can be rather sensitive to the assumptions made, especially to the utilisation factors.

It is rather less sensitive to the assumption made on the lifetime of the equipment as the other annual costs are significant. Going from a 5-year assumption to a 10-year assumption reduces the estimated hourly costs by less than 30%.

If this were part of a formal academic training, I'd be setting you a task to return to your own companies and do a critique of your equipment costing processes.

In practice, if we are bidding for work that requires the use of an AFP but will not fully utilise that AFP on a 24/7 basis, we should ideally cost at a rate that fully covers the cost of the machinery. However, this can lead to being too costly to win any bids, so accepting a cost on a higher utilisation rate may be acceptable - so long as a Business Development action is put into place to acquire additional activity for the machine.

**Using machinery/facilities costs**  
It should be emphasised that if machinery costs are being assigned by the hour it is the time that the machine is being devoted to one task that is important and not the time that the machine is carrying out effective work.

For example, carrying out regular debulks on a tool occupying an AFP is still consuming AFP time. Accepting a cost to allow the AFP to carry two tools so that it is always laying down prepreg may be sensible, and the machinery hourly cost allows a simple business case to be arrived at.

We should start the costing with a simple work breakdown structure, assigning the relevant machinery or facility costs as we go as this can quite quickly indicate where costs are likely to be falling.

We can put these costs into bands in an attempt to simplify matters a little, although if using a spreadsheet model it may be just as easy to populate a set of drop-down menus with real facility by facility data.

**Approximate cost levels**  
Very High – Probably >£100/hr
• For example, AFP, Large Autoclave, Automation cell, Large area NDE, Heavy or fast acting press.

High – probably £60 - £100/hr
• For example, CT scanning, Large area CMM, Large HDF, Heavy duty robot.

Moderate – probably £30 - £60/hr
• For example, Specialised materials characterisation kit, 3D scanning, small autoclave or press, ply cutter, waterjet cutter.

Low – probably < £30/hr
• For example, basic materials characterisation kit, small ovens, smaller press, hand scanners, resin injectors, clean room space.

A decision needs to be made about the right level to itemise the costing.

It would be very surprising if a company rolled AFP costs into general overhead or fully built up labour rate. I would expect to see the smallest cost elements being rolled into an overhead as the cost of itemising them becomes a significant cost in itself.

Cost Estimating
The easiest thing to do is generally to calculate the materials costs. From the design drawings or even sketches the size and shape of each ply can be found and nested together. This process gives the necessary cutting patterns and enables the total quantity of materials, including wastage, to be established.

It is usually possible to get at least an educated guess at the material content at a very early stage in the design, and certainly prior to the generation of formal drawings.

Manufacturing hours can be assessed from historical manhour records using suitable factors for learning curve reductions, on the basis of real experience on similar projects.

A complementary approach, which could be used if less historical data is available, is to break the total production scheme down into very small blocks, each of which can be assessed with a reasonable accuracy.

For example, the task of cutting rolls of prepreg into kits for lay-up might be assessed as a listing of all the sub-tasks:

1. Withdraw prepreg from stores, check and record stock level, transfer batch numbers to process sheets.
2. Leave prepreg to reach room temperature before opening bags.
3. Obtain templates, check against process sheet requirements.
4. Open bag, roll out 5m of prepreg onto cutting bench.
5. Cut out prepreg to templates; at an average speed of 1m/minute.
6. Label prepreg plies, with template and batch number.
7. Bag up, seal and identify kit.
8. Bag up, seal and record remaining length of prepreg.
9. Place prepreg roll in shop floor freezer, transferring batch details to freezer record book.
10. Transfer kit to holding freezer or shop-floor, with all paperwork filled in.
11. Return templates to storage.

Indirect Costs
Once labour hours and materials have been established (or more accurately estimated), we need to identify as many of the indirect costs as possible, especially those that are variable with production volume.

Some areas such as the number of supervisors, inspectors, production controllers, production engineers etc should be known, as should power requirements for curing components etc.

Stores costs, sales department costs, overall administration and management costs, rent and rates etc may be more difficult to apportion, but some attempt needs to be made.

An Example: 7 Different Designs
We have looked at outline designs for seven different alternative approaches to manufacturing floor beams suitable for a single aisle aircraft.

In each case we have looked at materials costs and prepared an activity list for the total manufacturing process and used that to derive a labour cost.

We have then taken the overheads costs associated with the project (including a constant NRC) and assessed that as a lump sum on the project and added a notional 5% scrap and rework cost and 10% profit to arrive at a suitable potential sales price.

Labour hours for 7 different designs

![Graph showing labour and inspection hours vs number of activities for 7 different designs of aircraft floor beam. Each dot represents a different design and manufacturing route.](image-url)
From Figure 2, we can very quickly see that there are 4, maybe 5 concepts that won’t fit the customer’s requirements. Then there is one which may just reach the customers requirements, and one which provides a bit of leeway (can increase profit, decrease sales price, provide better performance etc.).

Labour costs is not the whole story, the best outcome comes when labour and materials are in balance. Note - the profit as shown in the columns is calculated on the traditional cost-plus method and clearly bears no relationship to reality.

In the case illustrated here the outline costings for each design type took only a few hours to generate - but were able to discriminate very well between competing options and allowed the rapid elimination of the four designs not capable of meeting the cost targets.

Clearly these would have been imperfect, and not wholly captured every single element of each possibility. However, they have distinguished well at this stage between good and bad ideas for going forward.

A consideration of other cost elements might then be necessary to distinguish clearly between the three remaining options.

**Setting a Price**

So far, we have looked at how much it will cost us to make a product, but we also have to decide how much to ask for the products. Assuming that we are bidding against a request for proposals we should have a reasonable estimate of the production volume on an annualised and total basis.

This allows us to generate revenue predictions for multiple scenarios and try to understand the impacts of different scenarios.
Scenario planning

It will generally be the case that there will be a cost of getting into production, so that for the first stage of any project we are burning money today to develop business later. Any overspends, overruns or inadequacies in preparation at this stage will have serious implications at later stages in the project.

Unless we have complete clarity on the delivery schedule, we will have to make some assumptions about the volume of parts to be manufactured and delivered. We need to think through the implications of those assumptions.

We might well expect deliveries to start at a lower level and ramp up over time, but if we make the wrong assumptions about that ramp rate we can find ourselves unable to meet demand – annoying the customer, or with a much higher cost base than we have planned for – annoying the shareholders.

![Figure 3: Comparison of cost/profit margins for different production cost and sales figures scenarios](image)

Development costs will typically rise through the development process as tooling, prototypes or certification costs mount. Production rate may start low then rise to a constant rate, eventually dwindling to close to zero as the project starts to close out.

Worst case is an overrun on costs and an overestimate on production volume – best case is clearly an increase in production volume or reduction in production costs.

There is tendency to take a very bullish approach to production costing, assuming, for example, that sales volume will increase and production costs will fall (without the customer clawing that back).

Recent issues at both Airbus and Boeing show how dangerous those assumptions can be – the same is true in other industries as demonstrated by the Dieselgate issues in automotive.

Boeing would have assumed that the introduction of the 737 Max would provide a steady increase in volume, as the new, more fuel-efficient aircraft would continue to sell in ever increasing numbers. However, having lost two aircraft in quick succession so early into the expected production run has
put a halt on orders, and completely disrupted Boeing’s production plans. A similar issue is true with
the lack of pick-up of the A380 compared to expectation, and taking the automotive industry as an
example, a company making diesel injectors would have seen nothing but production increases for
the past 10 years until hitting a sudden and catastrophic halt. Can try to do your best to protect
yourself against these sorts of issues as much as possible.

Life Cycle Costing
There are really two versions of life cycle costing that have been used.

The first is what might be thought of as a narrowly defined business model – that is to say what is
the total cost of an asset or production capability over its entire life cycle from procurement to
disposal. We have largely covered that activity under Estimating Machinery Costs, apart from issues
of end of life disposal and reclamation of brown field factory sites – which are massive for nuclear
power but not for a composites factory.

The other approach to life cycle costing goes beyond the factory floor and looks at the costs in
operation of the manufactured components and structures.

For example, we can look at the total energy usage/CO2 emissions in a carbon fibre structure
compared to an aluminium one for an aircraft.

We tend to see that the Composite structure has a higher environmental footprint in its
manufacture and a much lower one in use – which is in many ways why we went down the
composites road for aircraft in the first place.

Life Cycle Assessment
Taking a wider view, we can examine the broader costs of extracting the materials that have gone
into the manufacturing process – critically including the costs of environmental harms remote from
our factory operations.

We can also attempt to cost the environmental harms done in the use of the products – the most
obvious current issue perhaps being air pollution.

This approach also forces us to look at our waste streams and drives a lot of the desire to develop
more recyclable composites and bio-based fibres and resins. However, just saying ‘bio-based’
doesn’t automatically make this a solution, and in fact some of the resin chemistries used in bio-
based resins are more toxic/harmful to those working with them than epoxies.

Methodology
Life cycle assessment (LCA) identifies environmental impacts of product from extraction of raw
materials, through use/re-use to eventual disposal. Holistic approach – avoids shifting burdens from
one part of system to another.

Various standards have been put in place to try and help with this. Standardised (uniform application
of LCA):

- Goal and scope definition (ISO 14041)
- Inventory analysis (ISO4041)
- Impact assessment (ISO1042)
- Interpretation (ISO1043)
There is very little doubt that life cycle assessment is here to stay and that the regulatory framework is likely to become tighter rather than looser.

We therefore are much better off to work with the grain and expand our cost horizons to be able to maintain that increasing composites use is a public good – especially when plastics are being viewed as a public enemy.

Conclusions
We live in an uncertain world and the best we can hope to do is to identify the risks and plan for them as best we can.

To do that we need an honest appraisal of our cost structures and a transparent system for assessing the costs of both doing business in general and of the specific products that we are making – and we increasingly need to be able to do that in a global context.
Costing and Decision making

Kevin Potter
Costing decision making - Learning Objectives

Learners will be able to:

- Understand different approaches to decision making in costing
- Identify when the different approaches should be used
- Put the learning into the context of their own organisations

We will take as the starting point the global supply chain we are all part of and where we fall in that supply chain.
The supply chain, very simplified material flows

Example – Aircraft secondary structure composite mouldings

- Ores
  - Copper
  - Aluminium
- Cement
  - Factory
- Crude Oil
  - PAN
  - Epoxy
  - Nylon
- Cores
  - Adhesives
  - CF
  - Prepreg
  - Resin

- Steel
  - Autoclave
  - Tooling
- Aluminium
  - AFP
- Adhesives
  - Prepreg
  - Resin

- Fasteners
  - Machining
  - NDI
  - Software
  - Knowledge
  - Tier 1
  - OEM
  - Lease Co
  - Airline
  - Passenger
Supply Chains

• Each heading has its own separate supply chain

• E.g. an autoclave needs:
  • Metal plate
  • Machining capability
  • Controllers and Control software
  • Computers
  • Seals and Motors
  • Construction equipment to build a pit if needed etc.

• Supply chains are not nice/tidy/linear
  • More like large 3D networks
The supply chain, materiel flows

- In principle:
  - Begins with raw material extraction
  - Ends at final end user.

- In practice:
  - Simply be taking in a large number of direct inputs
    - E.g. production materials, process equipment, data etc
  - Relate directly to our place in the supply chain.

- Many of those inputs will be provided on a COTS basis
  - Have little or no control or negotiating power over price, availability, delivery times etc.
The immediate supply chain

- Prepreg
- Autoclave
- Tooling
- AFP
- Factory
- Adhesives
- Cores
- Mouldings
- Fasteners
- Machining
- NDI
- Software
- Knowledge
- Tier 1
Make or buy decisions

• Immediate supply provides decision points:
  • Could either carry out an activity in house or purchase in goods or services

• Tendency to out-source
  • If it’s more efficient/cost effective

• This decision making process is a Make or Buy Decision

• Getting these right is critical to a smooth and profitable operation
## Make or buy decisions

<table>
<thead>
<tr>
<th>Most likely to make or carry out in house:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Ply cutting</td>
</tr>
<tr>
<td>• Lay-up</td>
</tr>
<tr>
<td>• NDI services</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Least likely to make or carry out in house:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Prepreg</td>
</tr>
<tr>
<td>• Adhesives</td>
</tr>
<tr>
<td>• Fasteners</td>
</tr>
<tr>
<td>• Autoclave supply or maintenance</td>
</tr>
<tr>
<td>• AFP supply or maintenance</td>
</tr>
<tr>
<td>• Software development</td>
</tr>
</tbody>
</table>

### Areas where a make or buy decision is needed:

- Machining services
- Tooling design and manufacture
- Machined/assembled cores
- Factory – own or rent decision
Make or buy decisions

- A series of make or buy decisions have already happened
  - Passenger: doesn’t buy own aircraft
  - Airframer: Tier 1 suppliers
  - Tier 1s: buy in composite parts from you

- A sign of market maturity
  - Every company used to make their own nuts and bolts – this would be madness today

- The first composite parts on aircraft were made by aircraft companies
  - The Bristol Aeroplane Company holds a raft of patents on composites from the 1950s.
Should Cost

• Only want to buy in where there is a quantifiable and sufficient value
  • E.g. requirement that bought in shows a saving of 20% over in-house

• This is obvious for a rivet, a sheet of film adhesive or an AFP machine.

• Some things are less obvious
  • E.g. machined or assembled cores

• What’s a fair price for the core from our proposed supplier?
  • That is to say what it should cost
Should Cost example

- Carry this out in essentially the same way as a production cost estimate

- For a make or buy decision we need to do two costings:
  1. Determine the cost in the way that we would have to do it in our facilities
  2. Determine the cost in the way that it would be done in a dedicated plant with full efficiency
## Should cost – our facilities core machining

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimated Time (hr elapsed)</th>
<th>Touch Labour Time (Lhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry and stabilise core</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Attach to fixture with tape</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Using templates manually cut the ramp angles</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Detach from fixture and clean up</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Manually check all ramp angles with appropriate gauge and report</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Record all process date, tag core and route to store</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>3.3</strong></td>
<td><strong>1.4</strong></td>
</tr>
</tbody>
</table>

*Note: These times are completely hypothetical!*
Should cost – our facilities core machining

• These cores are being made in a completely manual way
  • No machinery costs are allocated
  • A burdened labour rate of £60/hr gives cost/core of approx. £84

• Can estimate the potential output using this as approx. 5 cores/labour shift
  • Note: this could easily turn into 2 cores before lunch and two after
  • Then be over £110/core!

• To finalise, we need to know if there was a difference between our manual process and a brought-in process
  • In terms of materials utilisation or process yield
Should cost – our facilities core machining

- 24/7, three shift basis:
  - Would give about 5000 cores/labour year
  - Cost in the region of £0.5M/year plus materials
  - Might prefer 4 people working on a single shift basis on a 5 day working pattern.

- We might reasonably expect to have quality related costs
  - Manual process delivering quality critical
  - Can set that at 10%.

- So if we want to see a 20% reduction in costs for us to switch to a bought-in process we can set a should cost at £440k/year if we require 5000 cores/year
### Should cost – their facilities core machining

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimated Time (hr elapsed)</th>
<th>Touch Labour Time (Lhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Withdraw core from stable store environment</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Attach to machining centre with vac fixture</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Machine by CNC</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Check all ramp angles on CNC and report</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Record all process data, tag core and route to the store</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>0.35</strong></td>
<td><strong>0.35</strong></td>
</tr>
</tbody>
</table>

Note: These times are completely hypothetical!
Should cost – their facilities core machining

- Now automated, need a machinery cost
  - Assuming CNC router centre at £40/hr, assign a cost of £14/core

- Use a burdened labour rate of £60/hr
  - Gives us a labour cost/core in the region of £21/core

- Can also estimate the potential output using this approach
  - Approx. 20 cores/labour shift
  - So about 20,000 cores/year

- With this level of machine utilisation we have an estimated cost of £35/core compared to our in-house price of £84
Decision Making

- Should be investing in the CNC router ourselves?
  - Appears to offer a huge saving in costs.

- Capacity vs Need
  - If we need 2,000 cores/yr, the CNC router capacity is 20,000 cores/yr
  - Can annualise CNC router costs as 20,000 x 14 or £280,000 in the worst case

- Recovering those costs against 2000 units:
  - Unit cost is £140/unit plus labour!
  - Makes no sense to invest in our own facilities, unless we could feed it a significant amount of additional work.
Decision making

In house Router cost
Manual cost
Target cost
Decision Making

• Below about 4000 units/year:
  • Significantly cheaper to use a manual process than to invest in the capability to do it in house
  • If outsourcing is available at the right cost that should be taken

• Above about 7000 units/year:
  • Good business case that can be made for investing in in-house capability

• In the 4000-7000 units/year range:
  • More detailed analysis would need to be done
Other Issues

• Purchase price is important, but not the only issue.

• Security of delivery date/quality
  • Would fetch high cost in a just-in-time supply chain
  • Would be less important in a buffer stock scenario

• Costing that difference is not trivial
  • Needs to be done as part of the “should cost” estimating.

• Not uncommon in JIT supply chains for significant “fines” for late or poor quality delivery
Offshoring

• Use the same sort of costs-based decision making to decide whether to offshore
  • Build plant in a region of low cost labour

• Vital that assumptions are very carefully assessed
  • Productivity and learning curve effects
  • Possible need for high levels of supervision
  • High costs of expat management
  • High transport costs
  • Increased danger of disruptions in supply

• Many companies have moved offshore and then had to bring the business back home
The supply chain – information flows

- Autoclave
- Tooling
- AFP
- Factory
- Adhesives
- Cores
- Prepreg
- Fasteners
- Machining
- NDI
- Software
- Knowledge
- Tier 1
- OEM
- Lease Co
- Airline
- Passenger

© University of Bristol 2018
The supply chain – information flows

• Material flows downstream in the supply chain, information flows upstream
  • Requirements and specifications
  • Valued product features
  • Customer and end user price and performance expectations

• Need to understand and respond to changes
  • Marketing function of a company
  • Understand their markets and especially the target costs that relate to opportunities for the company
The supply chain – information flows

- Flows of information, both up and down the supply chains (or across the 3D Supply Network) have to be rapid and transparent

- This helps manage the various sources of risk in the supply chain such as:
  - Misunderstandings about end-customer demand
  - Disturbances in product flow; such as loss of a shipment or quality problems
  - External risks; such as changes in regulatory or political frameworks
  - Business risks; such as companies going bust
  - Physical risks; such as the production facility burning down
Target Cost

• Same as “Should Cost” but seen from the opposite direction

• We want to know:
  • “Should Cost” is from our potential supplier upstream in the supply chain to give us cost benefits.

• They want to know:
  • How to take that “Target Cost” and work with it
  • Determine their options in meeting the requirements set by their potential customer
  • Give them a profitable revenue stream.

• In everyone’s interests to have both sides sharing benefits
Target Cost

- Potential customer comes to us with a request to produce some composite structures

- We need to get from them an indication of their target cost
  - Without it we don’t have a starting point to design anything to meet their requirements

- Target costing then tends to operate on a Top-Down basis
  - A tool to support design activities
  - Contrast to the Bottom-Up process that we have looked at so far
Top-down costing

• Starts with what the customer is willing to pay

• Determine which technical solutions are acceptable within the price level
  • If any!

• It can then form the basis for a negotiation with the potential customer
  • Decision on whether or not to bid for work.
Top-down costing example

Selling price = £1000
- profit of £100 = £900 = cost to company
- G&A of £200 = £700 = cost to produce 1 unit
- If the materials cost is £300
- If the bought fasteners cost £60
- If the tooling costs £100/unit

Then the maximum burdened labour cost is £240

• So if the burdened labour rate is £60/hour as before
  • Need to make the part in less than 4 labour hours
  • OR significantly reduce the materials cost
• In all cases, quality costs were in excess of 2 hours of labour
  • In this scenario the manufacturing labour costs actually have to be a 2 hours max of labour/part rather than 4
Top-down costing

• Very crude approach

• However, even a crude budget for maximum materials and labour costs is greatly to be preferred to no budget at all

• Some sort of top-down costing should always be made at an early stage in the process.
  • Unless no indication of max price
  • Should be done as soon as we have an idea of the materials / processes and weight, and thus material budget, at the latest

• Usually have this information +/- 10% at a very early stage in the design process.
Cost breakdown for the 7 designs

• For the designs we looked at earlier:
  • Two or three of the potential designs would have been very quickly rejected on the basis of a top-down costing
  • Would free up resources to investigate the other designs
The importance of good market data

- Composites SME which got into trouble when designing and manufacturing butterfly valves for the chemical plant
  - Could make a large valve more cost effectively than a metal valve
  - Wrongly assumed the same would be true for small valves
  - Wasted a great deal of money chasing an error that should have been trapped on day 1
The importance of selecting your customers

- Obvious that one needs to be careful in selecting your suppliers
  - Without reliable suppliers the supply chain fails.

- Perhaps less obvious, but you also need to be careful in selecting your customers
  - Or at least modifying prices as a response to customers

- Prefer to work with OEMs that asked “How can we help?” when told of problems
  - Rather than the one that simply reminded us of the delivery date!
Conclusions

Costing is a very powerful tool in decision making – to the extent that it is perhaps the most important single tool.

It is critical to understand our position in the supply chains that we are part of and to understand the factors behind Make or Buy decisions and to be able to interrogate and carry out “Should Cost” and “Target Cost” approaches.

We also need to appreciate that there are very significant non-financial influences in the choice of our immediate partners in our supply chains.
Costing and Decision Making

Introduction
This lecture will demonstrate different approaches than can be taken in order to make decisions during the costing process, and when these should be used, along with looking at how this applies to individual companies.

Learning objectives:

- Understand different approaches to decision making in costing
- Identify when the different approaches should be used
- Put the learning into the context of their own organisations

The supply chain, very simplified materiel flows

![Supply Chain Diagram](image)

*Figure 1: An example of a supply chain for aircraft secondary structure composite mouldings*

Supply Chains
In principle we could take any one of the headings in Figure 1 and construct a supply chain around that. For example, to build an autoclave needs:

- Metal plate
- Machining capability
Controllers and Control software
Computers
Seals
Motors
Construction equipment to build a pit if needed and so on

Although we talk about supply chains as if they were nice, simple and linear it is probably more useful to think of them as 3D Supply Networks (think of the classic ‘duck paddling furiously underwater’ analogy).

Material Flows
In principle the supply chain extends all the way from raw material extraction through to the final end user.

In practice we will simply be taking in a large number of direct inputs such as production materials, process equipment, data etc that relate directly to our place in the supply chain.

Many of those inputs will be provided on a COTS basis where we have little or no control or negotiating power over price, availability, delivery times and so on – unless we are a huge company with multiple potential suppliers for each item to be purchased.

The Immediate supply chain

Figure 2: The immediate supply chain based around our area of production

Make or buy decisions
When we look at the immediate supply chain around our production, we will see some decision points where we could either carry out an activity in house or purchase in goods or services.
If we can more efficiently or cost-effectively outsource an activity than doing it ourselves then the tendency is to do that – and the decision-making process around that is a Make or Buy Decision.

Getting these decisions right is critical to a smooth and profitable operation. As an example of where these decisions would be taken:

**Most likely to make or carry out in house:**

- Ply cutting
- Lay-up
- NDI services

**Least likely to make or carry out in house:**

- Prepreg
- Adhesives
- Fasteners
- Autoclave supply or maintenance
- AFP supply or maintenance
- Software development

**Areas where a make or buy decision is needed:**

- Machining services
- Tooling design and manufacture
- Machined/assembled cores
- Factory – own or rent decision

It should of course be noted that a series of make or buy decisions has already cascaded down from the passenger (who has decided not to build their own aircraft) through the Airframer and its Tier 1 suppliers who prefer to prefer to buy composite parts from you than do it themselves.

In some ways this can be seen as a sign of market maturity. There was a time when every engineering company made their own nuts and bolts – this would be madness today. As the market matures, more and more of the work that is initially done in house is cascaded down the supply chain. In the same way the first composite parts on aircraft were made by aircraft companies – the Bristol Aeroplane Company holds a raft of patents on composites from the 1950s.

**Should Cost**

Clearly we only want to buy in materiel where there is a quantifiable and sufficient value for us to be doing that. We might, for example require that the bought in materiel shows a minimum saving of 20% over the cost of doing the job ourselves.

This is a no brainer for a rivet, a sheet of film adhesive or an AFP machine.

It's not so obvious for example for machined or assembled cores, and what we need is to know what is a fair price for the assembled core from our proposed supplier – that is to say what it should cost.
Should Cost: Example

We can carry out a should cost exercise in essentially the same way that we would do a production cost estimate.

In essence, for a make or buy decision we need to do two costings:

1. Determine the cost in the way that we would have to do it in our facilities.
2. Determine the cost in the way that it would be done in a dedicated plant with full efficiency

Core machining in our facilities

As an example, here is the process list for machining a core using our own, in-house facilities:

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimated Time (hr elapsed)</th>
<th>Touch Labour Time (Lhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry and stabilise core</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Attach to fixture with tape</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Using templates manually cut the ramp angles</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Detach from fixture and clean up</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Manually check all ramp angles with appropriate gauge and report</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Record all process date, tag core and route to store</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>3.3</strong></td>
<td><strong>1.4</strong></td>
</tr>
</tbody>
</table>

*Note: these times are completely hypothetical and just used to provide some numbers to the process*

These cores are being made in a completely manual way, so no machinery costs are allocated, and using a burdened labour rate of £60/hr gives us a cost /core in the region of £84.

We can also estimate the potential output using this approach as about 5 cores/labour shift (although that could easily turn into 2 cores before lunch and another two afterwards, which would then be over £110/core).

To finalise this, we would need to know whether there was a difference between our manual process and a brought-in process in terms of materials utilisation or process yield. On a 24/7 three shift basis that would give us about 5000 cores/labour year at a cost in the region of £0.5M/year plus materials, although we might well prefer 4 people working on a single shift basis on a 5-day working pattern.

We might reasonably expect to have quality related costs for a manual process delivering quality critical materials into the process chain and can set that at 10%. So, if we want to see a 20% reduction in costs for us to switch to a bought-in process we can set a should cost at £440k/year if we require 5000 cores/year.
Core machining in their facilities

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimated Time (hr elapsed)</th>
<th>Touch Labour Time (Lhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Withdraw core from stable store environment</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Attach to machining centre with vac fixture</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Machine by CNC</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Check all ramp angles on CNC and report</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Record all process data, tag core and route to the store</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>0.35</strong></td>
<td><strong>0.35</strong></td>
</tr>
</tbody>
</table>

*Note: these times are completely hypothetical and just used to provide some numbers to the process*

These cores are now being made in an automated way, so we need to allocate a machinery cost. Assuming the use of a CNC router centre at £40/hr we need to assign a cost of £14/core. Using a burdened labour rate of £60/hr gives us a labour cost/core in the region of £21/core.

We can also estimate the potential output using this approach as about 20 cores/labour shift or about 20,000 cores/year. On the basis of this level of machine utilisation we have an estimated cost of £35/core compared to our in-house price of £84.

**Decision Making**

The first question is really whether we should be investing in the CNC router ourselves as it appears to offer a huge saving in costs. If we actually only need 2000 cores/year and the CNC router capacity is 20,000 cores a year we can annualise the CNC router costs as 20,000 x 14 or £280,000 in the worst case.

If we had to recover those costs against 2000 units the unit cost is £140/unit plus labour and it would make no sense to invest in our own facilities, unless we could feed it a significant amount of additional work.
Below about 4000 units/year it should be significantly cheaper to use a manual process than to invest in the capability to do it in house, and if an outsourcing option is available at the right cost level that would be the route to follow.

Above about 7000 units/year there seems to be a good business case that can be made for investing in in-house capability. In the 4000-7000 units/year range a more detailed analysis would need to be done.

Other Issues
Whilst the purchase price is obviously very important it is not the only issue.

In a supply chain working on just-in-time principles the security of delivery date or delivered quality would attract a higher value than in a deliver to buffer stock scenario. Costing that difference is not a trivial matter but does need to be done as part of the “should cost” estimating.

It is not uncommon in JIT supply chains for there to be significant “fines” for late or poor-quality delivery.

Offshoring
The same sort of costs-based decision making can be used to decide whether to build our next plant in a region of low-cost labour if our processes cannot be automated.

It is vitally important in these cases to be very sure that assumptions about productivity, learning curve effects, the possible need for high levels of supervision, the high costs of expat management, high transport costs and the increased danger of disruptions in supply are very carefully assessed.
You might find, for example, that a job costed as 4 hours labour in the UK takes 6, 7 or even 8 hours when offshored. You’ll also find that there is not a massive pool of skilled labour and oversight to dip into in these regions.

More than one company has had to decide to bring production home after an attempt to move it to a low wage economy.

The supply chain – Information flows

Figure 4: The information flow in the supply chain around our immediate area. Note how this flows in the opposite direction to the material in the supply chain

Just as Materiel flows downstream along the supply chain there is a flow of information about requirements, specifications, valued product features, customer and end user price and performance expectations running in the opposite direction. This flow of information is crucial to ensuring the correct functioning of the supply chain. If we get bad information coming in from the customer, it is likely that bad decision making will follow every step of the process after.

An example of a valued product feature that drives decision making comes with the Boeing Dreamliner. Whilst the use of composites has the obvious benefits of lighter aircraft and better fuel savings, there is also the ability to pressurise the cabin better. This can be done to a lower altitude, and also with a more humid environment, increasing passenger comfort significantly and providing value to the product.

Understanding and responding to changes in the flow of this information is essentially the marketing function of a company, and one of their jobs is to understand their markets and especially the target costs that relate to opportunities for the company.
For supply chains to work effectively these flows of information, both up and down the supply chains - or across the 3D Supply Network – have to be rapid and transparent in order to manage the various sources of risk in the supply chain such as:

- Misunderstandings about end-customer demand
- Disturbances in product flow; such as loss of a shipment or quality problems
- External risks; such as changes in regulatory or political frameworks
- Business risks; such as companies going bust
- Physical risks; such as the production facility burning down

**Target cost**

This is in essence the same as “Should Cost” but seen from the opposite direction.

We want to know what a fair “Should Cost” is from our potential supplier upstream in the supply chain to give us cost benefits. They want to know how to take that “Target Cost” and work with it to determine their options in meeting the requirements set by their potential customer to give them a profitable revenue stream.

It’s in everyone’s interests to get to a point where both sides are sharing benefits

If a potential customer comes to us with a request to produce some composite structures for them, we need to get from them an indication of what constitutes their target cost. Without that information we don’t really have a starting point to design anything to meet their requirements.

Target costing then tends to operate on a Top-Down basis as a tool to support design activities in contrast to the Bottom-Up process that we have looked at so far.

**Top Down Costing**

Essentially target or top-down costing starts from what the customer is willing to pay for the convenience of buying a product or service from you rather than doing the job themselves.

It can be used to help determine which, if any, of the technically possible solutions are available within an acceptable price level. It can then form the basis for a negotiation with the potential customer and a decision on whether or not to bid for work.

**Example**

Selling price = £1000
- profit of £100 = £900 = cost to company
- G&A of £200 = £700 = cost to produce 1 unit
- if the materials cost is £300
- if the bought fasteners cost £60
- if the tooling costs £100/unit

Then the maximum burdened labour cost is £240

So, if the burdened labour rate is £60/hour as it was before, then we have two options. We need to either make the part in less than 4 hours, or significantly reduce the material costs
In all cases of this scenario, the quality costs were in excess of 2 hours of labour – in this scenario the manufacturing labour costs actually have to be a maximum of 2 hours of labour/part rather than 4.

The approach shown is very crude, but this should not blind us to the fact that even a crude budget for maximum materials and labour costs is greatly to be preferred to no budget at all.

Unless there is no indication at all of the maximum price, some sort of top-down costing should always be made at an early stage in the process. This should be done, at the latest, as soon as we have an idea of the materials / processes and weight, and can thus calculate the material budget. We usually have this information +/- 10% at a very early stage in the design process.

For the designs we looked at earlier two or three of the potential designs would have been very quickly rejected on the basis of a top-down costing, freeing up resources to investigate the other designs more thoroughly.
The importance of good market data

I worked with a composites SME which had got into trouble when designing and manufacturing butterfly valves for the chemical plant market. They could make a large valve more cost effectively than a metal valve and wrongly assumed the same would be true for small valves. They wasted a great deal of money chasing an error that should have been trapped on day 1.

![Diagram showing component cost vs component size for composite and metal parts](Image)

*Figure 7: Demonstration that cost does not directly scale with size when considering replacing a metal part with a composite part*

The importance of selecting your customers

It is more or less obvious that one needs to be careful in selecting your suppliers, as without reliable suppliers the supply chain fails. It is perhaps less obvious, but you also need to be careful in selecting your customers – or at least modifying prices as a response to customers.

Mentioning no names for fear of reprisals I have worked in a company supplying to different OEMs and much preferred to work for the one that asked “How can we help?” when told of problems rather than the one that simply reminded us of the delivery date!

Conclusions

Costing is a very powerful tool in decision making – to the extent that it is perhaps the most important single tool.

It is critical to understand our position in the supply chains that we are part of and to understand the factors behind Make or Buy decisions and to be able to interrogate and carry out “Should Cost” and “Target Cost” approaches.

We also need to appreciate that there are very significant non-financial influences in the choice of our immediate partners in our supply chains.
Factory/procurement Issues

Kevin Potter
Learners will be able to:

• Identify factory design principles
• Understand the impacts of factory design on costs
• Understand the basics of procurement
How do we scale a factory?

- Can assess the time taken and the associated cost of the various steps in composite components manufacture.

- One of those associated costs is the production facility:
  - Building
  - Equipping
  - Running

- Significant cost associated with the physical size of the factory:
  - Don’t want to build more than we need
  - Equally not big enough is even more of a problem.
Factory building costs

- Typical “Big Shed” light factory on a brownfield site will cost ~£800/sqm of floor space to construct.

- Other requirements or specialist facilities can cost much more
  - Air conditioning
  - Strong floors and isolation of vibrations
  - Pits for equipment
  - Office facilities

- Here we’ll assume a moderate value of £1200/sqm
  - Simple, naturally ventilated, 5000sqm flat floor facility
  - Cost around £6M to construct.
Factory building costs

• The construction costs are by no means the end of the story

• Before even production equipment, additional costs for:
  • Land acquisition
  • Local Authority Fees
  • Site preparation
  • Architects fees
  • Project management and project organisation fees
  • Fit out costs for furniture and fixtures
  • Specialist equipment such as cranes and so on
Factory building costs

- Hard to be specific about these costs
  - E.g. Land in London is far more expensive than in Avonmouth
  - Unlikely to be much less than 50% of the construction costs
  - Can be much more

- Cost of getting the keys to our new, bespoke but simple flat floor 5000sqm factory is unlikely to be much under £10M
  - Before we have installed any production specific equipment.

- Factory half this size would be a bit more than half the cost
  - Efficiencies with larger projects
  - Overestimating factory size needed can have serious cost implications
Factory Building Timescale

• Using the NCC phase 2 as an example of a relatively complex factory build with a large and complex pit and all the associated costs.
  • Design and planning took about 4 months
  • Procurement and Planning Application took about 4 months
  • Construction took about 13 months

• The message here is that you can’t get a bespoke facility quickly (or cheaply).
  • May be possible to modify an existing facility but that has problems of its own
Estimating the factory size needed

- We need to start with what we’ll be doing in the factory
  - How we’ll be doing it
  - With what equipment

- Need to “walk” a piece of incoming material through all the processes that will be carried out
  - Identify what equipment is needed
  - Start to think about product flow through the factory in a logical way

- Getting the product flow right is very important
  - The masters at it are IKEA
  - In that case the product is you and the critical thing is to keep you in front of buying opportunities for as long as possible
  - In a factory, we want the opposite
Estimating the factory size needed

• For example, normal assumption is that we’ll need a big freezer as the major part of our incoming materials handling

• Think about Just in Time prepreg deliveries first thing on a Monday morning
  • Why do we need a freezer?
  • Make or Buy decisions we discussed earlier have an impact on both operations and on the way that we might lay out a factory
Factory Layout

• Achieving a good flow of product, people and paperwork through the factory requires careful planning
  • Poor production flow will increase production
  • Hard to quantify by how much.

• Clear distinction between clean/dirty areas
  • Quality critical environment (e.g. aerospace)

• Other issues include autoclave choice
  • One very large oven or autoclave - efficiently cure large batches of tools at one time
  • Multiple smaller ovens or autoclaves - more flexible production and a level of risk mitigation against a single point of failure.
An example of a long life machine!

Factory layout

Achieving a good flow of product, people and paperwork through the factory does require careful planning and poor production flow will definitely increase production costs – although it’s hard to quantify by how much.

In a quality critical environment there will also be a need to maintain a very clear distinction between clean and dirty areas.

Other issues might include whether to have one very large oven or autoclave which can efficiently cure large batches of tools at one time or multiple smaller ovens or autoclaves permitting a more flexible production and a level of risk mitigation against a single point of failure.
## Poor plant Layout

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT 14</th>
<th>Machine shop 7</th>
<th>Paint shop 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cure parts 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cure bonding 9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Kit Cutting</td>
<td>2 Lay up</td>
<td>12 NDT / Inspect</td>
<td></td>
</tr>
<tr>
<td>Bond shop 8</td>
<td>5 Lay up</td>
<td>6 Tool clean 4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13 Pack and paperwork</td>
<td>4 Final assembly</td>
<td></td>
</tr>
</tbody>
</table>

Equipment choices

- Assumptions (purely hypothetical):
  - Manufacturing lightly double curved aircraft fairings (left and right handed)
  - Moulded mass 13kg,
  - After edge trimming shipped mass 12kg
  - 60 ship sets/month = 120 mouldings/month
  - Part footprint 2m x 1m (Tool slightly larger)
  - AFP lay-up required
  - Autoclave cure required
  - 100% ultrasonic NDE required
  - Edge trimming and hole drilling required (120 holes)
Equipment choices

- Assumptions:

- Monthly prepreg utilisation = 1600kg
  - Many AFP slit tape bobbins
  - If we want a one month buffer stock of prepreg that sizes our freezer

- AFP lay-up required
  - If we are achieving an effective lay-up rate of 5kg/hr on our AFP one moulding will take up 3hs of AFP time
  - Total of 360 hours of AFP time is needed each month to deliver 5 mouldings/day

- Single AFP machine operated on a 7days a week 2 shift basis
  - Can in principle deliver 7 x 2 x 8 = 112hrs/week
  - Thus meet the AFP time demand
Equipment choices

• The 5kg/hour effective lay-up rate is a key assumption
  • If we are not hitting that rate we might not meet demand
  • Or might have to invest in a second AFP
  • Will then disrupt our nice factory layout.

• Need to have demonstrated this lay-up rate before committing to factory design
  • And ideally before setting a price

• There is perhaps a little wriggle room
  • Will most likely be a ramp up to the 60ship sets/month
  • Ramp up phase can be used to improve the process efficiency
Equipment choices

• Assumptions:

• Autoclave cure required.
  • 8 hour cure cycle means running a single autoclave once a day with the five tools laid up in the previous day
  • Therefore have a need for multiple tool sets

• 100% ultrasonic NDE required
  • Ensure that inspection takes less than the 3hrs needed to lay up
  • Prevent this becoming a bottleneck.

• Edge trimming and hole drilling required (120 holes)
  • Ensure that drill and trim takes less than the 3hrs needed to lay up
  • Prevent this becoming a bottleneck
Autoclave choice

• We can procure a 2.5m diameter by 3.5m long autoclave
  • Can take the day’s batch of 5 mouldings in a single run

• OR we can procure a 1.9m diameter by 3.5m long autoclave
  • Can take 3 tools at a time
  • Would need to run twice a day

• The larger autoclave probably offers better value overall and gives a higher peak capacity if run twice a day
Estimating equipment footprint

- This autoclave is about the size needed to cure the day’s production as a batch

- The footprint is probably five times the working size of the vessel
  - Ancillary equipment
  - Control booth
  - Space for door opening
  - Trolley manoeuvring for loading.

- At this size there is no need for a pit
  - Cheap, flat floor

© University of Bristol 2018
Estimating equipment footprint

- Multiplier is between basic size and footprint needed operationally
  - This is not straightforward

- For this AFP cell, the cell size is ~12 times the tool footprint
  - ~7 times the basic footprint of the AFP machine itself

- Conversely for a manual lay-up cell, the cell size is 3 times the tool footprint as drawn here
  - Probably a bit tight
Office area

- Price and volume assumptions:
  - Fairings sell at £2500 each
  - Sell 1440 fairings/year
  - Factory turnover comes to £3.6M
  - Factory labour force is likely to be in the region of 30FTE.

- If half of them need office space
  - Need ~12sqm/person or 180sqm for them

- The other staff will still require breakout facilities, toilets and showers and we can guestimate this at 120sqm

- So the total “people space” comes to about 300sqm
Summing up the floor area

- Buffer stock of 1600kg of AFP bobbins
  - ~40 boxes
  - Each box might be 80cm x 80cm x 50cm.

- If we can stack 4 high we need 10 stacks
  - Walk-in freezer of 5m x 5m floor area
  - Plenty of space for working and spare capacity for other materials

- We will also need a general storage area as well as quarantine stores
  - General principle: it makes no sense to skimp on storage
  - Let’s say 100sqm of storage area
### Summing up the floor area

<table>
<thead>
<tr>
<th>Factory Floor Feature</th>
<th>Area Required (sqm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezer storage</td>
<td>25</td>
</tr>
<tr>
<td>General stores</td>
<td>100</td>
</tr>
<tr>
<td>AFP cell (estimated above)</td>
<td>50</td>
</tr>
<tr>
<td>Autoclave cell (estimated above)</td>
<td>50</td>
</tr>
<tr>
<td>Drill and trim cell (basically guessed)</td>
<td>50</td>
</tr>
<tr>
<td>NDE (basically guessed)</td>
<td>50</td>
</tr>
<tr>
<td>Packing and despatch (basically guessed)</td>
<td>20</td>
</tr>
<tr>
<td>Office space etc (estimated above)</td>
<td>300</td>
</tr>
<tr>
<td>Circulation space between cells (basically guessed)</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total floor area estimated</strong></td>
<td><strong>745</strong></td>
</tr>
<tr>
<td><strong>Total floor area to allow a little expansion</strong></td>
<td><strong>1000</strong></td>
</tr>
</tbody>
</table>
Factory cost

- Initial figure of £1200/sqm + land etc gives about £1500/sqm total
  - 1000sqm build
  - Factory costs us £1.5M.

- Likely to be paying about the same for the AFP
  - Perhaps half again for installation and environmental control of the cell

- The autoclave is likely to cost about half as much
  - Other major costs will be for the NDE and machining facilities.

- Taking everything together:
  - Likely that the factory will have cost in the region of £5M at the point of switching on production.
Factory cost recovery

• For the sake of making calculations:
  • Say that the cost of financing the factory build is 5% of the sunk costs
  • Value of the factory itself at the end of the 10 years will be just the £1.5M build value
  • Means factory “costs” us £600k/year.

• With ten years of assured production at a constant rate the factory will deliver £36M of revenue.

• In this case, the factory cost is a significant part of the total cost of the project
  • Must be a central part of the overall costing
Factory cost recovery

- Building a new factory looks quite expensive
  - Could well be a better bet than renovating an old factory
  - Or trying to fit the new production activity as an additional product into an existing production facility

- New production activity will not be as efficiently laid out as in a new build
  - May also disrupt the production activity for the current product lines
Procurement

• Procurement is the process of making everything we have gone through so far actually happen

• It is defined as:

  the process of finding, agreeing to terms and acquiring goods, services or works from external sources

• The aim of procurement is to get goods, services or works at the best overall value
  • This is not the same as getting them at minimum cost!
Best value

Best value considerations include:
- Quality
- Delivery
- Security of supply and price
- Intangible issues such as confidence in the potential suppliers’ ability to meet all of their commitments

Formal tendering or competitive bidding process required for public bodies
- Currently set at £181,302 for organisations such as UoB or the NCC

Commercial organisations are not covered by these rules
- Best practice requires some controlled process to be used
## Procurement process

<table>
<thead>
<tr>
<th>Activity</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyse requirements</td>
<td>What do we need?</td>
</tr>
<tr>
<td>Market analysis</td>
<td>Where can we get it?</td>
</tr>
<tr>
<td>Costs collection and analysis</td>
<td>Make or Buy?</td>
</tr>
<tr>
<td>Supplier identification</td>
<td>Who sells it?</td>
</tr>
<tr>
<td>Supplier selection</td>
<td>Who should we buy from?</td>
</tr>
<tr>
<td>Negotiation/Contract</td>
<td>What are the terms?</td>
</tr>
<tr>
<td>Evaluation</td>
<td>How is the supplier performing?</td>
</tr>
<tr>
<td>Supplier relationship</td>
<td>How can we all get value?</td>
</tr>
</tbody>
</table>

© University of Bristol 2018
Analyse requirements

- We need to work out what we need as an organisation based on the business objectives
  - E.g. if we need additional production capacity, options are:
    - Buying more equipment
    - Extending or building a new production facility
    - Sub-contracting some of our activity into the supply chain

- Careful analysis of various options
  - Not necessarily ‘make or buy’ at this point though
Analyse requirements

• What options are technically feasible?
  • Strategy for achieving business objectives

• E.g. if we have a requirement to do more material characterisation:
  • A manufacturing organisation would sub-contract to a test house
  • A University would most likely result in buying more test machines
  • An RTO could go either way

• The answer in each case depends on the business objectives
Market analysis

• We need to understand what’s out there in the market

• Is a well developed and competitive market is available?

• Or are there a very limited number of suppliers are available?
  • Or are all the players in the market are small start-ups?
  • Many OEMs can’t/won’t work with these

• Need to look at the direction of development of a market
  • Might be worthwhile to delay procurement in a rapidly changing market
Costs collection and analysis

• Need as much reliable cost data as possible
  • Allows us to make reasoned decision

• Probably one of the most difficult parts of the process.

• Generally possible to get a ballpark cost to acquire a piece of equipment, software or service
  • Much more difficult to get valid cost data for things like downtime/failure rates for production machinery
  • Talking to current users of the equipment is sensible
Supplier identification

• Finding the right supplier may be straightforward for some issues
  • E.g. many organisations offer facilities/PPE management services
  • A quick google search will provide a lot of choice!

• Finding a supplier for a complex system is more of an issue
  • Decision:
  • Procure the system elements individually and integrate them in house?
  • Work through a system integrator (who may not be familiar with all of the sub-systems)?

• Another area where the procuring organisation’s own expertise will have a significant impact on the decision
Supplier selection

• Most larger scale procurements will be carried out via a competitive bidding process

• May include some/all of:
  • Requests for information
  • Requests for proposals
  • Requests for quotation
  • Requests for tender
  • Requests for development
  • Requests for collaboration

• Different methods for these to go out
  • Direct contact with potential suppliers
  • Through notification services such as OJEU
OJEU

• OJEU: Official Journal of the European Union
  • Publication in which all tenders from the public sector must be published (above the financial threshold we established previously)

• Covers organisations/projects that receive public money, e.g.:
  • Local Authorities
  • NHS Trusts
  • MOD
  • Central Government Departments
  • The NCC and Educational Establishments

• The OJEU website allows any potential suppliers to identify business opportunities across the whole of the EU
Supplier selection

• Need for a clearly defined set of supplier selection criteria
  • Regardless of process used
  • Both to ensure that we procure the right goods or services and, in public procurement, that our decisions cannot be challenged

• It is common to split out proposals into parts, e.g.
  • Technical proposal
  • Management proposal
  • Costing proposal
  • This allows a more in-depth review by the relevant experts

• Outside of public procurement, there is likely to be a lot of contact with suppliers in this phase
Negotiation/Contract

• This is straightforward in principle
  • Although in practice it can get a bit fraught!

• We need to settle many details
  • Delivery/lead times
  • Acceptance testing
  • Commissioning
  • Service level agreements etc.

• At this stage, avoid changing the specification at all costs!
  • Will reopen the whole question of the contract value after we should have closed that down
Evaluation

• Getting a supplier is not the end of the procurement process
  • Arguably it’s just the beginning

• Must watch on the performance of the contract
  • Especially in the case of production equipment contracts
  • Carefully scrutinise the functioning and quality of the equipment as well as the supplier’s performance.

• Logging this information is key
  • Improve our understanding of the market
  • Rank potential suppliers
  • Make better decisions on future procurement activities.
Supplier relationship

- Have looked at procurement of particular goods and services
  - Not the whole story

- Various relationships are present in the supply chain
  - Simple/temporary, such as who does the laundry
  - Relationships of strategic importance, such as a material supplier or toolmaker

- It is usual to set up a formal relationship/partnership arrangement
  - Manages such strategic relationships
  - Avoids misunderstandings!
Supplier relationship

So far we have just looked at specific procurement of particular goods and services, but this is not the whole story.

In the context of the supply chains that we looked at earlier there will be some relationships that are simple or temporary (such as who does the laundry) and some relationships that are of strategic importance (such as a material supplier or toolmaker).

It is usual to set up a formal relationship/partnership arrangement to manage such strategic relationships and avoid misunderstandings.
Conclusions

Designing and operating an effective factory requires us to carefully analyse how our production operations can be fitted into a space that is adequate but not excessive.

The costs of acquiring the factory need to be identified as early as possible to form part of the overall project costing to permit a minimum selling price calculation.

We need to have efficient and effective procurement processes in place in order to be able to manage the risks and uncertainties in moving from a design activity into a production phase.
Exercise

For the carbon fibre road wheel considered earlier identify the production equipment that needs to be procured for a 500,000 unit/year facility.

Sketch out a suitable production facility and estimate the floor area required.
Introduction
Learning objectives:

- Identify factory design principles
- Understand the impacts of factory design on costs
- Understand the basics of procurement

How do we scale a factory?
We have seen how we can assess the time taken and the associated cost of the various steps in the manufacture of composite components. One of those associated costs is the costs of building, equipping and running the production facility.

There is a significant cost associated with the physical size of the factory, so in an ideal world we don’t want to build more than we need – equally not big enough is even more of a problem.

Factory building costs
A typical “Big Shed” light factory on a brownfield site will cost in the region of £800/sqm of floor space to construct.

The requirement for air conditioning, strong floors, isolation of vibrations, pits for equipment, or office facilities can easily double that cost, and specialist facilities such as labs or hospitals can certainly be more than three times as much. For example, a synthetic chemistry lab can easily exceed £3,000/sqm.

For our purposes here we’ll assume a moderate value of £1,200/sqm, so a simple, naturally ventilated, 5000sqm flat floor facility would cost around £6M to construct.

The construction costs are by no means the end of the story, before we even get to production equipment there will be additional costs for:

- Land acquisition
- Local Authority Fees
- Site preparation
- Architects fees
- Project management and project organisation fees
- Fit out costs for furniture and fixtures
- Specialist equipment such as cranes and so on

It’s very hard to be specific about these costs as, for example land in London is far more expensive than in Avonmouth, but they would be unlikely to be much less than 50% of the construction costs and can be much more.
So, the cost of getting the keys to the front door of our new, bespoke but simple flat floor 5000sqm factory is unlikely to be very much under £10M – before we have installed any production specific equipment.

A factory half this size would probably be a bit more than half the cost as there are some efficiencies with larger projects – but overestimating the factory size we need can have serious cost implications.

**Factory Building Timescale**

Using the NCC phase 2 as an example of a relatively complex factory build with a large and complex pit and all the associated costs:

- Design and planning took about 4 months
- Procurement and Planning Application took about 4 months
- Construction took about 13 months

The message here is that you can’t get a bespoke facility quickly (or cheaply). It may be possible to modify an existing facility but that has problems of its own.

**Estimating the factory size needed**

We need to start with what we’ll be doing in the factory, how we’ll be doing it and with what equipment.

Assuming we are generating a new factory for a specific product line we need to “walk” a piece of incoming material through all the processes that will be carried out to both identify what equipment is needed and start to think about the product flow through the factory in a logical way.

Getting the product flow right is very important. The masters at it are IKEA – and in that case the product is you and the critical thing is to keep you in front of buying opportunities for as long as possible. In a factory we want the opposite.

For example, the normal assumption is that we’ll need a big freezer as the major part of our incoming materials handling. That may be true but if we can get Just in Time (JiT) prepreg deliveries first thing on a Monday morning why do we need a freezer – the Make or Buy decisions we discussed earlier have an impact on both operations and on the way that we might lay out a factory.

**Factory layout**

Achieving a good flow of product, people and paperwork through the factory does require careful planning and poor production flow will definitely increase production costs – although it’s hard to quantify by how much.

In a quality critical environment there will also be a need to maintain a very clear distinction between clean and dirty areas.

Other issues might include whether to have one very large oven or autoclave which can efficiently cure large batches of tools at one time or multiple smaller ovens or autoclaves permitting a more flexible production and a level of risk mitigation against a single point of failure.

*Poor plant layout:*
Figure 1: An example of a poor production facility lay-out

Figure 1 shows an example of a very poorly designed production facility. Product is being carried all over the factory via various crossing routes, with workers having to transport everything around. Whilst no one would design a brand new production facility in this manner, we find that this is what production facilities tend to turn into over time, with the inclusion of a new product or attempts to improve/streamline one section leading to a reduction in efficiency of the facility overall. Endless transit of parts in production can lead to handling accidents and damaged parts, meaning more repair/rework jobs and overall increased costs.

Better plant layout:

Figure 2: Improved production facility lay-out
Figure 2 demonstrates a much better production facility design. There is a sensible flow of material, people and information around the facility. It is sane, quiet, stable and has far fewer people moving around it all the time.

**Equipment choices**

**Assumptions (purely hypothetical):**

- Manufacturing lightly double curved aircraft fairings (left- and right-handed)
- Moulded mass 13kg, after edge trimming shipped mass 12kg
- 60 ship sets/month = 120 mouldings/month
- Part footprint 2m x 1m (Tool slightly larger)
- AFP lay-up required
- Autoclave cure required
- 100% ultrasonic NDE required
- Edge trimming and hole drilling required (120 holes)

**Assumptions (utilisation and machines):**

- Monthly prepreg utilisation = 1600kg (or an awful lot of AFP slit tape bobbins!). If we want to have a one-month buffer stock of prepreg that sizes our freezer
- AFP lay-up required. If we are achieving an effective lay-up rate of 5kg/hr on our AFP one moulding will take up 3hs of AFP time and a total of 360 hours of AFP time is needed each month to deliver 5 mouldings/day
- A single AFP machine operated on a 7days a week 2 shift basis can in principle deliver 7 x 2 x 8 = 112hrs/week and thus meet the AFP time demand.

The 5kg/hour effective lay-up rate is really a key assumption, if we are not hitting that rate we might not meet demand or might have to invest in a second AFP, which will then disrupt our nice factory layout. We really need to have demonstrated this lay-up rate before committing to factory design (and ideally before setting a price).

There is perhaps a little wriggle room as there will most likely be a ramp up to the 60ship sets/month and that ramp up phase can be used to improve the process efficiency.

**Assumptions:**

- Autoclave cure required. If we have an 8-hour cure cycle, we can run a single autoclave once a day with the five tools laid up in the previous day. We will therefore have a need for multiple tool sets.
- 100% ultrasonic NDE required. We need to ensure that inspection takes less than the 3hrs needed to lay up the part to prevent this becoming a bottleneck.
- Edge trimming and hole drilling required (120 holes). We need to ensure that drill and trim takes less than the 3hrs needed to lay up the part to prevent this becoming a bottleneck

**Autoclave Choice**

We can procure a 2.5m diameter by 3.5m long autoclave which can take the day’s batch of 5 mouldings in a single run. Or, we can procure a 1.9m diameter by 3.5m long autoclave that can take 3 tools at a time and would need to run twice a day.
The larger autoclave probably offers better value overall and gives a higher peak capacity if run twice a day. However, this also offers higher risk, as it provides us with a single point of failure for our entire production line.

![Figure 3: Comparison of potential autoclave sizing choices](image)

**Estimating equipment footprint**

This autoclave is about the size needed to cure the day’s production as a batch. The footprint is probably five times the working size of the vessel including ancillary equipment, control booth, space for door opening and trolley manoeuvring for loading. At this size there is no need for a pit, so we have a cheap flat floor.

![Figure 4: Autoclave working vessel vs size of working footprint including ancillary equipment](image)

It is not straightforward to come to a generic multiplier between the basic equipment footprint and what is needed operationally.
For this AFP cell, the cell size is about 12 times the tool footprint and about 7 times the basic footprint of the AFP machine itself. Conversely for a manual lay-up cell the cell size is 3 times the tool footprint as drawn here – which is probably a bit tight.

Figure 5: Comparison of footprint needed for a single AFP machine vs five manual lay-up stations

What this shows us is that, taking customer requirements to one side, we have the potential to have five manual lay-up stations in the same footprint of a single AFP working area. As such, we could then ask the costing question of, is it worth the AFP usage compared to having this done by hand. Of course, the requirements in this instance dictate the use of an AFP machine for quality purposes, however the point of this example is to show that the working area of a tool that is required as a footprint on the factory floor may be significantly higher than the space required for the machine and tool itself.

Office area

On an unsubstantiated assumption that the fairings sell at £2500 each and we sell 1440 fairings/year the factory turnover comes to £3.6M, and the factory labour force is likely to be in the region of 30FTE.

If half of them need office space, we will need about 12sqm/person or 180sqm for them. The other staff will still require breakout facilities, toilets and showers and we can guestimate this at 120sqm.

So, the total “people space” comes to about 300sqm

Summing up the floor area

If we keep a buffer stock of 1600kg of AFP bobbins that’s going to be about 40 boxes and each box might be 80cm x 80cm x 50cm. If we can stack 4 high, we need 10 stacks and a walk-in freezer of 5m x 5m floor area would allow plenty of space for working and some spare capacity for other materials needing frozen storage.

We will also need a general storage area as well as quarantine stores – on the general principle that it makes no sense to skimp on storage let’s say 100sqm of storage area.
<table>
<thead>
<tr>
<th>Factory Floor Feature</th>
<th>Area Required (sqm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezer storage</td>
<td>25</td>
</tr>
<tr>
<td>General stores</td>
<td>100</td>
</tr>
<tr>
<td>AFP cell (estimated above)</td>
<td>50</td>
</tr>
<tr>
<td>Autoclave cell (estimated above)</td>
<td>50</td>
</tr>
<tr>
<td>Drill and trim cell (basically guessed)</td>
<td>50</td>
</tr>
<tr>
<td>NDE (basically guessed)</td>
<td>50</td>
</tr>
<tr>
<td>Packing and despatch (basically guessed)</td>
<td>20</td>
</tr>
<tr>
<td>Office space etc (estimated above)</td>
<td>300</td>
</tr>
<tr>
<td>Circulation space between cells (basically guessed)</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total floor area estimated</strong></td>
<td><strong>745</strong></td>
</tr>
<tr>
<td><strong>Total floor area to allow a little expansion</strong></td>
<td><strong>1000</strong></td>
</tr>
</tbody>
</table>

**Factory Cost**
At our initial figure of £1200/sqm plus land etc giving about £1500/sqm total and a 1000sqm build our factory costs us £1.5M.

We are likely to be paying about the same for the AFP and perhaps half as much for its installation and environmental control of the cell. The autoclave is likely to cost about half as much and other major costs will be for the NDE and machining facilities.

Taking everything together it is likely that the factory will have cost in the region of £5M at the point of switching on production.

**Factory cost recovery**
For the sake of making calculations if we say that the cost of financing the factory build is 5% of the sunk costs and that the value of the factory itself at the end of the 10 years will be just the £1.5M build value, then the factory “costs” us £600k/year. If we have ten years of assured production at a constant rate the factory will deliver £36M of revenue. In this case the factory cost is a significant part of the total cost of the project and must be a central part of the overall costing.

Building a new factory looks quite expensive but could well be a better bet than renovating an old factory or trying to fit the new production activity as an additional product into an existing production facility. In that case the new production activity will almost certainly not be as efficiently laid out as it would be in a new build factory and could well also disrupt the production activity for the current product lines.

**Procurement**
Procurement is essentially the process of making everything we have gone through so far actually happen.
It is defined as the process of finding, agreeing to terms and acquiring goods, services or works from external sources.

The aim of procurement is to get goods, services or works at the best overall value to the procuring organisation – which is not the same as getting them at minimum cost.

**Best Value**

Best value will include considerations such as quality, delivery, security of supply, security of price, as well as intangible issues such as confidence in the potential suppliers’ ability to meet all of their commitments.

It is generally a requirement in public procurement to use a formal tendering or competitive bidding process if the value of the procurement is above some cut-off level – currently set at £181,302 for organisations such as UoB or the NCC. Commercial organisations are not covered by these rules, but best practice would still require some controlled process to be used.

**Procurement process**

Below is listed the steps that are generally required to be covered in the procurement process, and a simple explanation of the key question posed by each step:

- Analyse requirements – What do we need?
- Market analysis – Where can we get it?
- Costs collection and analysis – Make or buy?
- Supplier identification – Who sells it?
- Supplier selection – Who should we buy it from?
- Negotiation/Contract – What are the terms?
- Evaluation – How is the supplier performing?
- Supplier relationship – How can we all get value?

Whilst, as engineers, we tend to focus on the upper points in this list, it should be noted that for long-term business security and strategy it is perhaps the lower points in this list that become the most crucial.

**Analyse requirements**

We need to work out what we need as an organisation based on the business objectives. For example, if we need additional production capacity, we might get this by buying more equipment, extending or building a new production facility, or by sub-contracting some of our activity into the supply chain. We need to do some careful analysis of the various options, but are not necessarily looking, for example, to make a make or buy decision at this point.

We need to define what options are technically feasible and what our strategy is for achieving the business objectives. For example, if we have a requirement to do more material characterisation in a manufacturing organisation that is most likely to result in a contract being let to a test house to carry out the work.

The same requirement in a University would most likely result in buying more test machines and in an RTO could go either way. The question is the same in all three cases, but the answer depends on the business objectives.
Market analysis
We need to understand what’s out there in the market.

Are we looking to procure equipment or services for which a well-developed and competitive market is available?

Or are we in a situation where a very limited number of suppliers are available – or where all the players in the market are small start-ups? (Many OEMs can’t or won’t work with such companies).

We also really need to take a view on the direction of development of a market – for example it might be worthwhile to delay a procurement in a rapidly changing market.

Costs collection and analysis
If we are to make sensible choices, we need to capture as much reliable costs data as we can in order to be able to make reasoned decisions. It is probably the case that this is one of the most difficult parts of the process.

It is generally possible to get a ballpark cost to acquire a piece of equipment, software or service – it is generally much more difficult to get valid cost data for things like downtime or failure rates for production machinery. Talking to current users of the equipment is certainly a sensible move.

Supplier identification
Finding the right supplier may be straightforward for some issues, for example there are many organisations offering facilities management or PPE management services – 5 minutes on Google will find you a selection.

Finding a supplier for a complex system is more of an issue as there is a decision to be made as to whether to procure the system elements individually and integrate them in house, or to work through a system integrator who may not be familiar themselves with all of the sub-systems.

This is another area where the procuring organisation’s own expertise will have a significant impact on the decision

Supplier selection
Most larger scale procurements will be carried out via a competitive bidding process which may include some or all of:

- Requests for information
- Requests for proposals
- Requests for quotation
- Requests for tender
- Requests for development
- Requests for collaboration

The mechanism by which these requests go out can be by direct contact with potential suppliers or through notification services such as OJEU.
**OJEU**

OJEU stands for the Official Journal of the European Union. This is the publication in which all tenders from the public sector which are valued above a certain financial threshold according to EU legislation, must be published.

The legislation covers organisations and projects that receive public money. Organisations such as Local Authorities, NHS Trusts, MOD, Central Government Departments, the NCC and Educational Establishments are all covered by the legislation.

The OJEU website allows any potential suppliers to identify business opportunities across the whole of the EU.

**Supplier selection**

Whatever the process there will be a need for a clearly defined set of criteria against which supplier selection decisions will be made. This is both to ensure that we procure the right goods or services and in public procurement to ensure that our selection decisions cannot be challenged.

It is common to split out proposals into parts, for example a technical proposal, a management proposal and a costing proposal to allow more in-depth review by the relevant experts.

Outside of public procurement there is likely to be a lot of contact with suppliers in this phase. This allows deals to start to be outlined in principle before the start of the actual negotiation process, and other similar discussions to take place to allow the quick and smooth start of the relationship.

**Negotiation/Contract**

This is, in-principle, straightforward (although in practice it can get a bit fraught!). We need to settle the details around delivery, lead times, acceptance testing, commissioning, service level agreements and so on.

One thing we normally try to avoid at all costs is a change to the specification of what we are procuring at this stage as that will reopen the whole question of the contract value after we should have closed that down.

**Evaluation**

Getting a supplier on board is certainly not the end of the procurement process and arguably is just the beginning.

We need to keep close watch on the performance of the contract, and, especially in the case of production equipment, contracts need to very carefully scrutinise the functioning and quality of the equipment as well as the supplier’s performance.

Logging this information allows us to improve our understanding of the market, rank potential suppliers and make better decisions on future procurement activities. For example, we might get an AFP from a supplier which they claim has an absolute positional accuracy of +/- 2mm on head position, but when we measure it we discover they haven’t done that. However, it’s very difficult to do these measurements to verify the performance. Ideally, we would have needed to identify the processes we were going to use to determine the accuracy of placement at the procurement stage. Only then are we able to hold the supplier to the accuracy that they have said they will provide.
Supplier relationship

So far, we have just looked at specific procurement of particular goods and services, but this is not the whole story.

In the context of the supply chains that we looked at earlier there will be some relationships that are simple or temporary (such as who does the laundry) and some relationships that are of strategic importance (such as a material supplier or toolmaker).

It is usual to set up a formal relationship/partnership arrangement to manage such strategic relationships and avoid misunderstandings.

Conclusions

Designing and operating an effective factory requires us to carefully analyse how our production operations can be fitted into a space that is adequate but not excessive.

The costs of acquiring the factory need to be identified as early as possible to form part of the overall project costing to permit a minimum selling price calculation.

We need to have efficient and effective procurement processes in place in order to be able to manage the risks and uncertainties in moving from a design activity into a production phase.
Topics

• Design characteristics and properties
• Design for manufacture and assembly
• Poka Yoke
• Life cycle assessment
• Design for sustainability
• Robust design
• Design of experiments
• Six-sigma and process capability
• Quality Function Deployment
• Failure Modes and Effects Analysis

These slides
Design characteristics and properties
Characteristics and Properties

Analysis (physical or “virtual”): Determining/predicting the product’s properties (behaviour) from known/given characteristics

Synthesis, product development: Establishing/assigning the product’s characteristics from given/required properties

Source: Christian Weber, TU Ilmenau
Design Activities

Environment: load cases

Methods: software, testing

Controls: standards codes

Characteristics: Product Models

Methods: generation/selection

Design elements

‘Experience’: guidelines

Analysis

Synthesis

Life Cycle Properties

Documentation and records

Design for X

05 April 2019
Topics in Engineering Infomatics

- FEA, CFD, MBA, other codes
- Design for Manufacture and Assembly and other DfX
- Six-sigma, Lean
- Design catalogues, materials selection charts
- Standards: IGES, STEP
- Computer-supported collaborative work
- Computer-integrated manufacturing, PLM
- Parametric, associative feature-based, solid modelling
- Designs: CALS – MIL-STD-1840a
- The Internet; ISO OSI standards
- Office software
- MRP/MRP II
- Text retrieval
- DoE, QFD, FMEA . . .
- Computer-supported collaborative work
- Environment: load cases
- Controls: standards codes
- Environment: Computer-supported collaborative work
- Standards: IGES, STEP
Development of the ilities with time

From De Weck et al., Engineering Systems, 2011, who argue that the ility explosion is part of the epoch of engineering systems.
Design tools and techniques may be divided into

A. Those that help estimate how well the design will perform in respect of property X, generally based on some model or representation of the design characteristics

B. Those that give guidelines or instructions on the characteristics a design should have in order to achieve a particular property

C. Those that can be applied across a range of properties for example to handle the effect of uncertainty in parameters describing the characteristics
Design Techniques

• *Design for Manufacture & Assembly* (DFM/DFA)
  • As the name implies, Design for X
  • Here X is the manufacturability and assemblability of the artefact
  • Both type A and type B techniques

• *Poka Yoke*:
  • Guidelines for producing designs or products and processes which are inherently reliable and resistant to operator mistakes
  • Type B techniques

• *Life Cycle Assessment* (LCA):
  • Predicting the environmental impact of an artefact or process
  • Type A techniques
Design Techniques

• **Design for End-of-Life:**
  • Allow the re-manufacturability/recyclability of the artefact to be estimated
  • Mainly type B techniques

• **Taguchi’s Robust Design:**
  • Techniques for predicting the sensitivity of an artefact to variations in its production or use
  • Type C techniques

• **Six-Sigma and Process Capability:**
  • Techniques to assist in reducing the impact of material and process uncertainty on artefact performance
  • Type A and C (mainly) techniques
Team Techniques

Techniques that help a design team organise its understanding of artefact and its performance (all C):

• **Design of Experiments (DOE):**
  - Allow the relationship between properties and characteristics to be experimentally explored

• **Quality Function Deployment (QFD):**
  - Understand and quantify the importance of customer needs
  - Support the definition of product requirements

• **Failure Modes and Effects Analysis (FMEA):**
  - Understand how the artefact might fail
  - Steps that can reduce the likelihood and impact of failures
# Mapping of Methods to Process

<table>
<thead>
<tr>
<th>PRODUCT DESIGN AND DEVELOPMENT PHASES</th>
<th>TOOLS AND TECHNIQUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task clarification (requirements specification)</td>
<td>Quality Function Deployment (QFD)</td>
</tr>
<tr>
<td>Concept design</td>
<td>FMEA</td>
</tr>
<tr>
<td>Embodiment design</td>
<td>DFMA</td>
</tr>
<tr>
<td>Detail design</td>
<td>Robust Design</td>
</tr>
<tr>
<td>Development</td>
<td>Design of Experiments</td>
</tr>
<tr>
<td>Production</td>
<td>Six-Sigma</td>
</tr>
</tbody>
</table>
Design for Manufacturing and Assembly

bristol.ac.uk/composites
DfM/A

• Design for manufacture and assembly (DFM/DFA)

• Covers techniques that assist in evaluating the manufacturability/assemblability of a design
  • Provides guidance on how manufacturing/assembly costs can be minimized

• In general, DFM/DFA is carried out through team-based product design evaluation tools and guides
Technique Application

• Commercial DFA/DFM techniques are used successfully by many companies
  • Either workbook or software versions

• The three most referred to methods are:
  • Boothroyd-Dewhurst’s Design for Manufacture & Assembly (DFMA)
    • http://www.dfma.com/software/index.html
  • Computer Sciences Corporation’s (CSC) DFA/Manufacturing Analysis (MA).
  • Hitachi’s Assembly Evaluation Method (AEM).
Design for Manufacture and Assembly (DFMA®) Product Costing and Simplification

Balancing the objectives of cost, time, function and quality

There is a project management saying about cost, time and quality; pick any two of the three. On top of that, the product must also function in a manner consistent with the expectations of consumers. But what if there was a way you could balance each of these goals? Using a question and answer approach, DFMA software tools allow you to achieve cost reduction and quality improvement in a short amount of time. The consumer receives the product they desire at a lower cost to the producer. From the earliest conceptual stages of product development, to the purchase of parts from your supply chain, DFMA provides a way to work creatively and objectively to find new avenues for improving profit margins.

PRODUCT COSTING

DFM Concurrent Costing software provides you with a thorough understanding of the primary cost drivers associated with manufacturing your product – and establishes a benchmark for what your product "should
DfM/A – Examples of Guidelines

• Reduce part count

• Fasteners:
  • Reduce number of fasteners
  • Avoid threaded fasteners
  • Use common, efficient fastening systems
  • Avoid unnecessary joining

• Design:
  • Modularise the design
  • Design parts for multi-functional use
  • Use standard components

• Assembly:
  • Design for an optimum assembly sequence
  • Provide a base for an assembly to act as a fixture
  • Design the assembly process in a layered fashion
  • Use gravity to aid assembly operations
  • Ensure adequate access and unrestricted vision
Fasteners

http://www.specialty-fasteners.co.uk/content/img/lib/Lge/33.jpg

http://www.gotstogo.com/misc/engineering_info/snap_design_files/image023.gif

http://www.learneasy.info/MDME/iTester/tests/11201_Fasteners/images/pop_rivet.jpg

http://www.gotstogo.com/misc/engineering_info/snap_design_files/image023.gif
Ceiling insulation behind the fittings for lighting tubes and air conditioning ducting.
DfM/A – Examples of Guidelines

• Handling
  • Minimise handling and re-orientation of parts
  • Design for ease of handling (avoid nesting, tangling)
  • Ensure that product weight allows easy handling

• Error Potential
  • Design parts that cannot be installed incorrectly
  • Design parts to be stiff and rigid, not brittle or fragile
  • Design parts to be self-aligning and self-locating
  • Avoid burrs and flash on component parts
  • Maximise part symmetry

• Strive to eliminate adjustments
DMA: Reduce/Eliminate/Reuse

http://www engr sjsu edu/minicurric images/lecture_powerpoints/DFMA_I_Design_for_Manufacturing & _Assembly pdf

http://www engr sjsu edu/minicurric images/lecture_powerpoints/DFMA_I_Design_for_Manufacturing & _Assembly pdf
Approaches of DMA: Parts

(a) Asymmetrical
(b) Slightly Asymmetrical
(c) Will Jam
(d) Will Tangle

(a) Symmetrical
(b) Pronounced Asymmetrical
(c) Cannot Jam
(d) Cannot Tangle

http://mail.esdnl.ca/~craig_cook/df2202/dfma/dfma1.jpg
When Apple began selling the iPhone 5 on September 21, it quickly became the fastest-selling iPhone to date, with five million units sold in the first three days. However, sales have started to slow down since then, and they’ve begun falling short of analyst expectations.

It’s not that customers aren’t buying it, or that the iPhone 5 isn’t successful. The reason it’s not meeting expectations is because Apple’s manufacturing partner, Foxconn, simply can’t make it fast enough. Its design is so complicated that it’s the most difficult device Foxconn has ever built.

“The iPhone 5 is the most difficult device that Foxconn has ever assembled,” a company official told The Wall Street Journal. “To make it light and thin, the design is very complicated. It takes time to learn how to make this new device. Practice makes perfect. Our productivity has been improving day by day.”

The executive also confirmed reports that Foxconn has taken steps to improve its manufacturing process in an effort to prevent chips and scratches on the iPhone 5’s aluminum casing. The company recently rolled out a new quality control procedure that should prevent damaged devices from leaving the factory.

However, he also noted that the iPhone 5’s new coating does make it more susceptible to scratching. “It’s always hard to satisfy both aesthetic needs and practical needs,” he said.
DfM Producibility Guidelines

• Identify critical characteristics (tolerances, finishes)
• Identify factors that influence their manufacture
• Establish maximum tolerances for characteristics
• Avoid tight tolerances
• Determine process capability to achieve characteristics early in the design process
• Design the part to be easily inspectable
DfM Producibility Guidelines

• Use standard manufacturing processes
• Avoid secondary processes
• Utilise the special characteristics of processes
• Minimise the number of machined surfaces
• Minimise the number of re-orientations
• Use generous radii/fillets on castings, mouldings and machined parts
• Design parts for ease of tooling/jigging/fixturing
Approaches of DfM

Near Net Shape/Forming

http://www.blueridgediecasting.com/images/homepic.jpg

http://www.whitesellcorp.com/images/product/cfl/neartonet.jpg

Stages of DfMA

1. Functional analysis
   a. Classify parts as essential ‘A’ parts or non-essential ‘B’ parts.
   b. Redesign around essential components, from which reduced part count normally results

2. Manufacturing analysis
   a. Component costs are calculated by considering materials, manufacturing processes and aspects such as complexity, volume and tolerance.
   b. This allows ideas for part count reduction to be tested since combining parts can lead to more complex components and changes to manufacturing processes.
3. Handling analysis
   a. Components must be correctly orientated before assembly can take place – use analysis to assess difficulty of achieving and modify as required
   b. Poka Yoke devices can be installed to help ensure zero defects

4. Fitting analysis
   a. Construct assembly sequence plan and assess difficulty of assembling each part in the sequence using the design for assembly analysis tables
DfMA Flowchart

PRODUCT DESIGN SPECIFICATION

PRODUCT DESIGN

FUNCTIONAL ANALYSIS

MANUFACTURING ANALYSIS

MANUAL HANDLING ANALYSIS

AUTOMATIC ANALYSIS

FEEDING

FITTING ANALYSIS

GRIPPING INSERTION FIXING

OPTIMISED DESIGN

Design for X

05 April 2019
Case Study

• Trim screws on a car headlight design - complex assembly structure, complex access, turnover operation and automation problems.

• Results of analysis are shown against a component list and a sequence of assembly. Undesirable elements of the design highlighted.

• Better design solution - number of parts in the redesign reduced from 5 to 2. A more simple product structure and increased assembly design efficiency resulted.
Case Study

a) Original Design

1. Insert
2. Rubber Washer
3. Starlock Washer
4. Screw
5. Knob
## Case Study

### ANALYSIS RESULTS

<table>
<thead>
<tr>
<th>COMPONENT DESCRIPTION</th>
<th>COMPONENT NUMBER</th>
<th>FUNCTIONAL ANALYSIS</th>
<th>MANUFACTURING ANALYSIS</th>
<th>FEEDING ANALYSIS</th>
<th>FEEDING TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSERT</td>
<td>1</td>
<td>A</td>
<td>1.09</td>
<td>2.4</td>
<td>MT</td>
</tr>
<tr>
<td>RUBBER WASHER</td>
<td>2</td>
<td>B</td>
<td>0.92</td>
<td>8</td>
<td>MT</td>
</tr>
<tr>
<td>STARLOCK WASHER</td>
<td>3</td>
<td>B</td>
<td>0.86</td>
<td>1.3</td>
<td>MT</td>
</tr>
<tr>
<td>SCREW</td>
<td>4</td>
<td>A</td>
<td>3.43</td>
<td>3</td>
<td>LT</td>
</tr>
<tr>
<td>KNOB</td>
<td>5</td>
<td>B</td>
<td>1.57</td>
<td>1.9</td>
<td>MT</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>5</strong></td>
<td><strong>2</strong></td>
<td><strong>7.87</strong></td>
<td><strong>16.6</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Key:**
- Insertion Process
- Work Holding Process
- Disassembly Process
- Non Assembly Process
- Gripping Process
- Reassembly Process
- Assembly Total

- Insert into Lamp Body
- Turnover operation
- Run Screw
- Turnover operation
- Rivetting type operation

**Design for X**

05 April 2019
Case Study

b) New Design

- Insert
- Screw
## Case Study

### ANALYSIS RESULTS

<table>
<thead>
<tr>
<th>COMPONENT DESCRIPTION</th>
<th>COMPONENT NUMBER</th>
<th>FUNCTIONAL ANALYSIS</th>
<th>MANUFACTURING ANALYSIS</th>
<th>FEEDING ANALYSIS</th>
<th>FEEDING TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSERT</td>
<td>1</td>
<td>A</td>
<td>1.03</td>
<td>1.5</td>
<td>MT</td>
</tr>
<tr>
<td>SCREW</td>
<td>2</td>
<td>A</td>
<td>3.74</td>
<td>3</td>
<td>LT</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>2</strong></td>
<td><strong>2</strong></td>
<td><strong>4.77</strong></td>
<td><strong>4.5</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Screw into Insert
- Insert into Lamp Body
- Run down Screw
- 3.8

---

**Design for X**

05 April 2019
c) Results Summary and Measures of Performance

<table>
<thead>
<tr>
<th></th>
<th>ORIGINAL</th>
<th>NEW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Parts Count</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Design Efficiency</td>
<td>40%</td>
<td>100%</td>
</tr>
<tr>
<td>Total Manufacturing Analysis</td>
<td>7.9</td>
<td>4.8</td>
</tr>
<tr>
<td>Total Feeding Index</td>
<td>16.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Feeding Ratio</td>
<td>8.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Total Fitting Index</td>
<td>13.9</td>
<td>3.8</td>
</tr>
<tr>
<td>Fitting Index</td>
<td>7</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Poka Yoke

• Poka Yoke = mistake/fool proofing

• Causes of most operator mistakes:
  • Fault in the design of process/system
  • *NOT* due to inattention/poor training

• Poka Yoke techniques eliminate the possibility of mistakes

• Two primary principles for designing a product/process:
  • So that a defect *cannot be made*
  • So that if a defect is created it is immediately obvious and can be corrected
Poka Yoke

• The process of Poka Yoke involves:
  • Self-Checks
    • Best person to detect mistakes is the operator
  • Successive Checks
    • Check carried out by the next operator in assembly line
  • Source Inspections
    • Best time to detect a mistake is immediately after it has happened
    • Hence, inspection should occur at the source of a mistake
    • System should be designed to highlight or prevent mistakes

• Mistakes will not turn into defects if operator errors are discovered and eliminated (or prevented) as they occur
Poka Yoke

• Vast range of possible Poka Yoke devices

• Three general categories have been identified:
  • Contact Type
    • Use of shape, dimensions or other physical properties of products to detect the contact or non-contact of a particular feature
  • Constant Number Type
    • Detects errors if a fixed number of parts have not been made
  • Performance Sequence Type
    • Detects errors if the fixed steps in a sequence have not been performed

(Good examples at http://www.referenceforbusiness.com/management/Or-Pr/Poka-Yoke.html)
Poka Yoke

- **Shut-out activation:**
  - Prevents incorrect action from taking place
  - Preferred as it acts even if operator inattentive

- **Attention activation**
  - Brings attention to an incorrect action but does not prevent it
Poka Yoke - Example 1

Standard 13 Amp mains plug:

- Consequences of connecting earth to live could be disastrous
- Making the plug impossible to plug in incorrectly eliminates the possibility of this happening
Poka Yoke - Example 2

Valve cover:

- Designing in part features to mistake-proof the assembly by only allowing assembly one way, the correct way.

http://www.npd-solutions.com/mistake.html
Poka Yoke - Example 3

Non-return valve

- Could be assembled the wrong way round
- Arrow marked on the valve showing the direction of flow was felt inadequate
- Valve was redesigned with two different size of thread at the input and output ports
Example from Medicine

Broselow® Pediatric Emergency Tape:
• Colour coded tape laid next to child
• Appropriate medical devices and medications contained in packets of the same colour

The oral syringes designed so that they will not fit onto any IV tubing

A conveyor carries the product under a pivoting flag. A correctly assembled product passes under the flag. An incorrectly assembled product tips the flag, and a sensor detects the flag movement.

http://www.npd-solutions.com/mistake.html
Automated Automotive Body Inspection System for Poka-Yoke Production Lines Using NI IMAQ Vision

"Using the NI Vision Assistant and NI Vision Builder for Automated Inspection, we could easily and quickly develop solutions for recognizing different frame components."

- Ferencz András, Naturen KTF

The Challenge:
Developing a machine vision inspection system for inspecting finished automotive bodies ("white bodies" or "bodies in white") prepared for painting at the end of the frame assembly line in the welding shop.

The Solution:
Deploying an inspection system that can decide if all necessary components have been mounted on the body under inspection and, in cases where missing or faulty components are detected, the system can remove the body under inspection from the assembly line so it cannot enter the paint shop.

“The Military have used composite tool kits for as long as I can remember ... Each time a tool is removed from the tool box, the person places one of their tags in its place. Every tech has their own tags with a specific number printed on the tag. Any aircraft that was worked on with tools from the tool kit does not fly until all the tools are accounted for from that tool kit.

The reason for the tag system with numbers is that when the tool board is cleared and there is a tool missing, no problem check the number on the tag against the technician assigned to that number. Ask them where is the tool? This normally happened on a Friday afternoon BTW. Everybody had to stay back after shift and look for the tool. Sometimes panels had to be removed from the jet for inspection to find the tool. Normally the tool e.g. a small socket would be found in their pocket or similar.”

• http://www.recreationalflying.com/threads/suspicious-screwdriver-found-in-plane-wreckage.34225/
Surgical Counting

http://www.gosh.nhs.uk/health-professionals/clinical-guidelines/surgical-count/

http://www.ucsf.edu/sites/default/files/legacy_files/towel.jpg

## Results of Survey of Finnish Firms

<table>
<thead>
<tr>
<th>Competence</th>
<th>Rank</th>
<th>Competence</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing cost management, DFM and DFMA</td>
<td>3.92</td>
<td>General problem solving skills</td>
<td>3.69</td>
</tr>
<tr>
<td>CAD skills (surface modelling, 3D)</td>
<td>3.92</td>
<td>Detail design (drawing with tolerances, tolerance chains)</td>
<td>3.69</td>
</tr>
<tr>
<td>QA of new products &amp; production processes</td>
<td>3.92</td>
<td>General team work skills (including concurrent engineering)</td>
<td>3.67</td>
</tr>
<tr>
<td>Product architecture, modularization</td>
<td>3.85</td>
<td>Perseverance in problem solving situations</td>
<td>3.62</td>
</tr>
<tr>
<td>Time and time schedule management</td>
<td>3.77</td>
<td>Product development network management</td>
<td>3.62</td>
</tr>
<tr>
<td>Communication of own ideas</td>
<td>3.77</td>
<td>English language skills</td>
<td>3.54</td>
</tr>
<tr>
<td>Product data management (PLM, PDM)</td>
<td>3.69</td>
<td>Ability to retrieve information from various sources</td>
<td>3.54</td>
</tr>
<tr>
<td>Production technology skills</td>
<td>3.69</td>
<td>Strength of materials</td>
<td>3.54</td>
</tr>
<tr>
<td>Problem formulating skills</td>
<td>3.69</td>
<td>Identification of customer needs</td>
<td>3.46</td>
</tr>
</tbody>
</table>
Life-Cycle Assessment
Life-Cycle Assessment

• Evaluates the environmental impact of a product throughout its *entire lifespan*
  • Extraction of materials → manufacture → use → disposal

• Covered by standards in the ISO 14000 Environmental Management series:
  • ISO 14040:2006
    • ‘Environmental management – Life cycle assessment – Principles and framework’
    • Overview of the practice, applications and limitations
  • ISO 14044:2006
    • ‘Environmental management – Life cycle assessment – Requirements and guidelines’
    • Guides preparation, conduct and review of inventory analysis, impact assessment and results interpretation
Four Stage Process

• **Goal and scope definition:**
  • Establishing the principal choices of the study
    • Methodological choices, assumptions and limitations
  • Particular focus on system boundaries and impacts to be considered

• **Inventory analysis:**
  • Life cycle inventory (LCI)
  • Information on all of the environmental inputs and outputs associated with a product or service
  • i.e. material and energy requirements/emissions and wastes
Four Stage Process

• **Impact assessment**
  - Inventory list is the result of all input and output environmental flows of a product system

• **Interpretation**
  - Describes checks to ensure conclusions are supported by data and procedures used in the study
  - Includes uncertainty, sensitivity analysis and contribution analysis
Impact Assessment

• Life Cycle Impact Assessment (LCIA)
  • Used as a long list of substances is difficult to interpret

• 4 Steps:
  • *Classification* of substances into classes according to their environmental impacts
  • *Characterisation* of impacts by multiplying by a factor which reflects their relative contribution.
  • *Normalization* of impacts by comparison to a reference value, e.g. the average impact of a European citizen in one year
  • *Weighting* of impact categories to generate a single score
Impact Themes

• Impacts may be translated into themes
  • E.g. climate change, acidification, human toxicity, etc.

• Also into issues of concern
  • E.g. human health, natural environment, and natural resources

• A 'big 6' environmental impact categories, considered to have a fundamental impact on the earth's eco-system, are:
  • Acidification potential
  • Eutrophication potential
  • Global warming potential
  • Ozone depletion potential
  • Photochemical ozone creation potential
  • Primary energy use
Variants

- Scope of an LCA varies with what aspect is being examined:
  - **Cradle-to-grave**: full LCA from resource extraction through use to disposal
  - **Cradle-to-gate**: partial life cycle to factory gate, omitting use and disposal phases
  - **Cradle-to-cradle**: Disposal phase involves a recycling process allowing new production of the same or different products.
  - **Gate-to-gate**: partial LCAs examining only one process in the entire production chain
  - **Well-to-wheel**: used for transport fuels and vehicles.
Software

• Many LCA software tools
  • E.g. SimaPro, GaBi, Quantis and EarthSmart.

• Model accuracy depends on the input data
  • E.g. Impacts of energy generation, transportation or different materials/processes in different countries
  • These are contained in public or for-purchase databases

• A unit process has data for material and energy flows for a unit of production, and can, in complex cases, track hundreds of flows
# Databases

## Public databases

<table>
<thead>
<tr>
<th>Database</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GREET Model, <a href="https://greet.es.anl.gov/">https://greet.es.anl.gov/</a></td>
<td>Transportation fuels, including bio-fuels</td>
</tr>
<tr>
<td>BEES, <a href="http://www.nist.gov/el/economics/BEESSoftware.cfm">http://www.nist.gov/el/economics/BEESSoftware.cfm</a></td>
<td>Construction</td>
</tr>
</tbody>
</table>

## Proprietary data

<table>
<thead>
<tr>
<th>Database</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE International <a href="http://www.pe-international.com/">http://www.pe-international.com/</a></td>
<td>Bundled in GaBi software</td>
</tr>
<tr>
<td>Eco Invent <a href="http://www.ecoinvent.ch/">http://www.ecoinvent.ch/</a></td>
<td>Thousands of European unit processes (analogous to control volumes/systems)</td>
</tr>
</tbody>
</table>
Example: Cooker Hood
Example: Cooker Hood

1. Mount for fan housing is rivetted to base. Mount for fan housing slides onto wall mount and is secured with screws.
2. Hemisphere on lighting unit slots into gap in base unit securing the lighting unit.
Example: Cooker Hood

Flowchart:

- Metal part
  - Unfold in CAD?
    - Yes: Find Volume
    - No: Re-draw part
    - Find Thickness
    - Find Area of cut out
      - (Area of cut out x Thickness x Density) + 10% Mass of Part
        - Mass Cut Out in Laser Cutting
      - Calculate Number of Bends
        - Number of bends in bending process
      - Calculate Perimeter
        - Laser Cut Length
      - Volume x Density
        - Mass of Part
  - Truck
  - Laser Cutting
  - Metal Bending
    - Recycling
  - O₂ gas steel, N₂ gas stainless, Electricity Italy, He Gas
  - Diesel
  - Electricity Italy
  - Part
<table>
<thead>
<tr>
<th>Life cycle phase</th>
<th>Data source</th>
<th>Reference area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacture</strong></td>
<td>PE International/GaBi</td>
<td>Germany</td>
</tr>
<tr>
<td>Stainless Steel Sheet</td>
<td>PE International/GaBi</td>
<td>Germany</td>
</tr>
<tr>
<td>Carbon steel sheet</td>
<td>PE International/GaBi</td>
<td>Italy</td>
</tr>
<tr>
<td>Laser Cutting</td>
<td>Manufacturer</td>
<td>Italy</td>
</tr>
<tr>
<td>Metal bending</td>
<td>Manufacturer</td>
<td>Italy</td>
</tr>
<tr>
<td>PP granular</td>
<td>PE International/GaBi</td>
<td>Germany</td>
</tr>
<tr>
<td>PVC granular</td>
<td>PE International/GaBi</td>
<td>Germany</td>
</tr>
<tr>
<td>Nylon 6.6 Granular</td>
<td>PE International/GaBi</td>
<td>Germany</td>
</tr>
<tr>
<td>Plastic injection moulding</td>
<td>PE International/GaBi</td>
<td>Europe</td>
</tr>
<tr>
<td>Power electricity</td>
<td>PE International/GaBi</td>
<td>Italy</td>
</tr>
<tr>
<td>Diesel production</td>
<td>PE International/GaBi</td>
<td>Italy</td>
</tr>
<tr>
<td>Transport data</td>
<td>PE International/GaBi</td>
<td>Germany</td>
</tr>
<tr>
<td><strong>To market</strong></td>
<td>PE International/GaBi</td>
<td>Italy</td>
</tr>
<tr>
<td>Transport data</td>
<td>Estimated</td>
<td>Europe</td>
</tr>
<tr>
<td>Distance of export</td>
<td>PE International/GaBi</td>
<td>Italy</td>
</tr>
<tr>
<td>Diesel production</td>
<td>PE International/GaBi</td>
<td>Italy</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Measured</td>
<td>-</td>
</tr>
<tr>
<td>Power consumption</td>
<td>PE International/GaBi</td>
<td>Great Britain</td>
</tr>
<tr>
<td>Power electricity</td>
<td>PE International/GaBi</td>
<td>Great Britain</td>
</tr>
<tr>
<td><strong>End of life</strong></td>
<td>Journal articles</td>
<td>Great Britain</td>
</tr>
<tr>
<td>Recycling</td>
<td>PE International/GaBi</td>
<td>Great Britain</td>
</tr>
<tr>
<td>Incineration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part name</td>
<td>Part code</td>
<td>Material</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------</td>
<td>----------------</td>
</tr>
<tr>
<td>Base unit</td>
<td>A17_040</td>
<td>AISI 1010</td>
</tr>
<tr>
<td>Blower Unit Side</td>
<td>A18_023</td>
<td>AISI 1010</td>
</tr>
<tr>
<td>Blower Unit Side</td>
<td>A18_024</td>
<td>AISI 1010</td>
</tr>
<tr>
<td>Blower Unit Top</td>
<td>A18_155</td>
<td>AISI 1010</td>
</tr>
<tr>
<td>Air Outlet Connector</td>
<td>A39_022</td>
<td>AISI 1010</td>
</tr>
<tr>
<td>Telescopic Chimney</td>
<td>A17_058_54</td>
<td>AISI 430</td>
</tr>
<tr>
<td>Lighting Base</td>
<td>A18_310</td>
<td>AISI 430</td>
</tr>
<tr>
<td>Outer Shell</td>
<td>AL2_001</td>
<td>AISI 430</td>
</tr>
<tr>
<td>Telescopic Chimney</td>
<td>A39_021</td>
<td>AISI 430</td>
</tr>
</tbody>
</table>
Design for X

05 April 2019
Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles

Global warming (GWP), terrestrial acidification (TAP), particulate matter formation (PMFP), photochemical oxidation formation (POFP), human toxicity (HTP), freshwater eco-toxicity (FETP), terrestrial eco-toxicity (TETP), freshwater eutrophication (FEP), mineral resource depletion (MDP), fossil resource depletion (FDP), internal combustion engine vehicle (ICEV), electric vehicle (EV), lithium iron phosphate (LiFePO4), lithium nickel cobalt manganese (LiNCM), coal (C), natural gas (NG), European electricity mix (Euro).
Light-weight LCA – Eco-Indicators

Eco-indicators concentrate on production of raw materials (e.g. polystyrene), processing & manufacture (e.g. injection moulding) transportation of product (e.g. shipping), energy in use (e.g. electricity), consumables in use (e.g. paper) and disposal.

A simple analysis of a coffee machine with Eco-indicators shows what design priorities should be: minimize the use of electricity and paper filters.
Design for Sustainability
Design for sustainability

• LCA tells us the potential impacts, but not how to reduce them

• Key approaches of sustainable product design:
  • Eliminate use of non-renewable natural resources
    • Including non-renewable sources of energy
  • Eliminate disposal of synthetic and inorganic materials that do not decay quickly.
  • Eliminate creation of toxic wastes (not part of natural life cycles)

• Application of a number of relatively straightforward design principles can be a very valuable guide.
Drivers for sustainability

• Internal drivers:
  • Public image
  • Operational safety
  • Employee motivation
  • Ethical responsibility
  • Influencing of consumer behaviour

• Standards and legislation
  • European WEEE
    • Waste Electrical and Electronic Equipment
  • RoHS
    • Restriction of Hazardous Substances

• External drivers:
  • Environmental legislation
  • Market demand
  • Competition
  • Trade organisations
  • Suppliers
  • Social pressures

05 April 2019
Waste Electrical & Electronic Equipment (WEEE)

Waste of electrical and electronic equipment (WEEE) such as computers, TV-sets, fridges and cell phones is one the fastest growing waste streams in the EU, with some 9 million tonnes generated in 2005, and expected to grow to more than 12 million tonnes by 2020.

WEEE is a complex mixture of materials and components that because of their hazardous content, and if not properly managed, can cause major environmental and health problems. Moreover, the production of modern electronics requires the use of scarce and expensive resources (e.g. around 10% of total gold worldwide is used for their production). To improve the environmental management of WEEE and to contribute to a circular economy and enhance resource efficiency the improvement of collection, treatment and recycling of electronics at the end of their life is essential.

To address these problems two pieces of legislation have been put in place: The Directive on waste electrical and electronic equipment (WEEE Directive) and the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive)

http://ec.europa.eu/environment/waste/weee/index_en.htm
Recast of the RoHS Directive

EU legislation restricting the use of hazardous substances in electrical and electronic equipment (RoHS Directive 2002/95/EC) and promoting the collection and recycling of such equipment (WEEE Directive 2002/96/EC) has been in force since February 2003. The legislation provides for the creation of collection schemes where consumers return their used e-waste free of charge. The objective of these schemes is to increase the recycling and/or re-use of such products. It also requires heavy metals such as lead, mercury, cadmium, and hexavalent chromium and flame retardants such as polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) to be substituted by safer alternatives.

Inadequately treated e-waste poses environmental and health risks. In December 2008, the European Commission therefore proposed to revise the directives on electrical and electronic equipment in order to tackle the fast increasing waste stream of such products. The aim is to increase the amount of e-waste that is appropriately treated and to reduce the volume that goes to disposal. The aim of the RoHS recast was also to reduce administrative burdens and ensure coherency with newer policies and legislation covering, for example, chemicals and the new legislative framework for the marketing of products in the European Union. The RoHS Recast Directive was published in the Official Journal on 1 July 2011.

Introduction

Every year, end-of-life vehicles (ELV) generate between 7 and 8 million tonnes of waste in the European Union which should be managed correctly. Directive 2000/53/EC (Directive 2000/53/EC - the "ELV Directive") on end-of-life vehicles aims at making dismantling and recycling of ELVs more environmentally friendly. It sets clear quantified targets for reuse, recycling and recovery of the ELVs and their components. It also pushes producers to manufacture new vehicles without hazardous substances (in particular lead, mercury, cadmium and hexavalent chromium), thus promoting the reuse, recyclability and recovery of waste vehicles (see also Directive 2005/64/EC on the type-approval of motor-vehicles with regards to their reusability, recyclability and recoverability). The remaining specific exemptions to the prohibition of the use of hazardous substances in vehicles are listed in Annex II to the ELV Directive and are subject to regular reviews according to technical and scientific progress.

Alongside a number of other waste stream directives, the ELV Directive was subject to an ex-post evaluation ("fitness check") in 2014.

http://ec.europa.eu/environment/waste/elv_index.htm
The ‘Blue Guide’ on the implementation of EU product rules 2014

UNEP 6 REs

• RE-think the product and its functions
  • E.g. the product may be used more efficiently

• RE-place harmful substances with safer alternatives

• RE-pair: make the product easy to repair
  • e.g. via modules that can easily be changed

• RE-use: design for disassembly so parts can be reused

• RE-duce: energy, material and socio-economic impact
  • Throughout a product’s life cycle

• RE-cycle: select materials that can be recycled
### Material Selection Guidelines

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoid regulated and restricted materials.</td>
<td>They are high impact.</td>
</tr>
<tr>
<td>Minimize the number of different types of material.</td>
<td>Simplifies the recycling process.</td>
</tr>
<tr>
<td>For attached parts, standardize on the same or a compatible material.</td>
<td>Reduces the need for disassembly and sorting.</td>
</tr>
<tr>
<td>Eliminate incompatible materials.</td>
<td>Many materials’ value is increased by accurate identification and sorting.</td>
</tr>
<tr>
<td>Mark the material on all parts.</td>
<td>Stimulate the market for material that has been recycled.</td>
</tr>
<tr>
<td>Use recycled materials.</td>
<td>Minimize waste; increase the end-of-life value of the product.</td>
</tr>
<tr>
<td>Use materials that can be recycled, typically ones as pure as possible (no additives).</td>
<td>Composites are inherently not pure materials, and so not amenable to recycling.</td>
</tr>
<tr>
<td>Avoid composite materials.</td>
<td>Reduce moving mass and therefore energy consumption.</td>
</tr>
<tr>
<td>Use high strength-to-weight materials on moving parts.</td>
<td>More pure metals can be recycled into more-varied applications.</td>
</tr>
<tr>
<td>Use low-alloy metals that are more recyclable than high-alloy ones.</td>
<td>Aluminum, steel, and magnesium alloys are readily separated from shredder output and recycled.</td>
</tr>
<tr>
<td>If the same base metal can be used, different metals can be fastened.</td>
<td>Rapidly eliminate parts of negative value.</td>
</tr>
<tr>
<td>Hazardous parts should be clearly marked and easily removed.</td>
<td></td>
</tr>
<tr>
<td>Car components (kg)</td>
<td>Metal</td>
</tr>
<tr>
<td>--------------------</td>
<td>-------</td>
</tr>
<tr>
<td>body</td>
<td>520</td>
</tr>
<tr>
<td>bumper</td>
<td>5.5</td>
</tr>
<tr>
<td>electronics</td>
<td>2</td>
</tr>
<tr>
<td>engine</td>
<td>90</td>
</tr>
<tr>
<td>exhaust</td>
<td>10</td>
</tr>
<tr>
<td>fuel tank</td>
<td>0.1</td>
</tr>
<tr>
<td>gear box</td>
<td>27</td>
</tr>
<tr>
<td>grille</td>
<td>30</td>
</tr>
<tr>
<td>wheels</td>
<td>1.4</td>
</tr>
<tr>
<td>lights</td>
<td>93</td>
</tr>
<tr>
<td>rubber's</td>
<td>7.7</td>
</tr>
<tr>
<td>seals</td>
<td>6.5</td>
</tr>
<tr>
<td>tires</td>
<td>28</td>
</tr>
<tr>
<td>windows</td>
<td>25</td>
</tr>
<tr>
<td>wiring</td>
<td>5</td>
</tr>
</tbody>
</table>

### Input streams

- Aluminium (cast)
- Aluminium (wrought)
- Copper alloys
- Lead alloys
- Magnesium alloys
- Pt-family alloys
- Stainless steels
- Steel + Cast Iron
- Zinc alloys
- Glass
- Elastomers
- Natural Fibers
- Natural Rubber
- Porcelain
- Thermosets
- Thermoplastics

### Industrial streams (metals)

- Aluminium (cast)
- Aluminium (wrought)
- Copper
- Lead
- Magnesium
- Pt-family alloys
- Stainless steels
- Steel + Cast Iron
- Zinc

Compatibility matrix for materials in a car

Source: UNEP report *Metal Recycling, Opportunities, limits, infrastructure.*


- Minor component (kg)
- Major component (kg)
- 0 – MUST separate, avoid mixing
- 1 – SHOULD separate, problems can occur
- 2 – DON’T separate, good combination
Design for End-of-Life

• "Design for recycling is a method that implies the following requirements of a product: easy to dismantle, easy to obtain 'clean' material-fractions, that can be recycled (e.g. iron and copper should be easy to separate), easy to remove parts/components, that must be treated separately, use as few different materials as possible, mark the materials/polymers in order to sort them correct, avoid surface treatment in order to keep the materials 'clean'." (Source: Danish EPA Eco Design Guide)
Some Examples

• BMW Group Sustainable Value Report
  http://www.bmwgroup.com/e/0_0-www_bmwgroup_com/verantwortung/svr_2012/produktv
  erantwortung.html

• Dartmouth University Design for Recycling

• Information Inspiration at Loughborough
  http://ecodesign.lboro.ac.uk/?section=97
Design Characteristics and Properties

**Figure 1:** Design characteristics and properties; the difference moving between analysis and synthesis showing a general process of design evolving
Figure 2: The elements that feed into different aspects of this cycle

Figure 3: Cumulative number of journal articles in which any ‘ility’ appears in the title or abstract of the paper (1884-2010). Source: Inspec and Compendex, accessed via Engineering Village (8 August 2010.)
Figure 3 is from De Weck et al., Engineering Systems, 2011, who argue that the ‘ility’ explosion is part of the epoch of engineering systems.

Design tools and techniques
Design tools and techniques may be divided into:

A. Those that help estimate how well the design will perform in respect of property X, generally based on some model or representation of the design characteristics

B. Those that give guidelines or instructions on the characteristics a design should have in order to achieve a particular property

C. Those that can be applied across a range of properties for example to handle the effect of uncertainty in parameters describing the characteristics

Design techniques
Design for Manufacture & Assembly (DFM/DFA): as the name implies, Design for X, where X is the manufacturability and assemblability of the artefact (both type A and type B techniques).

Poka Yoke: guidelines for producing designs or products and processes which are inherently reliable and resistant to operator mistakes (type B techniques).

Life Cycle Assessment (LCA): techniques for predicting the environmental impact of an artefact or process (type A techniques).

Design for End-of-Life: techniques that allow the re-manufacturability and recyclability of the artefact to be estimated (mainly type B techniques)

Taguchi’s Robust Design: techniques for predicting the sensitivity of an artefact to variations in its production or use (type C techniques).

Six-Sigma and Process Capability: techniques to assist in reducing the impact of material and process uncertainty on artefact performance (type A and C (mainly) techniques).

Team Techniques
Techniques that help a design team organise its understanding of artefact and its performance (all C)

Design of Experiments (DOE): allow the relationship between properties and characteristics to be experimentally explored.

Quality Function Deployment (QFD): to understand and quantify the importance of customer needs and to support the definition of product requirements.

Failure Modes and Effects Analysis (FMEA): to help understand how the artefact might fail and steps that can reduce the likelihood and impact of failures.
### Design for Manufacturing and Assembly

Design for manufacture and assembly (DFM/DFA) covers techniques that assist in evaluating the manufacturability/assemblability of a design and provide guidance on how manufacturing and assembly costs can be minimised. The core thing here is minimising costs by controlling your decisions.

In general, DFM/DFA is carried out through team-based product design evaluation tools and guides.

Commercial DFA/DFM techniques are used successfully by many companies in either workbook or software versions. The three most referred to methods are:

- Boothroyd-Dewhurst’s Design for Manufacture & Assembly (DFMA) (http://www.dfma.com/software/index.html)
- Computer Sciences Corporation’s (CSC) DFA/Manufacturing Analysis (MA).
- Hitachi’s Assembly Evaluation Method (AEM).

Examples of guidelines:

- Reduce part count
- Reduce number of fasteners; avoid threaded fasteners; use common, efficient fastening systems; avoid unnecessary joining.
- Modularise the design; design parts for multi-functional use; use standard components.
Design for an optimum assembly sequence; provide a base for an assembly to act as a fixture; design the assembly process in a layered fashion; use gravity to aid assembly operations; ensure adequate access and unrestricted vision.

Minimise handling and re-orientation of parts; design for ease of handling (avoid nesting, tangling); ensure that product weight allows easy handling.

Design parts that cannot be installed incorrectly; design parts to be stiff and rigid, not brittle or fragile; design parts to be self-aligning and self-locating; avoid burrs and flash on component parts; maximise part symmetry.

Strive to eliminate adjustments

Figure 4: The Apple iPhone 5 is a key example of DFMA not being undertaken.

A key example of DFMA not being properly undertaken comes with Apple’s iPhone 5 upon its release in September 2012. Sales figures slowed after the first few days of record-breaking sales post-release. This wasn’t due to any issues with the phone itself, nor with consumers being disappointed with the product released. Instead, it was simply due to Foxconn, the company who manufactures the phones, not being able to keep up with demand. They stated that the iPhone 5 was “the most difficult device [they] had ever assembled”. This demonstrates how even the largest of companies can fall foul of not fully considering their assembly operations in the design of their products, and suffer the inherent costs of not being able to deliver to meet demand.

DfM Producibility Guidelines
A number of DfM guidelines should be followed in order to maximise the producibility of a part. These include:

- Identify critical characteristics (tolerances, finishes)
- Identify factors that influence their manufacture
- Establish maximum tolerances for characteristics
- Avoid tight tolerances
- Determine process capability to achieve characteristics early in the design process
- Design the part to be easily inspectable
- Use standard manufacturing processes
Avoid secondary processes
- Utilise the special characteristics of processes
- Minimise the number of machined surfaces
- Minimise the number of re-orientations
- Use generous radii/fillets on castings, mouldings and machined parts
- Design parts for ease of tooling/jigging/fxturing

**Stages of DfMA**

1. Functional analysis.
   - a. Classify parts as essential ‘A’ parts or non-essential ‘B’ parts.
   - b. Redesign around essential components, from which reduced part count normally results.
2. Manufacturing analysis.
   - a. Component costs are calculated by considering materials, manufacturing processes and aspects such as complexity, volume and tolerance.
   - b. This allows ideas for part count reduction to be tested since combining parts can lead to more complex components and changes to manufacturing processes.
3. Functional analysis.
   - a. Classify parts as essential ‘A’ parts or non-essential ‘B’ parts.
   - b. Redesign around essential components, from which reduced part count normally results.
   - a. Component costs are calculated by considering materials, manufacturing processes and aspects such as complexity, volume and tolerance.
   - b. This allows ideas for part count reduction to be tested since combining parts can lead to more complex components and changes to manufacturing processes.

**Case Study**

Trim screws on a car headlight design - complex assembly structure, complex access, turnover operation and automation problems.

Results of analysis are shown against a component list and a sequence of assembly. Undesirable elements of the design highlighted.

Better design solution - number of parts in the redesign reduced from 5 to 2. A simpler product structure and increased assembly design efficiency resulted.

![](image)

*Figure 5: The original design with 5 distinct components*
Figure 6: Component analysis for the design

Figure 7: New, simplified design with only two distinct components

Figure 8: Component analysis for the new design
Poká Yoke

Poká Yoke = mistake/fool proofing

Most operator mistakes are not the result of inattention or poor training, but because the system or process has been badly designed.

Poká Yoke techniques eliminate the possibility of mistakes occurring. They are based on two primary principles:

- Designing a process or product so that a defect cannot be made
- Designing a product/process so that if a defect is created it is immediately obvious and can be corrected

The process of Poká Yoke involves:

- Self-Checks - the best person to detect mistakes is the operator carrying out the operation
- Successive Checks – when, in an assembly line, a check is carried out by the next operator
- Source Inspections - the best time to detect a mistake is immediately after it has happened. Hence, inspection should occur at the source of a mistake, with the system should be designed to highlight or prevent mistakes.

Mistakes will not turn into defects if operator errors are discovered and eliminated (or prevented) as they occur.

The range of possible Poká Yoke devices that could be applied is vast. Three general categories have been identified:

- Contact Type – the use of shape, dimensions or other physical properties of products to detect the contact or non-contact of a particular feature
- Constant Number Type – detects errors if a fixed number of parts have not been made
- Performance Sequence Type – detects errors if the fixed steps in a sequence have not been performed

The process of poka yoke follows two primary principles:

- **Shut-out activation** - prevents incorrect action from taking place. Preferred as it acts even if operator inattentive
- **Attention activation** - brings attention to an incorrect action but does not prevent its execution.

![Poka Yoke flow chart showing categories and activation types](image)

**Poka Yoke Examples**

**Standard 13 Amp mains plug:**

- Consequences of connecting earth to live could be disastrous
- Making the plug impossible to plug in incorrectly eliminates the possibility of this happening

**Valve cover:**

- Designing in part features to mistake-proof the assembly by only allowing assembly one way, the correct way.

![Valve cover designed to prevent incorrect assembly](image)

**Non-return valve:**
• Could be assembled the wrong way around
• Arrow marked on the valve showing the direction of flow was felt inadequate
• Valve was redesigned with two different size of thread at the input and output ports

Figure 12: Non-return valve with flow arrow visible

As an example from medicine, Broselow® Pediatric Emergency Tape:

• Colour coded tape laid next to child
• Appropriate medical devices and medications contained in packets of the same colour
• The oral syringes designed so that they will not fit onto any IV tubing

Figure 13: Colour coded kit to prevent mistakes when applying crucial treatment under time pressure

Other examples include things such as SD cards, which include a cut corner on an otherwise rectangular card to insure these are inserted correctly. Automated assembly lines often also have stations whereby, if a product is too large/missshapen, it will trigger a sensor/camera/mechanical switch, alerting the operators of a faulty product, or even completely pausing the production line.

Tool counting and such techniques also fall into this bracket. Most people who have worked at some point in a technical environment will have seen tool boards with the outlines of the tools marked out. This denotes where each tool should sit and shows up when a tool is missing.
Life-Cycle Assessment

LCA evaluates the environmental impact of a product throughout its lifespan, from extraction of materials through manufacture and use to disposal.

LCA is covered by standards in the ISO 14000 Environmental Management series:


LCA is a four-stage process:

- **Goal and scope definition:**
  - Establishing the principal choices of the study (methodological choices, assumptions and limitations), particularly with regard to system boundaries and impacts to be considered.
- **Inventory analysis:**
  - A life cycle inventory (LCI) includes information on all of the environmental inputs and outputs associated with a product or service, i.e. material and energy requirements, as well as emissions and wastes.
- **Impact assessment:**
  - The inventory list is the result of all input and output environmental flows of a product system.
- **Interpretation**
  - Describes checks to make to ensure conclusions are adequately supported by data and procedures used in the study, including uncertainty, sensitivity analysis and contribution analysis.

![Figure 14: Example of a diagram that shows where chemicals/pollution/costs come from in the cycle](image)

**Impact Assessment**

A long list of substances is difficult to interpret so a further activity takes place called life cycle impact assessment (LCIA), comprising 4 steps:
- Classification of substances into classes according to their environmental impacts
- Characterisation of impacts by multiplying by a factor which reflects their relative contribution.
- Normalization of impacts by comparison to a reference value, for example the average impact of a European citizen in one year.
- Weighting of impact categories to generate a single score.

**Impact Themes**

Impacts may be translated into themes such as climate change, acidification, human toxicity, etc. and into issues of concern such as human health, natural environment, and natural resources.

A 'big 6' environmental impact categories, considered to have a fundamental impact on the earth’s eco-system, are:

- Acidification potential;
- Eutrophication potential;
- Global warming potential;
- Ozone depletion potential;
- Photochemical ozone creation potential;
- Primary energy use.

**Variants**

There are variants in the scope of an LCA according to the aspect of the life cycle being examined:

- Cradle-to-grave: full LCA from resource extraction through use to disposal.
- Cradle-to-gate: partial life cycle to factory gate, omitting use and disposal phases.
- Cradle-to-cradle: the disposal phase involves a recycling process allowing new production of the same or different products.
- Gate-to-gate: partial LCAs examining only one process in the entire production chain.
- Well-to-wheel: used for transport fuels and vehicles.

**Software**

Many software tools have been developed to assist, such as SimaPro, GaBi, Quantis and EarthSmart.

Models built into these tools depend, for their accuracy, on the accuracy of the data on which they are built – for example concerning the impacts of energy generation in different countries, of transportation and of different materials and processes – and these are contained in public or for-purchase databases.

A unit process has data for material and energy flows for a unit of production, and can, in complex cases, track hundreds of flows.
Table 1: A number of databases that can be used to aid LCA, both free and at cost

<table>
<thead>
<tr>
<th>Public databases</th>
<th>Proprietary data</th>
</tr>
</thead>
<tbody>
<tr>
<td>GREET Model, <a href="https://greet.es.anl.gov/">https://greet.es.anl.gov/</a></td>
<td>Eco Invent <a href="http://www.ecoinvent.ch/">http://www.ecoinvent.ch/</a> Thousands of European unit processes (analogous to control volumes/systems)</td>
</tr>
<tr>
<td>BEES, <a href="http://www.nist.gov/el/economics/BEESSoftware.cfm">http://www.nist.gov/el/economics/BEESSoftware.cfm</a></td>
<td></td>
</tr>
</tbody>
</table>

Simplified Example of using LCA: Cooker Hood

Figure 15: Breakdown of power energy/emissions/fuel that goes in to produce the component
Figure 16: Breakdown of the part into its components.

Figure 17: LCA flowchart breakdown to understand how the product is manufactured, where the energy systems are coming in etc.
### Table 2: Identifying the best data source for each operation

<table>
<thead>
<tr>
<th>Life cycle phase</th>
<th>Data source</th>
<th>Reference area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacture</td>
<td>Stainless Steel Sheet</td>
<td>Germany</td>
</tr>
<tr>
<td></td>
<td>Carbon steel sheet</td>
<td>Germany</td>
</tr>
<tr>
<td></td>
<td>Laser Cutting</td>
<td>Italy</td>
</tr>
<tr>
<td></td>
<td>Metal bending</td>
<td>Italy</td>
</tr>
<tr>
<td></td>
<td>PP granular</td>
<td>Germany</td>
</tr>
<tr>
<td></td>
<td>PVC granular</td>
<td>Germany</td>
</tr>
<tr>
<td></td>
<td>Nylon 6.6 Granular</td>
<td>Germany</td>
</tr>
<tr>
<td></td>
<td>Plastic injection moulding</td>
<td>Europe</td>
</tr>
<tr>
<td></td>
<td>Power electricity</td>
<td>Italy</td>
</tr>
<tr>
<td></td>
<td>Diesel production</td>
<td>Italy</td>
</tr>
<tr>
<td></td>
<td>Transport data</td>
<td>Italy</td>
</tr>
<tr>
<td>To market</td>
<td>Transport data</td>
<td>Italy</td>
</tr>
<tr>
<td></td>
<td>Distance of export</td>
<td>Europe</td>
</tr>
<tr>
<td></td>
<td>Diesel production</td>
<td>Italy</td>
</tr>
<tr>
<td>Use</td>
<td>Power consumption</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Power electricity</td>
<td>Great Britain</td>
</tr>
<tr>
<td>End of life</td>
<td>Recycling</td>
<td>Great Britain</td>
</tr>
<tr>
<td></td>
<td>Incineration</td>
<td>Great Britain</td>
</tr>
</tbody>
</table>

### Table 3: Definition of mass/process required etc. for component manufacture

<table>
<thead>
<tr>
<th>Part name</th>
<th>Part code</th>
<th>Material</th>
<th>Mass/kg</th>
<th>Laser cutting process</th>
<th>Metal bending process</th>
<th>Waste/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base unit</td>
<td>A17_040</td>
<td>AISI 1010</td>
<td>1.1</td>
<td>14 s, 3.5 m</td>
<td>9 Bends</td>
<td>0.6</td>
</tr>
<tr>
<td>Blower Unit Side</td>
<td>A18_023</td>
<td>AISI 1010</td>
<td>0.4</td>
<td>5 s, 1.2 m</td>
<td>5 Bends</td>
<td>0.01</td>
</tr>
<tr>
<td>Blower Unit Side</td>
<td>A18_024</td>
<td>AISI 1010</td>
<td>0.4</td>
<td>6 s, 1.5 m</td>
<td>5 Bends</td>
<td>0.01</td>
</tr>
<tr>
<td>Blower Unit Top</td>
<td>A18_125</td>
<td>AISI 1010</td>
<td>1.1</td>
<td>10 s, 2.5 m</td>
<td>/ Bends</td>
<td>0.1</td>
</tr>
<tr>
<td>Air Outlet Connector</td>
<td>A39_022</td>
<td>AISI 1010</td>
<td>0.4</td>
<td>14 s, 3.5 m</td>
<td>7 Bends</td>
<td>0.2</td>
</tr>
<tr>
<td>Telescopic Chimney</td>
<td>A17_058_54</td>
<td>AISI 430</td>
<td>1.8</td>
<td>11.2 s, 2.8 m</td>
<td>10 Bends</td>
<td>0.2</td>
</tr>
<tr>
<td>Lighting Base</td>
<td>A18_310</td>
<td>AISI 430</td>
<td>0.6</td>
<td>6.4 s, 1.6 m</td>
<td>7 Bends</td>
<td>0.03</td>
</tr>
<tr>
<td>Outer Shell</td>
<td>AL2 001</td>
<td>AISI 430</td>
<td>2.7</td>
<td>22 s, 5.5 m</td>
<td>15 Bends</td>
<td>0.3</td>
</tr>
<tr>
<td>Telescopic Chimney</td>
<td>A39_021</td>
<td>AISI 430</td>
<td>1.5</td>
<td>6 s, 1.3 m</td>
<td>10 bends</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Figure 18: Scores can begin to be seen with regards to various aspects of LCA across three graphs
Figure 19: Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles

The key to decode the acronyms for Figure 19 is as follows: Global warming (GWP), terrestrial acidification (TAP), particulate matter formation (PMFP), photochemical oxidation formation (POFP), human toxicity (HTP), freshwater eco-toxicity (FETP), terrestrial eco-toxicity (TETP), freshwater eutrophication (FEP), mineral resource depletion (MDP), fossil resource depletion (FDP), internal combustion engine vehicle (ICEV), electric vehicle (EV), lithium iron phosphate (LiFePO4), lithium nickel cobalt manganese (LiNCM), coal (C), natural gas (NG), European electricity mix (Euro).

As you can see, the deeper into the process you go, the more complex the output becomes!


Eco-Indicators

Eco-indicators concentrate on production of raw materials (e.g. polystyrene), processing & manufacture (e.g. injection moulding), transportation of product (e.g. shipping), energy in use (e.g. electricity), consumables in use (e.g. paper) and disposal.
**Figure 20:** A simple analysis of a coffee machine with Eco-indicators shows what design priorities should be: minimize the use of electricity and paper filters.

**Design for Sustainability**

LCA tells us what impacts might be, but not so well how to reduce them.

Key approaches of sustainable product design:

- Eliminate use of non-renewable natural resources (including non-renewable sources of energy).
- Eliminate disposal of synthetic and inorganic materials that do not decay quickly.
- Eliminate creation of toxic wastes that are not part of natural life cycles.

Application of a number of relatively straightforward design principles can be a very valuable guide.

There are a number of drivers for sustainability:

- Internal drivers: public image, operational safety, employee motivation, ethical responsibility, and influencing of consumer behaviour.
- External drivers: environmental legislation, market demand, competition, trade organisations, suppliers, and social pressures.
- Standards and legislation such as the European WEEE and RoHS Directives covering waste electrical and electronic equipment and hazardous substances respectively.

One approach to sustainability is showcased by the United Nations Environment Program (UNEP)'s ‘6 REs’:

- RE-think the product and its functions. For example, the product may be used more efficiently
- RE-place harmful substances with safer alternatives
- RE-pair. Make the product easy to repair e.g. via modules that can easily be changed.
- RE-use. Design the product for disassembly so parts can be reused.
- RE-duce energy, material consumption and socio-economic impacts throughout a product’s life cycle.
- RE-cycle. Select materials that can be recycled.
Design for End-of-Life is crucial: "Design for recycling is a method that implies the following requirements of a product: easy to dismantle, easy to obtain 'clean' material-fractions, that can be recycled (e.g. iron and copper should be easy to separate), easy to remove parts/components, that must be treated separately, use as few different materials as possible, mark the materials/polymers in order to sort them correct, avoid surface treatment in order to keep the materials 'clean'."
(Source: Danish EPA Eco Design Guide).

Some examples of sustainability design include:

- BMW Group Sustainable Value Report
- Dartmouth University Design for Recycling
- Information Inspiration at Loughborough
  - http://ecodesign.lboro.ac.uk/?section=97
DfM in Manufacturing

Production Costing

05 April 2019

bristol.ac.uk/composites
Introduction

• Design for Manufacture (DfM): designing products with manufacturing in mind

• Goal:
  • Reduce cost of manufacture
  • Improve ease of manufacture

• Not a new concept
  • LeBlanc, 1788: devised the concept of interchangeable parts in the manufacture of muskets
  • Previously were handmade individually
  • Implemented limited tolerances on the components and developed basic manufacturing processes for repeatability
  • Could be made far more quickly, cheaply, and reliably than before
Introduction

• It is increasingly important because present day products are:
  a) Tending to become more complex
  b) Made/required in increasingly larger numbers
  c) Intended to satisfy a wide variation in user population
  d) Required to compete aggressively with similar products
  e) Required to be of a consistently high quality

• The design of any commercial product is a compromise between conflicting goals

• The most common (and important) conflict is between the cost of consumers requirements, what the customer is willing to pay, and the cost of rival products
Design (generally)

• Traditionally, companies used the sequential approach to product development
  • Does not recognize the impact of design on the downstream functions
• Introduces potential for poor design
• Negative impact product cost
• The cost of a product includes multiple aspects
  • Design costs
  • Manufacturing costs
  • Expenses associated with product warranties
  • Engineering redesign costs

[Diagram of Marketing, Design, Manufacturing, Sales]
Design (generally)

• On a simplistic level manufacturing costs can be broken down into three categories of:
  • Labour (direct and indirect): 2-15% of total
  • Materials and manufacturing processes: 50-80% of total
  • Overheads: 15-45% of total

• Design:
  • Costs typically consume around 10% of the budget
  • However, typically **80%** of manufacturing costs are determined by the design of the product

• Therefore, manufacturing engineers/production managers cannot influence manufacturing costs of a product by more than 20%...
DfM Principle (generally)

• DfM aims to avoid redesign and cost pitfalls through the integration of the following activities:
  • User needs and requirements
  • Market forecasts, projected sales volumes, unit price and demand
  • Product development process (including concept, definition, development of prototype and testing phases)
  • Component design, subassembly design, and assembly analysis
  • Quality requirements
  • Process selection, materials selection and suitability
  • Economic analysis and cost evaluation
  • Design feasibility investigations and redesign
  • Production and commercialisation
DfM Principle (generally)

• The DfM principle has been extremely influential in industry
• Many organisations have adopted Dfm principles
  • E.g. Hitachi, General Electric, IBM, Xerox and Loctite
  • Developed corporate guidelines particularly suited to their needs

• Documented evidence of the success of DFM indicates the possibility of:
  • Reducing product assembly time by up to 61%
  • Reducing number of assembly operations by up to 53%
  • Reduction in number of assembly defects of 68%
  • Cutting time to market by up to 50%
DfM Principle (generally)

• Example of successful DfM: Nortel
  • Redesign reduced a product cost from US$410 to US$65
    • Total number of parts reduced from 59 to 32
    • Time to assembly reduced from 15 to 5 min
    • Entire redesign process, from defining the functional requirements to part production, was 10 months
    • Annual expected savings estimated at US$3.45M

• Another example: Ciba Corning Diagnostics Corporation
  • Manufacturers of blood gas analysers
  • In one particular product design, used DfM to reduce the number of subassembly parts by 48%
  • Reduced cost by 22%
DfM Implementation

• The ease with which DfM principles may be integrated into an organization is directly dependent on the current state of the organisation’s Product Design Process (PDP)

• An organization with a well-defined, well-structured PDP could integrate DfM principles very quickly, maybe as little 3 months

• One suggested method of implementation of DfM may be divided into two sections: restructuring of the PDP and establishment and functioning of the DfM team…
DfM Implementation

• During PDP restructuring, DfM ‘checkpoints’ are positioned within the product definition, development and validation/scale up phases of the PDP

• To pass each of these checkpoints, documents, in the form of questionnaires must be completed

• To answer these questionnaires, pertinent information about the new product must be gathered which will help the DfM team and review board to pre-empt and prevent any pitfalls before the product is approved for manufacture...
## DfM Implementation

<table>
<thead>
<tr>
<th>Product development phase</th>
<th>DFM activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposal</td>
<td>None</td>
</tr>
<tr>
<td>Definition</td>
<td>Initial process list and performance indices</td>
</tr>
<tr>
<td></td>
<td>Measurement</td>
</tr>
<tr>
<td></td>
<td>Initial feasibility and impact assessment</td>
</tr>
<tr>
<td>Development</td>
<td>Recording of performance data</td>
</tr>
<tr>
<td></td>
<td>Revision of initial process list</td>
</tr>
<tr>
<td></td>
<td>Update of impact assessment</td>
</tr>
<tr>
<td>Validation/scale up</td>
<td>Recording of performance data</td>
</tr>
<tr>
<td></td>
<td>Final review of impact assessment</td>
</tr>
<tr>
<td></td>
<td>Completion of DFM manual</td>
</tr>
</tbody>
</table>

DfM in Manufacturing

05 April 2019
Definition phase - initial process list and performance indices measurement:

- List the process steps as per the proposed routing and indicate the critical steps
  - i.e. steps that directly impact manufacturing costs/performance metrics
- Agree performance metrics to be measured at each critical step
  - (e.g. Cpk, %yield, %rework)
- If the product is an updated version of an existing product, use performance metrics from that product's DfM manual
  - This is the benchmark
- This document is then completed and signed by the members of the DfM team
DfM Implementation

Definition phase - initial feasibility and impact assessment:

• Complete a tabulated comparison of performance metrics if the product/process is an updated version of an existing one
  • Estimated vs existing

• Identify what is new about the product and process and identify the reasons for these changes

• Cost comparisons are included
  • E.g. labour, overhead, materials, unit cost, standard time, sales price, margin and forecasted volume
  • Negative variances highlighted/explained, proposals for improvement

• For an entirely new product/process, comparisons are made against most similar product/process currently in production
DfM Implementation

Definition phase - initial feasibility and impact assessment:

• Prediction and assessment of any potential impacts on manufacturing, with particular attention to:
  • New materials
  • New equipment
  • Environmental and ergonomic concerns

• Following compilation and sign-off of this document by the DfM team it should then be submitted for management review, seeking approval to proceed to the next phase of product development...
DfM Implementation

Development phase - recording of performance data:
- Following approval to proceed, actual products can now be made, and real data recorded.
  - Data analysed and compared against estimated performance metrics
- Any variances between actual and estimated data should be investigated and documented

Development phase - revision of initial process list:
- Any amendments to the routing should be included at this stage (can some steps be eliminated or combined?), following analysis of the selected performance metrics to ascertain if they’re correct or more metrics should be included?
DfM Implementation

Development phase - update of impact assessment:

• Performance metrics and cost comparisons should be reviewed
  • Ensure that they are on target with the original projections
• Any variances must be investigated and resolved/justified
• Must verify completion of original proposals for improvement
• Following review and resolution/acceptance of any potential manufacturing impacts, the updated documents should then be submitted for approval by the management review board
DfM Implementation

Validation/scale up - recording of performance data:

• Analysis of data and comparison against data acquired during pilot testing is advised during the scale up phase
• Recording of data at the scaled-up validation stage may highlight problems not evident during development

Validation/scale up - final review of impact assessment:

• Performance metrics check and cost comparisons review (against original projections) should be completed
DfM Implementation

Validation/scale up - completion of DfM manual:

- Compile documents and data from all three phases of product development
- This creates the DfM manual for the new product
- Submit this for final review by the management review board
- Following approval, the product may then be released for commercialized full-scale production
- The characteristics of the product/process can be quickly referenced in the DFM manual
  - Potential to make it a powerful tool for process development
DfM Implementation

Establishment and function of the DfM team:

• This team will comprise of engineering and quality representatives from the R&D and manufacturing (assembly and sub-assembly) departments

• When implementing DfM initially, the team should focus on an existing product and process

• This provides the advantage of being able to refer to performance metrics from an established historical database

• In addition, the team members’ familiarity with the product and process will allow them to focus on the aspects that require improvement, and aid in the establishment of a more effective DfM system
DfM in/for Composites

• This method works for well established materials and products
  • Largely subtractive processing
• For composite materials it is arguable that DfM and costs support as we’ve run through does not exist yet in anger
• There have been examples in DfM for composites
• There are later examples:
  • Bader (Composites: Part A 33 (2002) 913–934)
  • C. Monroy Aceveset al (Materials and Design 29 (2008) 418–426)
  • (though neither reference the earlier example…)

05 April 2019

DfM in Manufacturing
DfM in/for Composites

**COMPOSITE-BASED PART/SUB-ASSEMBLY SPECIFICATION**

- Loading specification: Mechanical, thermal, impact, chemical, electrical, magnetic
- Performance specification: Stresses, deflections, settling-time, frequency response
- Other specifications: Fatigue life, costs, production rates, production volume

**MATERIAL SELECTION**

Matrix materials
- Fibres (continuous, discontinuous)

**PART GEOMETRY**

- Form synthesis
- Synthesis of parts

**HYBRIDS**

- Continuous, discontinuous
- Glass, aramid, graphite

**CHARACTERISTICS AND CONSTRAINTS IMPOSED BY MANUFACTURING PROCESS**

- Pultrusion, filament winding, lay-up, moulding, laminating, weaving, mechanical fasteners, adhesive bonding, antifriction bearings

**Aerospace**
- High-strength, high stiffness composites
- High-toughness thermoplastics
- High-temperature thermoplastics

**Military**
- High-toughness braided and other damage-tolerant systems

**Industrial**
- Fast-curing resins
- Hybrid composites
- Medium-toughness thermoplastics

**Lower cost**

**Higher production rate**
DfM in/for Composites

MACROMECHANICAL CHARACTERISTICS OF COMPOSITE-BASED PART
- Fibre volume fraction, fibre orientation, stacking sequence, ply thickness

ELASTODYNAMIC CHARACTERISTICS OF COMPOSITE-BASED PART
- Mass, stiffness, damping

FINITE ELEMENT ANALYSIS
- Deflections, stresses, settling-time, fatigue life

PART PERFORMANCE SPECIFICATION SATISFIED?
Yes
- PART MANUFACTURING SPECIFICATION
  - Material specification, part geometry specification, manufacturing process specification

STOP
DfM in/for Composites

• But nothing has really stuck... Why!?
• Is it a major difficulty that the material and structure are created simultaneously?
  • Defects in the manufacturing phase have a direct effect on the strength/robustness of the component
• Is it because aero has dominated the use and processing of composites?
• Or is it simply the fact that composite design is still misunderstood?
  • Relating back to earlier, still have a sequential flow with enormous reliance on simulation
  • At this stage, cannot simulate manufacture in its entirety
# DfM in/for Composites

<table>
<thead>
<tr>
<th>Tool Module</th>
<th>Manage</th>
<th>Component design</th>
<th>Process design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Costing</td>
<td>Materials</td>
<td>CAD</td>
</tr>
<tr>
<td>Conceptual design</td>
<td>Materials process &amp; selection</td>
<td>Selection</td>
<td>Concept</td>
</tr>
<tr>
<td>Detailed design</td>
<td>Process optimisation</td>
<td>Modeling &amp; characterisation</td>
<td>Details</td>
</tr>
</tbody>
</table>
DfM in/for Composites
Design for Manufacturing

Introduction
Design for Manufacture (DfM) is the practice of designing products with manufacturing in mind. Its goal is to reduce the costs required to manufacture a product and improve the ease with which that product can be made.

It is not a new concept - for example LeBlanc in 1788 devised the concept of interchangeable parts in the manufacture of muskets, which previously were handmade individually.

By implementing limited tolerances on the components and developing basic manufacturing processes for repeatability, the muskets could be made far more quickly, cheaply, and reliably than hitherto by craftsmen.

It is increasingly important because present day products are:

- Tending to become more complex
- Made/required in increasingly larger numbers
- Intended to satisfy a wide variation in user population
- Required to compete aggressively with similar products
- Required to be of a consistently high quality

The design of any commercial product is a compromise between conflicting goals. The most common (and important) conflict is between the cost of consumers requirements, what the customer is willing to pay, and the cost of rival products.

Design (generally)
Traditionally, many companies followed the sequential approach to product development, which does not recognize the impact that design has on the downstream functions. In addition to introducing potential for poor design, this approach can negatively impact product cost. The cost of a product includes the design costs, the manufacturing costs, expenses associated with product warranties and engineering redesign costs.

![Figure 1: Tradition, linear approach to product development, not allowing for design impact on production cost to be properly assessed](image)

On a simplistic level manufacturing costs can be broken down into three categories of:

- Labour (direct and indirect): 2-15% of total
- Materials and manufacturing processes: 50-80% of total
- Overheads: 15-45% of total
Although design costs consume around 10% of the budget, typically 80% of manufacturing costs are determined by the design of the product. So, no matter how creative manufacturing engineers and production managers are, they cannot influence the manufacturing costs of a product by more than 20%...

**DfM Principle (generally)**

DfM aims to avoid redesign and cost pitfalls through the integration of the following activities:

- User needs and requirements
- Market forecasts, projected sales volumes, unit price and demand
- Product development process (including concept, definition, development of prototype and testing phases)
- Component design, subassembly design, and assembly analysis
- Quality requirements
- Process selection, materials selection and suitability
- Economic analysis and cost evaluation
- Design feasibility investigations and redesign
- Production and commercialisation

*Figure 2: Flowchart showing interaction/loops between product development, cost and process selection and the requirements from the user/market*
The DfM principle has been extremely influential in industry. Many organisations, including Hitachi, General Electric, IBM, Xerox and Loctite have adopted these principles and developed corporate guidelines particularly suited to their needs.

Documented evidence of the success of DFM indicates the possibility of:

- Reducing product assembly time by up to 61%
- Reducing the number of assembly operations by as much as 53%
- Reduction of 68% in the number of assembly defects
- Cutting the time to market by as much as 50%

One example of the success of DfM is Nortel who successfully used it to redesign and reduce a particular product cost from US$410 to US$65:

- Concurrently, the total number of parts to make the product were reduced from 59 to 32 pieces, and the time to assembly reduced from 15 to 5 min
- The entire redesign process, from defining the functional requirements to part production, was 10 months
- The annual expected savings were estimated at US$3.45M

Another case in hand is Ciba Corning Diagnostics Corporation (manufacturers of blood gas analysers). In a particular product design, they have used DfM to reduce the overall number of subassembly parts by 48% and the cost by 22%.

**DfM Implementation**

The ease with which DfM principles may be integrated into an organization is directly dependent on the current state of the organisation’s Product Design Process (PDP). An organization with a well-defined, well-structured PDP could integrate DfM principles very quickly, maybe as little 3 months.

One suggested method of implementation of DfM may be divided into two sections: restructuring of the PDP and establishment and functioning of the DfM team...

During PDP restructuring, DfM ‘checkpoints’ are positioned within the product definition, development and validation/scale up phases of the PDP. To pass each of these checkpoints, documents, in the form of questionnaires must be completed. To answer these questionnaires, pertinent information about the new product must be gathered which will help the DfM team and review board to pre-empt and prevent any pitfalls before the product is approved for manufacture...

*Table 1: DfM activities shown at each product development phase.*
Definition phase - initial process list and performance indices measurement:

- List the process steps as per the proposed routing and indicate the critical steps (i.e. those steps that directly impact manufacturing costs and performance metrics of the product)
- Agree upon the performance metrics to be measured at each of these critical steps (e.g. Cpk, %yield, %rework)
- If the product is an updated version of an existing product, the performance metrics, from that product’s DfM manual, are used as a benchmark
- This document is then completed and signed by the members of the DfM team

Definition phase - initial feasibility and impact assessment:

- If the product/process is an updated version of an existing one, a tabulated comparison of performance metrics (estimated versus existing) should be completed
- Identify what is new about the product and process and identify the reasons for these changes
- Cost comparisons are included (e.g. labour, overhead, materials, unit cost, standard time, sales price, margin and forecasted volume). Any -ve variances should be highlighted and explained with proposals for improvement
- For an entirely new product/process, comparisons are made against most similar product/process currently in production

Definition phase - initial feasibility and impact assessment:

- Prediction and assessment of any potential impacts on manufacturing, with particular attention to new materials, new equipment, and environmental and ergonomic concerns
- Following compilation and sign-off of this document by the DfM team it should then be submitted for management review seeking approval to proceed to the next phase of product development...

Development phase - recording of performance data:

- Following approval to proceed, actual products can now be made and real data recorded. This data must be analysed and compared against the estimated performance metrics
- Any variances between actual and estimated data should be investigated and documented

Development phase - revision of initial process list:

- Any amendments to the routing (can some steps be eliminated or combined?) should be included at this stage following analysis of the selected performance metrics to ascertain whether they are correct or more metrics should be included?

Development phase - update of impact assessment:

- The performance metrics and cost comparisons should be reviewed to ensure that they are on target with the original projections
- Any variances must be investigated and resolved/justified
- Verification of completion of original proposals for improvement must be performed
- Following review and resolution/acceptance of any potential manufacturing impacts, the updated documents should then be submitted for approval by the management review board
Validation/scale up - recording of performance data:

- Analysis of data and comparison against data acquired during pilot testing is advised during the scale up phase
- Recording of data at the scaled up validation stage may highlight problems not evident during development

Validation/scale up - final review of impact assessment:

- At this point, a performance metrics check and cost comparisons review (against original projections) should be completed

Validation/scale up - completion of DfM manual:

- Documents and data from all three phases of product development are finally compiled into the DfM manual for the new product
- This manual is submitted for final review by the management review board
- Following approval, the product may then be released for commercialized full-scale production
- The characteristics of the product/process can be quickly referenced in the DfM manual, potentially making it a powerful tool for process development

Establishment and function of the DfM team:

- This team will comprise of engineering and quality representatives from the R&D and manufacturing (assembly and sub-assembly) departments
- When implementing DfM initially, the team should focus on an existing product and process
- This provides the advantage of being able to refer to performance metrics from an established historical database
- In addition, the team members’ familiarity with the product and process will allow them to focus on the aspects that require improvement, and aid in the establishment of a more effective DfM system

DfM in/for Composites

All of the previous is fantastic for well-established materials and products (and largely subtractive processing). But in composite materials it is arguable that DfM and costs support as we’ve run through does not exist as yet in anger.

There have been examples in DfM for composites, notably M V Gandi, B S Thompson, F Fischer ‘Manufacturing-process-driven Design Methodologies for Components Fabricated in Composite Materials’ (Materials & Design 11 (5) 1990). Then there are later examples such as Bader (Composites: Part A 33 (2002) 913–934) and C. Monroy Aceves et al (Materials and Design 29 (2008) 418–426) [though neither reference the earlier example...].

But nothing has really stuck... Why!?  

Is it still a major difficulty that the material and the structure are created at the same time so that any defect(s) in the manufacturing phase have a direct effect on the strength and robustness of the component manufactured?

Is it the fact that aero has dominated the application of the material and processing?
Or is it simply the fact that composite design is still misunderstood, and relating back to earlier, that we still have a rather sequential flow with enormous reliance on simulation (that cannot at this stage simulate manufacture in its entirety)?

![Figure 3: Standard flow for a composite component. Note the sequential nature.](image1)

![Figure 4: Engineering drawing of a trial composite component. Here, a metallic component has been taken and an attempt has been made to transform it into a composite component. This has led to a whole raft of problems, as the part has not been designed with the manufacture of a composite component properly considered.](image2)
Top Down Costing Exercise

Production Costing

05 April 2019
Introduction

- Requirement: An initial design is required for a UAV box-spar demonstrator based on a single critical load case.
Introduction

Top Down Exercise

05 April 2019
Top Down Exercise

05 April 2019
Introduction

• **Part:** The design shall consist of a closed-section monolithic beam. Core material is not allowed.

• **Geometry:** The geometry is as defined in the previous figures. The width (Z dimension) must be constant along the span. The depth (Y dimension) must be constant along the span (X dimension) between X = 0 to 150mm and taper linearly between X = 150 to 1500mm

• **Adjoining structure:** The design shall allow for bolted attachment to root fixing brackets at the upper and lower surface which extend up to 100mm from the root
Introduction

• **Materials:** The design shall only select materials from the following sanctioned list:
  - UD/WV HSCFEP, HMCFEP, GFEP, KFEP
  - UD (CFEP) material cured ply thickness = 0.125mm, WV (CFEP) material cured ply thickness = 0.25mm
  - UD (GFEP) material cured ply thickness = 0.2mm, WV (CFEP) material cured ply thickness = 0.4mm
  - Stress free temperature = 70ºC
  - The CDM generic material data can be applied directly as the design allowable values for prepreg material but must be knocked down by a factor of 1.20 for dry materials (which need in-situ resin infusion). For generic fastener and adhesive data see relevant BB space
Introduction

• **Loading:** The design shall account for a critical limit load case:
  - 1.0 kN offset by 25mm in the Z direction to the rear of the beam central longitudinal X axis, applied through a wiffle tree arrangement

• **Design considerations:** Ensure to observe that:
  - **Stiffness:** The tip deflection shall be greater than 50mm and less than 150mm at limit load. The tip twist shall be greater than 0.25° and less than 0.5° at limit load
  - **Strength:** No fibre dominated failures or inter-laminar failures shall occur below ultimate load
  - **Stability:** No global or local buckling shall occur below ultimate load
  - **Account for operating temperatures from -20℃ to +50℃**
  - **The design shall be lightweight but robust enough to cope with an impact up to 15J at any position by ensuring adequate reserve**
Introduction

- **Design Practice**: Ensure that:
  - Ultimate safety factor = 1.5
  - Ultimate reserve factors shall be above 1 with further margin for uncertainties including impact damage
  - Ultimate reserve factors for the root joint shall be above 1.5 for the box and above 2.0 for the fasteners
Introduction

• Manufacturing Considerations: The component, once designed, has to be appropriate for production in aerospace certified advanced composite materials and processes; and should consist of a closed-section monolithic beam of appropriate geometric profiling. The component must not use a sandwich structure design, thus no core or honeycomb will be allowed. Equally the internal cavity must be free from any moulded surfaces once the component is complete (i.e. any mouldings must release once curing is finished). The component must be free from any observable surface defects, demonstrating finish to typical aerospace tolerances, and overall be within typical aerospace geometrical limits (envelope tolerances and variations due to mould stresses)...
• Manufacturing Considerations: The component is expected to be defect-free throughout its thickness - whether from moulding or machining operations - although the manufacturer is allowed to set defect sizes and allowables according to their determined quality requirements (to aerospace standards & rigour). The root section of the inner top surface is expected to act as the primary datum source, however the manufacturer may suggest the use of inner or outer mould lines as required by their choice of process (that again must meet aerospace manufacturing requirements)…
• **Manufacturing Considerations:** The manufacturing constraints are:

“This component is to be treated as a primary structure (i.e. if it fails then the product could be lost) thus all manufacturing decisions (such as traceability) must reflect this status. As this is a demonstrator, the production volume is set at 1 shipset, with two components required per shipset, and manufacturing considerations must address this production risk (such as impacts on time/quality). Any and all manufacturing decisions must be justified and highlighted where necessary.”
Introduction

- **Client**: The client reserves the right to make nominal changes at any time in the design and manufacturing process…
Manufacturing Plan Needs:

1. **Component Fabrication:** Identify all materials, processes, and mouldings used for the component over its additive build phases; including consideration of tooling and demoulding actions. (15)

2. **Component Machining & Assembly:** Identify all machining, assembly, and finishing method(s) to be used for the component over its sacrificial build phases; including the use of any inserts, joining operations, jigging/fixtures, and any pertinent detail of operation etc. (15)
3. **Geometric Dimensioning & Tolerance:** Identify suitable GD+T options/standards for the component. Based on those GD+T details identify the minimum defect allowables (as well as max/min material variability) for the component and outline a suitable acceptance criteria - taking into account the capabilities of the chosen manufacturing processes, the safety-critical nature of the structure, and chosen assembly requirements (10)
Manufacturing Plan Needs:

4. **Non-Destructive Testing:** Identify the inspection, NDT, and Quality Assurance methods to be used throughout the manufacturing of the component; ensuring that the methods are suitable based on your previously supplied details (10)

5. **Utilisation:** Estimate the materials utilisation in your manufacturing plan; i.e. what proportion of the purchased materials forms part of the finished component. Identify how this utilisation could be improved to reduce material waste and scrap risk (5)
Manufacturing Plan Needs:

6. **Initial Costing:** Based on all previous sections, report the likely industrial cost to build the component, using an initial sale price of £3,750. Identify the touch labour time available according to the cost, and suggest your confidence in this being met in terms of the initial manufacturing plan. Note: undertake this as a top down costing, but be aware of the potential risks in this approach (5)
**Introduction and Description**

**Requirement:** An initial design is required for a UAV box-spar demonstrator based on a single critical load case.

*Figure 1: Geometric description of the required part, including resultant loading point.*
Part - The design shall consist of a closed-section monolithic beam. Core material is not allowed.

Geometry - The geometry is as defined in the previous figures. The width (Z dimension) must be constant along the span. The depth (Y dimension) must be constant along the span (X dimension) between X = 0 to 150mm and taper linearly between X = 150 to 1500mm.

Adjoining structure - The design shall allow for bolted attachment to root fixing brackets at the upper and lower surface which extend up to 100mm from the root.

Materials - The design shall only select materials from the following sanctioned list:

- UD/WV HSCFEP, HMCFEP, GFEP, KFEP
- UD (CFEP) material cured ply thickness = 0.125mm, WV (CFEP) material cured ply thickness = 0.25mm
- UD (GFEP) material cured ply thickness = 0.2mm, WV (CFEP) material cured ply thickness = 0.4mm
- Stress free temperature = 70°C
- The CDM generic material data can be applied directly as the design allowable values for prepreg material but must be knocked down by a factor of 1.20 for dry materials (which need in-situ resin infusion). For generic fastener and adhesive data see relevant BB space

Loading - The design shall account for a critical limit load case:
1.0 kN offset by 25mm in the Z direction to the rear of the beam central longitudinal X axis, applied through a whiffletree arrangement

**Design considerations** - Ensure to observe that:

- **Stiffness:** The tip deflection shall be greater than 50mm and less than 150mm at limit load. The tip twist shall be greater than 0.25° and less than 0.5° at limit load
- **Strength:** No fibre dominated failures or inter-laminar failures shall occur below ultimate load
- **Stability:** No global or local buckling shall occur below ultimate load
- **Account for operating temperatures from -20ºC to +50ºC**
- **The design shall be lightweight but robust enough to cope with an impact up to 15J at any position by ensuring adequate reserve**

**Design Practice** - Ensure that:

- **Ultimate safety factor = 1.5**
- **Ultimate reserve factors shall be above 1 with further margin for uncertainties including impact damage**
- **Ultimate reserve factors for the root joint shall be above 1.5 for the box and above 2.0 for the fasteners**

**Manufacturing Considerations** - The component, once designed, has to be appropriate for production in aerospace certified advanced composite materials and processes; and should consist of a closed-section monolithic beam of appropriate geometric profiling. The component must not use a sandwich structure design, thus no core or honeycomb will be allowed. Equally the internal cavity must be free from any moulded surfaces once the component is complete (i.e. any mouldings must release once curing is finished). The component must be free from any observable surface defects, demonstrating finish to typical aerospace tolerances, and overall be within typical aerospace geometrical limits (envelope tolerances and variations due to mould stresses)...

The component is expected to be defect-free throughout its thickness - whether from moulding or machining operations - although the manufacturer is allowed to set defect sizes and allowables according to their determined quality requirements (to aerospace standards & rigour). The root section of the inner top surface is expected to act as the primary datum source, however the manufacturer may suggest the use of inner or outer mould lines as required by their choice of process (that again must meet aerospace manufacturing requirements)...

**Manufacturing Constraints** – The manufacturing constraints are given as follows: “This component is to be treated as a primary structure (i.e. if it fails then the product could be lost) thus all manufacturing decisions (such as traceability) must reflect this status. As this is a demonstrator, the production volume is set at 1 shipset, with two components required per shipset, and manufacturing considerations must address this production risk (such as impacts on time/quality). Any and all manufacturing decisions must be justified and highlighted where necessary.”

**Client** - The client reserves the right to make nominal changes at any time in the design and manufacturing process...
Manufacturing Plan Needs

1. **Component Fabrication**: Identify all materials, processes, and mouldings used for the component over its additive build phases; including consideration of tooling and demoulding actions. (15)

2. **Component Machining & Assembly**: Identify all machining, assembly, and finishing method(s) to be used for the component over its sacrificial build phases; including the use of any inserts, joining operations, jigging/fixtures, and any pertinent detail of operation etc. (15)

3. **Geometric Dimensioning & Tolerance**: Identify suitable GD+T options/standards for the component. Based on those GD+T details identify the minimum defect allowables (as well as max/min material variability) for the component and outline a suitable acceptance criteria - taking into account the capabilities of the chosen manufacturing processes, the safety-critical nature of the structure, and chosen assembly requirements (10)

4. **Non-Destructive Testing**: Identify the inspection, NDT, and Quality Assurance methods to be used throughout the manufacturing of the component; ensuring that the methods are suitable based on your previously supplied details (10)

5. **Utilisation**: Estimate the materials utilisation in your manufacturing plan; i.e. what proportion of the purchased materials forms part of the finished component. Identify how this utilisation could be improved to reduce material waste and scrap risk (5)

6. **Initial Costing**: Based on all previous sections, report the likely industrial cost to build the component, using an initial sale price of £3,750. Identify the touch labour time available according to the cost, and suggest your confidence in this being met in terms of the initial manufacturing plan. Note: undertake this as a top down costing, but be aware of the potential risks in this approach (5)
Virtual Composites Company – Worked Example

Introduction
This document outlines a worked example of the utilisation of the Virtual Composites Company (VCC) model for a bottom up costing methodology. Before beginning, please ensure that you have read and understood the details laid out in the Virtual Composites Company Instruction Sheet.

The instruction sheet outlines the VCC model. This includes a flowchart of the VCC model structure, instructions on how to use the model, and notes on how to run the model smoothly within Microsoft Excel. Crucially, assumptions upon which the model is based are also listed. These should be carefully noted, as trying to carry out a costing process outside of the limitations laid out by these assumptions may give severely inaccurate results.

Starting Up
To begin, open the VCC model spreadsheet. You will be greeted by the home page, as shown in Figure 1. If this is not the tab that is open upon opening the model, then click the ‘Home’ link, situated at the top of every tab.

From the home page, progress to the ‘instructions’ tab. This will give you an additional overview into the practical use of the model. Here, instructions are given on how to use the model, and a key
denotes the different types of cells that will be encountered within the model. The assumptions are also listed again. Finally, a check cell is provided at the top of the page. This will be green if all the model inputs are valid.

**Inputs**
Proceeding to the inputs tab, you will see that the inputs are separated into three categories. These are Manufacturing Details, Part Details and Financing.

*Manufacturing Details*
The first input page is for manufacturing details. This begins by the input of general information, as shown in Figure 2. The intended production volume should be put in, alongside the production start time and expected production life. The manufacturing and curing methods are also chosen here. Ensure that these are accurate, as the model is simply for costing purposes and makes no claims on ensuring the suitability of these method choices. Finally, also ensure the Exchange Rates are updated.

For this example, a production volume of 27,000 parts per year is chosen, over a 20-year production life from the beginning of 2013. These will manufactured utilising hand lay-up with autoclave curing.

![Figure 2: Manufacturing details – general](image)

The next section deals with the manufacturing facilities. Whilst there are multiple inputs for this section, most have recommended values (alongside the data source for these values). These recommended values are used in this example, alongside an additional space value of 10% and a part shipping cost of 0. There are also two drop down menus in this section, detailing the currency to be used and the material delivery schedule. This example will work in pound sterling and with a stock delivery schedule, as opposed to just in time.

![Figure 3: Manufacturing Facilities](image)
The next section details the production schedule. Here, the number of parts per shipset is determined, alongside the number of shipsets per year. It can be seen that, upon reaching a steady state, the number of parts here should match that in the general section. This production volume should also include a ramp up to begin production (as shown in Figure 4) and a ramp down during the last years of the production cycle.

The volume of parts sold is also shown (in shipsets), allowing you to determine the number of spares in stock. The final values in this section detail the number of prototype parts made. Once again, these have recommended values, but can also be input to a different value. For example, as we have chosen hand lay-up, the sale price we will use is significantly lower than the recommended value/}

![Figure 4: Production Schedule](image)

The next section details production capacity. Recommended values are given for the working schedule and patterns throughout the year, and these are used in this example.

![Figure 5: Production capacity](image)

The efficiency of material usage and the learning curve are the next inputs. Once more, the recommended values will be used here, whilst our material scrap will be taken to landfill rather than being sold, as is possible within the dropdown menu.

![Figure 6: Production efficiencies and learning](image)

The final input section on this tab is the labour rates of various staff. Here, the recommended value varies with production rates, as higher numbers of staff will be required for higher production rates. As stated in the VCC Instruction sheet, only certain employees will have annual salaries, whilst others will have hourly rates that scale with production. All of these are listed here with the ability to define them at or away from the recommended values, as shown in Figure 7.
The rest of this tab does not require input, but instead shows useful information. The first part of this is sensitivity analysis, whilst the second is comparisons between the various manufacturing and curing methods.

**Part Details**
The next tab details the part itself that is being produced. Here a description of the part is given. The overall sizing/weighting etc is laid out, in accordance with the stated assumptions. This provides both the untrimmed and the final part dimensions, alongside the core and tool dimensions. For the first part of this tab, the only two inputs are fibre volume fraction and tooling. In this example, we will use a 60% fibre volume fraction and INVAR tool, as shown in Figure 8.
The next two boxes contain drop down menus detailing the materials to be used. The first refers to the use of prepreg, whilst the second the use of dry fibre and resin infusion. The appropriate box will remain visible, whilst the box which is not relevant for the chosen method will be greyed out. In this case, as prepreg is chosen, we will choose our prepreg type from the drop-down list. Following this, we can choose to either provide a cost for the prepreg material, or have one given automatically, as shown in Figure 9.

The final aspect requiring input in this tab is the core material, as shown in Figure 10. Here, the core type is selected, alongside once again choosing whether to define the core cost or have it automatically chosen for you.

The remainder of this tab details aspects of the part. Firstly, the lay-up sequence is detailed, and shown for each of the three methods (hand lay-up, resin infusion or AFP), alongside a diagram of the
ply boundaries. Following this, material properties for the chosen materials (both laminate and core) are given, and finally a table detailing the costs with regards to tooling requirements is shown.

**Financing**
The final, and shortest, input tab is financing. Firstly, the inflation rate and corporate tax rates are defined, alongside a recommended value. The capital structure is then defined, again alongside recommended values for these. Depreciation is then given, split into various aspects from the property values to tooling and IT equipment. Finally, the payment terms for both debtor and creditor are given.

The values used in this example are all shown in Figure 11. Here, the recommended values were all used if given. However, it should be noted that the recommended values should always be ‘sanity checked’. For example, the model was created in 2011, and corporate and inflation rates change over time, so some of the recommended values may be out of date by the time you come to use the model. The sources provided and notes on this should give a good idea of the necessity of checking the recommended values further.

<table>
<thead>
<tr>
<th>General</th>
<th>Recommended Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation rate</td>
<td>2.0%</td>
<td>2% IMF</td>
</tr>
<tr>
<td>Corporate tax rate</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Debt/equity ratio</td>
<td>65%</td>
<td>65%</td>
</tr>
<tr>
<td>Interest rate payable on bank loans and overdrafts</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>WACC</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depreciation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freehold buildings and long leasehold property improvements</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Short leasehold property improvements</td>
<td>NA</td>
<td>period of lease</td>
</tr>
<tr>
<td>Plant, machinery and fixtures</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>IT equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payment Terms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Debtor days</td>
<td>75 days</td>
<td></td>
</tr>
<tr>
<td>Creditor days</td>
<td>40 days</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 11: Financing Inputs*

**Outputs**
After inputting the required data in the previous tabs, the desired cost data will be output in the following sections. These will update if further changes are made to the input data.

The first output tab shows schematics of an optimised factory layout with process flow for each of the three manufacturing methods. Above this, for the chosen method, the factory dimensions and parameters are listed. These are calculated from the input data.

The next tab gives an overall cost summary. This includes key outputs of cost, revenue and profit margins. A cost breakdown by part is given in graphical form, and further details of how the cost is spread/made up is tabulated. For the example inputs we have run here, an average net profit of £13 per part is given, providing a net profit margin of 3%.
The next tab provides a more detailed overview of the expected Financial statements across the entire production run. This includes a breakdown of profit and loss, a Balance Sheet and cash flow details. These can then be thoroughly checked for discrepancies and potential problems during the production run.

Financial Analysis is undertaken on the next tab. This again shows profit and loss, the balance sheet and cash flow. However, this time this is analysed in graphical form, providing a visual guide into such things as profit margin throughout the lifetime of the production run. This can very quickly highlight issues such as potential cash flow problems when large investment in new production equipment etc is needed, and allow secure financial planning for this point.

Next, the direct production costs are shown, broken down into categories. The makeup of the production costs by process are shown, and broken down into both labour and utilities costs.

Yearly cost per part is the next output. This allows you to see a breakdown the cost and profit/loss per part in a given production year, which may be input at the top of the page. The costs are shown graphically, and broken down into category and production stage, as well as being tabulated.

The following tab shows the learning curve analysis, in both graphical and tabulated form. This shows the projected efficiency improvements and potential savings in process time that would be expected across the product life cycle, if the hand lay-up method is utilised.

Risk analysis is given next. This is in the form of sensitivity tables, showing the changes from the baseline values provided if certain assumed values change. This can give an idea of how sensitive the cost data is to certain parts of the input data, and thus enables further focus on providing accurate data in the most key areas.

The next two tabs show a case study and its application. Here, the VCC model is compared to a basic costing method case study. This highlights disparities in comparison to other costing methods, and shows potential pitfalls in the method. It also provides a graphical comparison of cost per part across the different methods, and how this cost is broken down by type in each method.

The final four output tabs display a series of tradeoffs with regards to the process/materials chosen and the other possible options. Firstly, the tooling is shown. Here, the cost and cash flow of the tooling are given across the lifespan. This is followed by a production method comparison, showing the cash flow across the product life-cycle when comparing both hand lay-up and AFP production. Next, the same comparison is shown between the three curing methods available, namely autoclave, oven and heated tool curing. Finally, a comparison between low, medium and high production volumes is shown, detailing the percentage each cost type will contribute to the final overall cost for each of the production volumes available.

Cost Calculation
The next section details the cost calculations. This is broken into numerous tabs, showing the calculations of the costs in various different ways.

Firstly, a yearly cost breakdown is supplied. The variable and fixed costs and broken down into smaller categories, and each of these is shown on a yearly basis. This allows you to understand exactly what is generating the cost each year, and how this all sums to produce the final cost.

By contrast, the following tab details the set-up costs. This is not done yearly, as the costs for set-up are one off costs. However, this does provide a breakdown of the yearly cost, if you were to
theoretically spread the cost of set-up across the entire production runs. This tab includes various aspects of set-up, from part design to factory floor office desks and hardware.

Next, the general overheads are shown. These includes aspects such as rent, tax, utilities and general cleaning and maintenance. This also includes aspects such as labour costs for salaried staff, as these are annual and do not vary by production volume. Some inputs are available on this page, whereby the cost for waste disposal or resale price can be added in £/tonne.

The costs for the chosen process are given next. This details the total per part and per year, and also shows the effects of the learning curve over time.

Finally, the calculations for the facilities are given. This shows the production and power capacity of the plant, alongside detailing the required production and non-production floorspace, and how this is obtained. The assumptions of how office/break-out space is calculated is also given.

Process Calculations

The next three sections each consist of an overview tab, and two further tabs. These are the sections covering the calculations for the specific processes. For example, the first group covers hand lay-up, the second group resin infusion, and the third AFP manufacture. As each of these covers similar material but simply a different process, only the hand-lay up tabs will be covered here, as the example we are working with utilises a hand lay-up process. The work on these tabs can then be taken and a similar process utilised for both resin infusion and AFP.

The first section of lay-up facilities shows the production capacity. In this example, we have stated that a steady-state production of 27,000 parts per year is required, and as such it has been determined that 115 parts per day are required to meet this (including reject rate etc.). This data is used to determine the staff/facilities/space required within the plant to meet this, ranging from basic manufacturing personnel through to QC/NDT. The time at each production stage is given, and the required number of parallel machines is shown.

Following on from this, the required floor space for the factory is then displayed. This is broken down into individual features (e.g. for the stock prepreg deliveries we have asked for in this example, a freezer with a 41m² area is required), and then summed to show total factory space. The specific machinery required, and number, cost and depreciation of these is also shown.

The second process specific tab details with the costs of the process as a whole. As such, we will look here at the hand-lay up costs. In this instance, as opposed to in the previous tab, the input cells here should be manually input by the user in this tab. This is as they do not draw from earlier data. A number of the potential inputs are shown in Figure 12, alongside the values used in this example.
To begin, a number of parameters are defined, including scrap rate of both the prepreg and part, and the part rejection rate. If work has begun on the design of a product, then general work on final part shape before trimming and nesting of plies within the prepreg should have been carried out, allowing for fairly accurate values to be entered here.

Following the input of this, results to show the idle time of operators are shown, alongside the utility of both the prepreg roll and any consumables. Further data should be input into the consumables calculations in order to allow for the most accurate calculation of consumables cost. In this example, we shall use a 25mm overlap for consumables around the part, alongside a consumable wastage factor of 0.2 and 2 sets of consumables required.

Tooling costs are shown next, with a breakdown of cost and life of the tool, and a comparison of each tool type available. This also shows a number of parameters for each tool type, from initial cost to density and heat capacity.

Following this, the process calculations are given in totals both per part and per year, and then broken down into further details. This includes the time taken per part for each individual process and the cost of each individual process, from taking material from the freezer through to final debagging post cure and NDT. The final part of this tab then details how the learning curve applies to each part of the process, and provides further sensitivity tables to show the effects of changes in the calculations.
As noted, these facilities and calculations tabs follow for both resin infusion and AFP also, but as these are similar to the hand-lay up we will not cover them further. Instead, we will move on to the tab that follows these, namely Machining, QA/QC and other operations.

This tab follows a similar format to the previous, without the inputs. Specifically, this means the totals for time taken, cost etc are shown both per part and per year for the machining/QC operations etc. This is then followed once again by a breakdown by individual process, ranging from the beginning of core trimming to part transfer around the factory and the final shipping of the part. Finally, learning curve effects and sensitivity tables are again given.

### Data Tables

The final tabs of the model consist of the model’s tables of data. These tabs store all of the data for machinery and materials that are used within the calculations. Here, the cost of each process/material etc is shown, alongside the source of where this data is acquired. In this example, the default data is kept.

One of the aspects of the VCC model is that it allows for more advanced users to edit these databases. To begin with, if prices change or a user has a particular supplier/deal, they can change the price of certain materials or processes. However, as noted on the instruction sheet, further data may be added in here. This will allow users to utilise the current costing model, but expand the database upon which it draws in order to allow a wider range of costing and comparisons between materials/processes etc. to take place.
THE VIRTUAL COMPOSITES COMPANY - INSTRUCTION SHEET

Adam M. Moss
am8151@my bristol.ac.uk

The VCC model uses a bottom up costing methodology and provides the user with a structure within which production steps can be added or modified to allow a detailed cost estimate to be generated. The VCC contains suggested data based on a medium sized aerospace company manufacturing a single part as an element of a supply chain and it must be noted due to the commercially sensitive nature of costing data some of these inputs are approximations. This guide contains some basic information as to how to use the model and some tips on modifying the model. For more detailed information on how the calculations have been formulated and example outputs refer to the journal paper “The Virtual Composites Company, a model for improved decision making and cost estimation.”

### HOMEPAGE

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>Part Details</th>
<th>Financing</th>
<th>Manufacturing Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>Machinery Database</td>
<td>Materials Database</td>
<td></td>
</tr>
<tr>
<td>PROCESS</td>
<td>Hand Lay-up</td>
<td>Resin Infusion</td>
<td>Machining, QA and Other</td>
</tr>
<tr>
<td>FACILITY</td>
<td>Facility Parameters</td>
<td>Set-up Costs</td>
<td>Overhead Costs</td>
</tr>
<tr>
<td>OUTPUTS</td>
<td>Average Costs-per-part</td>
<td>Sensitivity Analysis</td>
<td>Financial Statements</td>
</tr>
<tr>
<td></td>
<td>Annual Costs-per-part</td>
<td>Financial Analysis</td>
<td>- P&amp;L</td>
</tr>
</tbody>
</table>

**Figure 1:** Flow chart of the VCC model structure showing the individual model tabs

**Navigation**

The model structure is shown in figure 1 and can be navigated using the provided hyperlinks at the top of each tab which takes you to a contents page. This can be added to manually as new tabs as the user wishes. Cells and arrays of cells have been named where appropriate to make formula easier to understand. By pressing F5 and typing the name of the cell in, excel will then take you to the desired cell.

**Important Notes on Excel**

Excel data tables have been used extensively in the model to create sensitivity analyses and compare the effect of different model inputs automatically. To prevent excel constant recalculating these and it is highly recommended automatic updating of data tables is switched off in the excel options otherwise
the model will run very slowly. When inputs are changed data tables must then be recalculated manually (in excel 2007 click formulas tab then click calculate now).

When changing the number of production years some charts will not change their range automatically and this must be done manually in chart options if required. Note this can cause later years to appear hidden if the axes are not set to the correct range.

Where cell text is a faint grey colour this data is used for the operation of the model usually for reference in lookup functions or dropdown option boxes. Modifying this data can cause the model to stop working and is not recommended.

**Using the Model - Inputting Data**

Firstly using the three input tabs, data about the company to be modelled should be input. Recommended values or drop down options are provided in case the exact data is unknown. An automatic checking feature ensures model inputs are valid and calculations are working and will output red warnings in the case of errors in the inputs or calculations. Three production cases (high/medium/low volume) have been included as options to speed up the input and comparison process. These can be modified or overwritten completely if desired in the input tab.

The model will now generate outputs from these three input tabs. Additional graphical outputs can be added by the user and most data required for the average user can be found in these output tabs.

More advanced users may then wish to view and modify the model calculations which are contained in the further tabs discussed briefly below.

**Database – Materials and Machinery**

The model pulls data from materials and machinery databases when required and although the databases are currently small, the model structure allows these to be expanded. When adding in extra data it is important to insert a new line in excel within the desired area so that the range of cells used in vlookup functions includes the cells where the new data has been input.

**Process Calculations**

The main calculations and data that can be modified are contained in the two tabs for each manufacturing method, for example the “Hand Lay-up” and “Hand Lay-Up Facilities” tabs. In the hand lay-up tab there is a list of production steps and time for each step. These are times for the first production part as a learning curve is applied to these times later. From these times a cost is allocated based on the appropriate labour rate. Materials and utilities used are also added in. The facilities tab then calculates the number of machines required to meet the production rate and from this calculates the floor space required for each stage.

**Facility Details**

Details of the company are then collated into the facility tabs from the costs and times from the process calculation tabs. Costs are also categorised here so they can be grouped for output (cost categories are shown in the appendix below). A learning curve is then applied and the costs for each production year are then calculated depending on the number of parts produced for that year.
APPENDIX

Cost Categorisations

A brief outline of how costs are categorised is shown in table 1 for reference.

Table 1: Cost category breakdown for non-process costs

<table>
<thead>
<tr>
<th>Overhead Costs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>General facility</td>
<td>Rent, non-manufacturing utilities (water, electricity, heating), council tax etc.</td>
</tr>
<tr>
<td>Factory process</td>
<td>Machinery maintenance, parts and training. Tool inspection and maintenance</td>
</tr>
<tr>
<td>Manufacturing overheads</td>
<td>Waste disposal (active and other waste), worker safety equipment and clothing, factory safety equipment, testing and training.</td>
</tr>
<tr>
<td>Non-manufacturing Labour</td>
<td>Annual salaries include all expenses such as national insurance, sick pay, company car etc. Examples are Directors, Accountants, Secretaries, Receptionists, Operations, IT, R&amp;D staff, Sales, Costing and HR.</td>
</tr>
<tr>
<td>Part development</td>
<td>R&amp;D equipment, materials and prototyping costs (not including labour).</td>
</tr>
<tr>
<td>Insurance</td>
<td>Public liability, building and contents, machine insurance.</td>
</tr>
<tr>
<td>Other overheads</td>
<td>Annual IT software subscriptions, recruitment, general staff training (production and office staff), advertising and marketing, trade shows etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Set-up Costs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>General facility set-up</td>
<td>Factory design and customisation, electrical connection, health and safety installations, office furnishings, bathrooms, kitchens etc. Capitalised and depreciated</td>
</tr>
<tr>
<td>Manufacturing tools and equipment</td>
<td>Machine purchase and installation, general tools, trolleys, tool stations  Capitalised and depreciated</td>
</tr>
<tr>
<td>Initial part design</td>
<td>Design and stress, design for manufacture, quality, production engineering, machine programming, prototype manufacture/test. One-off Exceptional Cost (OEC) in year 1 of the accounts.</td>
</tr>
<tr>
<td>Tooling</td>
<td>Design, testing and purchase                                               Design and testing classed as an OEC in year 1. Purchase cost is capitalised and depreciated.</td>
</tr>
<tr>
<td>Overheads during set-up</td>
<td>Facility overheads (utilities etc), non-manufacturing labour, initial recruitment, initial staff training Broken down into labour and utilities. Sum is added as an OEC in year 1 of the accounts.</td>
</tr>
</tbody>
</table>

Model Assumptions

To constrain the model complexity, some limits and assumptions are imposed. Deviations from these assumptions may require major modifications to the model. The main ones are listed below:

1. The company manufactures an aircraft trailing edge wing access sandwich panel of dimensions 690mm by 290mm. The part is of aerospace commercial grade quality.
2. The model is based on a company purchasing in materials i.e. prepreg, fabric and resin as well as tooling. The company assumes all design roles of the both the part and the tooling and takes on all tooling costs just as a risk sharing partner would.
3. The sales price per part is assumed constant through the production life.
4. Process step times are for the first production part made and learning curve effects applied.
5. Production start date is input into the model which is assumed to be the start of the financial year, termed year one. The inflation rate input is applied to figures assuming model costs are as at the production start date. The maximum number of production years is 50.
6. All set-up costs are assumed to occur in the year prior to production start, termed year zero. Set-up costs are spread over the total number of parts produced when calculating cost-per-part.
7. Production capacity and machinery required is based on the factory operating at full steady state capacity and all machinery required is purchased in year one. Production rates are limited to between 5,000 and 72,000 parts per year. Outside of this range the production flow and machinery assumed for this factory would not be necessarily be appropriate.

8. Production labour is assumed to be employed on a per hour basis and therefore scales with production volume. Non-production labour is assumed to be employed on an annual basis.

9. General factory overhead costs are calculated on an annual basis depending on the steady state production volume and does not scale with production volumes during ramp-up/down.

10. The quality of the end part is not considered, but will depend on the production processes.
HEFCE Composites Curriculum Development Project
Assignment : Composite Testing

The Task

Note: The assignment is designed as a Project Based Learning exercise, to assess the learning of the following units:

Product Design B
• Micromechanics
• Laminate design and analysis
• Stress analysis – classical laminate theory

Manufacturing Processes A
• Prepreg processes: vacuum bag

Performance A
• Mechanical properties and testing - anisotropic elasticity
• Mechanical properties and testing - static strength, failure modes and failure criteria.

The content not directly related to testing is types in grey font colour, and can be left out is the assignment is to be designed for Testing only.

Depending on the resources available, the experimental procedure can be carried out by a technician or lecturer as a demonstration and analysis and interpretation of results can be assigned as an individual assignment.

You will work in groups to manufacture and then analyse and test at least two different configurations of composite samples: One UniDirectional (UD) and One Cross-Ply (XP) Sample. You need to find out how to use the materials and chemicals correctly and safely, consult standard test methods to determine how to carry out tests and research how to analyse and predict the properties of the materials that you have manufactured.

You are allocated 16 hours of laboratory time to progress the project and you are expected to attend these sessions. The lecturer and technician will guide you through the phases of the project and ensure that you work safely. They are also there to provide you with feedback on your progression and understanding of the project task.

Your safety and the safety of others must override any other considerations. Do not use any materials or chemicals without studying the material safety data sheets (all available on Blackboard). Always wear the recommended personal protective equipment (PPE) and follow recommended safety procedures. If in any doubt about safe working – stop - and ask the technical supporting staff or consult the safety data sheets.
The project is designed to provide you with practical ‘hands-on’ experience of working autonomously with composite materials, calculating the theoretical properties of the materials and then testing them to analyse and evaluate the accuracy of your predictions. You will learn a great deal about composite materials: how they are manufactured, how they fail when tested and the methods available to composite designers for predicting the material properties and failure mechanisms.

You should keep good quality accurate notes of all of the work that you do in a log book so that you can analyse your results and produce your group report.

Project Stages

Stage 1: Manufacture of Composite Panels

1 Unidirectional and 1 CrossPly sample will be produced from a Carbon Fibre Reinforced Epoxy prepreg material with well documented properties of the composite itself as well as its constituents.
- Carbon Fibre Reinforced Epoxy panel (280mm x 280 mm)
- 8 layers thick, balanced and symmetrical
- Cure in autoclave

The following documents will be provided:
- H&S data sheets
- Datasheets including the material properties and Manufacturer’s Recommended Cure Cycle
- Data sheets for consumables

Stage 2: Analysis of Composite Panels

Predict theoretical properties of composite panels using range of methods:
- Micromechanics approaches
- Rule of Mixtures with Efficiency Factor
- Classical Laminate Analysis (software)
- Failure Theories

Stage 4: Preparation of Test Samples

Follow these steps to prepare specimens for tensile testing, compression testing, and shear testing
- Cutting of specimens from panels
- Bonding of tabs
- Bonding of strain gages
- Wiring
Stage 5: Testing of Test Samples

5.1 Use standard tensile testing methods to test the UD and XP specimens to determine:
- The Young’s modulus in tension
- The Tensile Strength
- Poisson’s Ratio
- Failure mechanisms

5.2 Use standard compressive testing methods to test the UD and XP specimens to determine:
- The Young’s modulus in compression
- The Compressive Strength
- Failure mechanisms

5.3 Use standard shear testing methods to test the UD and XP specimens to determine:
- The Shear Modulus
- The Shear Strength
- Failure mechanisms

Assessment

Your will produce two outputs for this project:
- A group report

The Group Report
The group will produce a 30 page report that explains and summarises the Composite Manufacture, Analysis and Testing Units.

Marking Guide for Report:
Introduction 5%
- Should be a clear and concise introduction to the team and the purpose of the task.

Experimental procedure 20%
- To show test results in appropriate engineering form showing how key mechanical parameters & material characteristics were obtained. To include testing and material failure observations.
- To present the variability of results in a clear and structured manner.

Discussion & analysis of results 65%
- To present the theoretical stiffness and strength predictions for the materials to facilitate a clear and concise comparison with each other and with the test results (20%)
- Analysis of the theoretical results and of the potential sources of error with each theoretical approach in relation to the test results and observations. (25%)
• Analysis of the test results in comparison to the theoretical results and suggestions for why they may be different. Present research into how the testing could be carried out differently to obtain more reliable and accurate test data (20%)

Conclusions 10%
• A clear and concise conclusion explaining what you have learnt from the exercise about the prediction and measurement of the mechanical properties of composite materials.
COMPOSITE MATERIALS

Mechanical properties and testing - anisotropic elasticity

Dr. Nuri Ersoy
Senior Lecturer
University of the West of England, Bristol
Nuri3.Ersoy@uwe.ac.uk
Aims and Outcomes

Background: Review of Orthotropic and Transversely Isotropic materials

Engineering properties of orthotropic and transversely isotropic materials

Strength Properties of transversely isotropic materials

Testing for Measuring the Engineering Properties of Composites

Testing standards for Measuring the Mechanical Properties of Composites

Test Machines and Sensors

Preparation of Test Specimens

Mechanical Tests:
  Tensile Tests, Compression Test, Shear Tests, Flexural Tests, Thermal Expansion Coefficient Measurements

Conclusions
Aims of the Unit

• Acquire an understanding of the mechanical properties of unidirectional fibre reinforced composite materials
• Identify the tests methods required for mechanical characterization of these materials
• Comprehend how these materials fail under pure tension, compression and shear loading.
• Have a preliminary consideration of how the properties measured relate to stress and strength analysis of composite laminates
Learning Outcomes

• Provide Learners with an overview of the concepts of isotropy, orthotropy, and transverse isotropy

• Identify the engineering constants required to define isotropic, orthotropic, and transversely isotropic materials

• Provide the learners with an understanding of testing machines, measuring devices, and specimen preparation

• Give learners an understanding of the standardized test methods to measure the engineering properties of composites
Background

Review of Orthotropic and Transversely Isotropic materials
Orthotropic Materials

- In a unidirectional composite, 1-axis is aligned with the fibre direction, 2-axis with the transverse direction, and 3-axis with the through-the-thickness direction.
- 1-2-3 axis form a right handed Cartesian coordinate system.
- The fibres are distributed uniformly in 2- and 3-directions, however, the density of fibres in these two directions are different.
- The material than has three planes of symmetry. 12-, 13- and 23-planes are planes of symmetry.
- Material symmetry implies that the material and its mirror image about the plane of symmetry are identical.
- Those type of materials are called «Orthotropic Materials»
Transversely Isotropic Materials

• In a unidirectional composite, 1-axis is aligned with the fibre direction, 2-axis with the transverse direction, and 3-axis with the through-the-thickness direction.
• 1-2-3 axis form a right handed Cartesian coordinate system.
• The fibres are distributed uniformly in 2- and 3-directions, the density of fibres in 2- and 3-directions are identical.
• The material is then isotropic in 23-plane.
• Material symmetry implies that the material and its mirror image about the plane of symmetry are identical.
• These materials are called «Transversely Isotropic» material, which means it has identical mechanical properties in 2- and 3- directions.
• The material is yet not an Isotropic material, since it has different properties in 1-direction (fibre direction).
Engineering properties of orthotropic and transversely isotropic materials
Compliance Matrix \([S]\) of an Orthotropic Material

- Compliance matrix relates six components of stress to six components of strain. Designated by \(S, \text{ not } C(\text{ompliance})\!\)! 

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{23} \\
\gamma_{31} \\
\gamma_{12}
\end{bmatrix} = 
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & 0 & 0 & S_{16} \\
S_{12} & S_{22} & S_{23} & 0 & 0 & S_{26} \\
S_{13} & S_{23} & S_{33} & 0 & 0 & S_{36} \\
0 & 0 & 0 & S_{44} & S_{45} & 0 \\
0 & 0 & 0 & S_{45} & S_{55} & 0 \\
S_{16} & S_{26} & S_{36} & 0 & 0 & S_{66}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{23} \\
\tau_{31} \\
\tau_{12}
\end{bmatrix}
\]
Stiffness Matrix of [C] an Orthotropic Material

- Stiffness matrix relates six components of strain to six components of stress. Designated by \( C \), not \( S \)(iffness)!

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{23} \\
\tau_{31} \\
\tau_{12}
\end{bmatrix} = \begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\
C_{12} & C_{22} & C_{23} & 0 & 0 & C_{26} \\
C_{13} & C_{23} & C_{33} & 0 & 0 & C_{36} \\
0 & 0 & 0 & C_{44} & C_{45} & 0 \\
0 & 0 & 0 & C_{45} & C_{55} & 0 \\
C_{16} & C_{26} & C_{36} & 0 & 0 & C_{66}
\end{bmatrix} \begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{23} \\
\gamma_{31} \\
\gamma_{12}
\end{bmatrix}
\]
Stiffness and Compliance Matrices

• Stiffness and Compliance Matrices are inverse of each other.

\[
\{\sigma\} = [C] \{\varepsilon\}
\]

\[
[C]^{-1} \{\sigma\} = \{\varepsilon\}
\]

\[
[S]\{\sigma\} = \{\varepsilon\}
\]

\[
[S] = [C]^{-1}
\]
OUTLINE

• Background: Review of Orthotropic and Transversely Isotropic materials

• Engineering properties of orthotropic and transversely isotropic materials

• Strength Properties of transversely isotropic materials

• Testing standards for Mechanical Properties of Composites

• Measurement Devices and Testing Machines

• Test Specimen Preparation, Tab Bonding, Force, Displacement and Strain measurements

• Mechanical Tests:
  Tension Tests, Compression Tests, Flexural Tests, Shear Tests, Sandwich Structures
Orthotropic Compliance Matrix in terms of Engineering Constants

- Symmetrical with respect to the diagonal
- There are 9 independent engineering properties to be measured experimentally:
  - Elastic Moduli: $E_1, E_2, E_3$
  - Poisson's Ratios: $\nu_{12}, \nu_{13}, \nu_{23}$
  - Shear Moduli: $G_{12}, G_{13}, G_{23}$

Others are dependent properties:

\[
\nu_{21} = \frac{E_2}{E_1} \nu_{12}
\]

\[
\nu_{32} = \frac{E_3}{E_2} \nu_{23}
\]

\[
[S_{ij}] = \begin{bmatrix}
\frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{54}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}}
\end{bmatrix}
\]
Transversely Isotropically Compliance Matrix in terms of Engineering Constants

- Symmetrical with respect to the diagonal
- There are 5 independent engineering properties to be measured experimentally:
  - Elastic Moduli: $E_1, E_2$
  - Poisson's Ratios: $\nu_{12}, \nu_{23}$
  - Shear Modulus: $G_{12}$

Others are dependent properties:

$$G_{23} = E_2(1 - \nu_{23})$$

Note that the material is isotropic in the 12-plane, so the relationship between $E$, $\nu$ and $G$ holds here:

$$E = G(1 - \nu)$$
Plane stress state

• Most composite structures are thin walled
• They are loaded only in the plane of the structure
• This corresponds to «plane stress» state
• We expect to load a lamina only in plane stress because carrying in-plane stresses is its fundamental capability.
• For a unidirectional reinforced lamina, a plane stress state is defined by setting
  • $\sigma_3 = 0$; $\tau_{23} = 0$; $\tau_{31} = 0$
Plane stress State

The compliance matrix is then reduced to:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & 0 \\
S_{12} & S_{22} & 0 \\
0 & 0 & S_{66}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_1 \\
\tau_{12}
\end{bmatrix}
\]

• Or in terms of engineering properties:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix} =
\begin{bmatrix}
1/E_1 & -\nu_{12}/E_1 & 0 \\
-\nu_{12}/E_1 & 1/E_2 & 0 \\
0 & 0 & 1/G_{12}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\tau_{12}
\end{bmatrix}
\]

• Supplemented by:

\[
\varepsilon_3 = S_{13}\sigma_1 + S_{23}\sigma_2; \quad \gamma_{23} = 0; \quad \gamma_{31} = 0
\]

There are 4 independent engineering properties to be measured experimentally:

- Elastic Moduli: \(E_1, E_2\)
- Poisson's Ratio: \(\nu_{12}\)
- Shear Modulus: \(G_{12}\)
Strength Properties of transversely isotropic materials
Intralaminar Failure modes in composites

(a) Shear matrix failure due to compression in transverse direction. (b) Tensile matrix failure perpendicular to tensile load in transverse direction. (c) Shear fiber failure due to compression in fiber direction. (d) Tensile fiber failure perpendicular to tensile load in fiber direction.

Shear failure. (a) in the 2-3 plane, (b) in 1-2 plane
Strength in the fibre direction

\[ Y_c: \text{Compressive strength in transverse direction} \]
\[ Y_t: \text{Tensile strength in transverse direction} \]
\[ X_c: \text{Compressive strength in fiber direction} \]
\[ X_t: \text{Tensile strength in fiber direction} \]
\[ S_{12}: \text{Shear strength in 12-plane} \]

There are 5 strength properties to be measured experimentally:

- Tensile Strength: \( X_t, Y_t \)
- Compressive Strength: \( X_c, Y_c \)
- Shear Strength: \( S_{12} \)
Testing for Measuring the Engineering Properties of Composites
Testing for measuring the engineering properties

- In order to find the properties in various directions five different tests should be carried out.

\[ E_1, \nu_{12}, X_t \]
\[ E_2, \nu_{23}, Y_t \]
\[ G_{12}, S_{12} \]
Testing for measuring the engineering properties

- In order to find the properties in various directions, five different tests should be carried out.
Testing standards for Measuring the Mechanical Properties of Composites
Standards

• ASTM International, formerly known as American Society for Testing and Materials, is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.

• BSI Group, also known as the British Standards Institution (BSI), is the national standards body of the United Kingdom. BSI produces technical standards on a wide range of products and services, and also supplies certification and standards-related services to businesses.

• ISO, The International Organization for Standardization is an international standard-setting body composed of representatives from various national standards organizations

• The European Committee for Standardization is EU’s public standards organization provides an efficient infrastructure to interested parties for the development, maintenance and distribution of coherent sets of standards and specifications. It work together to develop European Standards (ENs) in various sectors to build a European internal market for goods and services and to position Europe in the global economy.

• BS EN ISO standards are mostly aligned to a single standard, so that they are called with three organizations’ names, e.g., BS EN ISO 527-5 for tensile testing of composites.
Test Machines and Sensors
Universal Testing Machine-Servohydraulic

- Upper Crosshead
- Load Cell
- Columns
- Specimen
- Grips
- Actuator
- Fixed Crosshead
- Servo Valve

CONTROLLER

- Load
- Strain
- Disp.
- Control Signal

PUMP

Extensometer
Universal Testing Machine-Screw Driven

- Movable Crosshead
- Load Cell
- Specimen
- Fixed Crosshead
- Grips
- Timing belt
- Electric Motor
- Bearings
- Screw Columns
- Extensometer
- Load
- Strain
- Disp.
- Control Signal
- CONTROLLER
Strain Gages
What is Strain?

• Strain is the amount of deformation of a body due to an applied force. More specifically, strain (ε) is defined as the fractional change in length.

\[ \varepsilon = \frac{\Delta L}{L} \]

• Strain can be positive (tensile) or negative (compressive). Although dimensionless, strain is sometimes expressed in units such as in./in. or mm/mm.

• In practice, the magnitude of measured strain is very small. Therefore, strain is often expressed as microstrain (\( \mu \varepsilon \)), which is \( \varepsilon \times 10^{-6} \).
What is a Strain Gauge?

• Strain Gauge is a device used to measure deformation (strain) of an object.
• Strain gauges have been developed for the accurate measurement of strain.
• Fundamentally, all strain gauges are designed to convert mechanical extension into an electronic signal.
The gauge shown here is primarily sensitive to strain in the X direction, as the majority of the wire length is parallel to the X axis.
The name "bonded gauge" is given to strain gauges that are glued to a larger structure under stress (called the test specimen).
Gage Length

• Gage length is an important consideration in strain gage selection

• The gage length is the dimension of the active grid as measured inside the grid end loops.

• The gage length (GGG) ranges from 0.008 in (0.2 mm) to 4 in (100 mm).
Strain Gauge Operation

- This schematic shows how the strain gauge resistance varies with strain (deformation).
- On applying a force a change in resistance takes place.
- Tension causes resistance increase.
- Compression causes resistance decrease.
Grid Pattern

(a) Uniaxial Gage with a single grid for measuring strain in the grid direction.

(b) Biaxial Rosettes Gage with two perpendicular grids used to determine principal strains when their directions are known.

(c) Three-Element Rosettes Gage with three independent grids in three directions for ascertaining the principal strains and their directions.

(d) Shear Patterns Gage having two chevron grids used in half-bridge circuits for direct indication of shear strains (difference in normal strains).
Strain Gauge Installation

• The Strain Gauge is bonded to the specimen under test, only after the following:
  • cleaning the surface using a degreaser
  • cleaning it again with a conditioner solution (mild acid that accelerates the cleaning process)
  • neutralizing by applying a base (neutralizes any chemical reaction introduced by the Conditioner)
  • finally bonding it with a super glue.
• The Strain Gauge has 2 leads which exhibit variation in resistance when strain is applied.
The bonded metallic strain gauge

- The metallic strain gauge consists of a very fine wire or metallic foil arranged in a grid pattern.
- The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction.
- The grid is bonded to a thin backing, called the carrier, which is attached directly to the test specimen.
- The strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in electrical resistance.
- Gauge factor is defined as:

\[
GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}
\]
Measuring Circuits

- In order to measure strain with a bonded resistance strain gauge, it must be connected to an electric circuit that is capable of measuring the minute changes in resistance corresponding to strain.
- Strain gauge is connected in a Wheatstone bridge circuit.
- A strain gauge bridge circuit indicates measured strain by the degree of imbalance.
- It provides an accurate measurement of that imbalance.
Wheatstone Bridge (Quarter Bridge)

- Strain gauges are almost always used in a bridge configuration with a voltage or current excitation source.

- The general Wheatstone bridge, illustrated here, consists of four resistive arms with an excitation voltage, $V_{EX}$, that is applied across the bridge.

- The sensor, however, can occupy one, two, or four arms of the bridge, depending on the application. Here a quarter bridge configuration is shown, where the gage occupies only one arm of the bridge.

- If $R_1$, $R_2$, $R_3$, and Strain gauge resistance $R_g$ are equal, and a voltage, $V_o$, is applied between points A and C, then the output between points B and D will show no potential difference.
Wheatstone Bridge (Quarter Bridge)

• The output voltage of the bridge, \( V_o \), will be equal to:

\[
V_o = \left[ \frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2} \right] \times V_{EX}
\]

• From this equation, it is apparent that when \( R_1/R_2 = R_3/R_g \), the voltage output \( V_o \) will be zero. Under these conditions, the bridge is said to be balanced.

• Any change in resistance in any arm of the bridge will result in a nonzero output voltage.

• In this figure, if \( R_1, R_2, R_3, \) and Strain gauge resistance \( R_g \) are equal, and a voltage, \( V_{IN} \), is applied between points A and C, then the output between points B and D will show no potential difference.
Wheatstone Bridge (Quarter Bridge)

• However, if $R_g$ is changed to some value $\Delta R$ which does not equal $R_1, R_2,$ and $R_3,$ the bridge will become unbalanced and a voltage will exist at the output terminals.

• The relation between the total strain $\varepsilon$, and output voltage of the circuit $V_o$ is given by:

\[
\frac{V_o}{V_{EX}} = -\frac{GF \times \varepsilon}{4} \left( \frac{1}{1 + GF \times \frac{\varepsilon}{2}} \right)
\]
Wheatstone Bridge (Quarter Bridge)

- Alternatively, the sensitivity of the bridge to strain can be doubled by making both gauges active, although in different directions.

\[
\frac{V_O}{V_{EX}} = - \frac{GF \times \varepsilon}{2}
\]
Wheatstone Bridge (Full Bridge)

• The sensitivity of the circuit can be increased by making all four of the arms of the bridge active strain gauges, and mounting two gauges in tension and two gauges in compression.

• The relation between the total strain $\varepsilon$, and output voltage of the circuit $V_o$ is given by:
\[
\frac{V_o}{V_{EX}} = -GF \times \varepsilon
\]
Load Cells

• A load cell is a sensor or a transducer that converts a load or force acting on it into an electronic signal. This electronic signal is a voltage change in the case of strain gage based load cells.

• When the load is applied to the body of a resistive load cell as shown, the elastic member, deflects and creates a strain at four locations due to the stress applied. As a result, two of the strain gauges are in compression, whereas the other two are in tension.

• They are configured in Full Bridge configuration.
Extensometers

An extensometer is a sensor or a transducer that converts a displacement into an electronic signal. This electronic signal is a voltage change in the case of strain gage based load extensometers.
Video Extensometer

• Strain is measured by using a high-resolution digital camera to track two contrasting marks on the specimen. The marks can be in the form of dots or lines, and the use of optional Digital Image Correlation software supports speckle or even natural patterns on the specimen surface.

• Real-time image processing algorithms locate the centres of the two gauge marks (or up to four marks if a transverse strain option is installed). Specimen strain is then calculated from the mark separation at the start of the test (gauge length) and the current mark separation. Tracking the centre of the mark eliminates possible errors caused by stretching of the marks at high elongations.
Load Cells, Extensometers, Testing Machines

- Load Cell
- Test Specimen
- Upper Grip
- Lower Grip
- Video Extensometer
- Dynamic (Clip-on) extensometer
- Anti-rotation bar

Gauge Lengths for video extensometer (vertical dots enable Poisson’s ratio calculations)
Preparation of Test Specimens

Cutting the panel
Bonding of tabs
Bonding strain gages
Preparation of specimens: Cutting the panel

• Care must be taken when cutting composite materials for use as test specimens.

• The material can be damaged in the process, resulting in reduced strength properties.

• One way this damage can be induced is by excessive heat buildup in the cutting zone.

• It may be necessary to alter the cutting tool speed, reduce the feed rate, use a different type of cutter, and use a cooling fluid.

• A water cooled diamond circular saw tile cutter may be a good cost effective solution.
Preparation of specimens: Cutting the panel

• For general-purpose use, carbide milling cutters and drills and aluminum oxide abrasive cutoff blades and grinding wheels are an appropriate starting point.

• Diamond particle impregnated cutting tools are extensively used and are very durable.

• Water-jet and abrasive water-jet cutting of composites is being used more often in composite structural component fabrication.
Preparation of specimens: Tabbing the Specimens

• Some test methods, tensile and compressive tests in particular, require the use of tabs on the test specimen.
• Tabs are used to transfer the applied loading into the test specimen from the loading device.
• Often these loading devices are wedge grips, with roughened gripping surfaces.
• The tabs then also protect the surface of the composite test material from damage by the grips.
• Currently, glass fabric/epoxy tabs are most commonly used.
Preparation of specimens: Tabbing the Specimens

Tabs are normally not bonded to each individual specimen, but rather to the full composite plate from which a group of specimens is to be cut.

Preparation of specimens: Tabbing the Specimens

Using the reference edge of the panel, draw lines on the subpanel marking the ends of the gage section. A standard no. 2 pencil and a 90° triangle or framing square are suggested for drawing these lines on the panel.
Preparation of specimens: Tabbing the Specimens

Lightly sand or grit blast the regions of the panel where the tabs are to be bonded, and the bonding surfaces of the tab strips. Use a medium-fine sandpaper or emery cloth (about 180 grit). This step both cleans and slightly roughens the surfaces, enhancing adhesive bonding.

Use a wire brush to remove loose particles.

Clean the surfaces with a solvent such as acetone to remove any remaining loose particles. Do not touch the cleaned surfaces.
Preparation of specimens: Tabbing the Specimens

When tabbing panels, it is convenient to make a set of two identical spacers to be placed onto the gage section of the panel during tab bonding. These spacers are secured to the gage section of the subpanel to maintain proper tab alignment during adhesive curing. Additionally, the spacers prevent excess adhesive from flowing onto the gage section of the panel. Carefully coat the spacers with a mould release agent and let air-dry. Of particular attention are the edges of the spacers placed adjacent to the tabs. The application of release agent facilitates removing the spacers after the cure cycle.
Preparation of specimens: Tabbing the Specimens

• Attach the spacers that were previously prepared to the gage section of the subpanel.

• Position the two fasteners on either side of the panel over the gage section.

• Connect the spacers together using the four corner fasteners, but do not tighten the fasteners beyond finger tight. Align the two spacers with the masked gage section then tighten the fasteners.

• Tightening slightly beyond finger tight is required to prevent slippage. However, do not excessively tighten the fasteners because it may damage the subpanel.
Preparation of specimens: Tabbing the Specimens

• Cut strips of tabbing material 5 mm longer and wider than the specified tabbing area. The excess length will be used to machine a straight edge that will serve as the tab termination edge adjacent to the gage section. The excess width is simply used to ensure that the tabbing material will extend beyond the width of the subpanel. Four tabbing strips will be required for each subpanel to be tabbed.

• The straight edge required along one edge of each tabbing material can be obtained using a belt sander.

• Grit blast or sand the surface of the tab strips to be bonded to the subpanel.
Preparation of specimens: Tabbing the Specimens

• The tabbing strip is secured to a wedge support
• The wedge support is secured to the magnetic table of the surface grinder such that the tab edge is aligned parallel to the path of the grinding wheel
• The grinding wheel is then passed over the tab edge to produce the desired taper
Preparation of specimens: Tabbing the Specimens

- To control the adhesive thickness, wire spacers may be used. The diameter of the wire placed between the tabbing strip and subpanel will determine the thickness of the adhesive when cured.
- To accommodate the wire spacers while keeping the tab edge flush with the gage section spacer, small notches are cut into the tab edge.
- The notches are placed near the outer edges of the tab strip so that the wire spacers will rest near the outer edges of the subpanel where they will be trimmed away during specimen cutting. A small file or hand saw may be used to cut the small notches in the tabbing strips.
- The wire spacers are placed along the bonding surface of the tabbing strip and bent upward and through the notches.
Preparation of specimens: Tabbing the Specimens

Prepare the adhesive. Mix the components of a two-part adhesive. In the test environment the shear strength of the adhesive must be adequate.

Apply the adhesive to the bonding surfaces of both the specimen panel and the tabbing strips and assemble.

C-clamps or vacuum bagging can be used to apply pressure on the bond line.

Cure the assembly as required for the adhesive being used.

Inspect the cured panel for proper positioning and alignment of the tabs, absence of excess adhesive, and bond lines of uniform thickness.
Bonding of Strain Gages to Composites*

• The surface should be degreased to prevent embedment of contaminants in the surface.

• Surface abrasion (with abrasive paper, grit blasting, or otherwise) is a common procedure in preparing metals for strain gage bonding.

• For some high-performance composites, however, abrasion may not be permitted because of the risk of damage to near-surface fibres.

• Moreover, abrasion is not always adequate with certain types of plastics (e.g., fluoro carbons, polyolefins) for achieving optimum bond strength.

• The bondability of plastic adherents can often be improved by chemically altering the surface.

• A commonly used technique, for instance, is to oxidize the surface by flame burnishing.

• The more adhesion-resistant plastics can also be treated with etchants such as TetraEtch for the fluoro carbons, and a sodium dichromate/sulfuric acid solution for polyethylene and polypropylene.

• Significant improvements in bond strength have been reported for "plasma" treatment of these plastics.

*VISHAY MICRO-MEASUREMENTS, Application Note VMM-1
Strain Gage Measurements on Plastics and Composites
Bonding of Strain Gages to Composites

• The usual practice, following any of these treatments, is to neutralize the surface with a mild ammonia solution, leaving it with a slightly alkaline pH. In any case, the bonding operation should normally be performed within a few minutes after completing the surface conditioning.

• Strain gage manufacturers typically supply adhesives which have been developed and validated for use in gage bonding, and can recommend the most suitable adhesive for any particular circumstances.

• For relatively short-term applications in a benign environment, cyanoacrylate adhesive (where compatible with the plastic) is often a convenient choice because of the simple, quick curing procedure.

• Epoxy adhesives that cure at room temperature or somewhat above are eminently suitable for bonding strain gages to most types of plastics and composites.
Bonding of Strain Gages to Composites

• When necessary for elevated-temperature testing, epoxies which cure or post-cure at higher temperatures can be employed; assuming, of course, that such temperatures are suitable for the plastic or composite.

• An unfilled adhesive is the normal choice for gage bonding, in order to produce a thin, creep-free glueline.

• However, a filled epoxy is sometimes used to level an irregular or textured surface prior to gage installation.

• In a composite which is reinforced with continuous fibres, for example, the fibre pattern may be replicated in the surface texture. For such cases, a layer of partially filled adhesive (or matrix resin) can first be applied, smoothed, and cured to form a level surface.

• After curing, the levelled area is cleaned and abraded in the usual manner, preparatory to bonding the gage with an unfilled adhesive.

• Basically, the procedure for installing the strain gage on a plastic or composite is the same as that for a pre wired gage (and the selected adhesive) on any other material, as recommended by the manufacturer.
Bonding of Strain Gages to Composites

https://youtu.be/MSz_9JKpqmA
Bonding of Strain Gages to Composites

https://youtu.be/RO5f33lYuy4
Tensile Testing

1 (fibre direction)

2 (transverse direction)

\[ \sigma_1, \sigma_2, \sigma_3 \]

\[ E_1, \nu_{12}, X_t \]

\[ E_2, \nu_{23}, Y_t \]
Tensile Testing

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS EN ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 3039/D 3039M</td>
<td>527-5</td>
</tr>
</tbody>
</table>

BRITISH STANDARD

Plastics — Determination of tensile properties

Part 5: Test conditions for unidirectional fibre-reinforced plastic composites

Designation: D 3039/D 3039M – 00 (Reapproved 2006)

Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

1
Tensile Testing, Specimen Geometry

- According to ASTM D 3039/D 3039M

0° Unidirectional Specimen

90° Unidirectional Specimen
Tensile Testing, Specimen Geometry

- According to BS EN ISO 527-5
Tensile Test

Procedure:

- *Displacement/Load controlled* tests are available. Static tests are generally displacement controlled.
- *Test speed* should be determined. Test speed should be chosen such that test duration should be around and higher than 60 seconds.
- *Preload* should be applied to prevent small compressive stresses which can cause inconsistent results.
- Extensometer should be used for accurate strain, modulus and Poisson’s ratio measurements.
  - *Modulus* and Poisson’s ratio calculations are recommended to be done in 0.1%-0.3% strain range.
Tensile Testing, Acceptable Failure Modes

ASTM D 3039/D 3039M recommends

- to record the mode and location of failure of the specimen and choose, if possible, a standard description using the three-part failure mode code.

<table>
<thead>
<tr>
<th>First Character</th>
<th>Second Character</th>
<th>Third Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Type</td>
<td>Failure Area</td>
<td>Failure Location</td>
</tr>
<tr>
<td>Angled</td>
<td>Inside grip/tab</td>
<td>Bottom</td>
</tr>
<tr>
<td>edge Delamination</td>
<td>At Grip/tab</td>
<td>Top</td>
</tr>
<tr>
<td>Grip/tab</td>
<td>1 W from grip/tab</td>
<td>Left</td>
</tr>
<tr>
<td>Lateral</td>
<td>Gage</td>
<td>Right</td>
</tr>
<tr>
<td>Multi-mode</td>
<td>Multiple Areas</td>
<td>Middle</td>
</tr>
<tr>
<td>Long Splitting</td>
<td>Various</td>
<td>Various</td>
</tr>
<tr>
<td>eXplosive</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Ohter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td>Code</td>
<td>Code</td>
</tr>
<tr>
<td>A</td>
<td>I</td>
<td>B</td>
</tr>
<tr>
<td>D</td>
<td>A</td>
<td>T</td>
</tr>
<tr>
<td>G</td>
<td>W</td>
<td>L</td>
</tr>
<tr>
<td>L</td>
<td>G</td>
<td>R</td>
</tr>
<tr>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>S</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>X</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>O</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LGM SGM XGM
Tensile Testing, Unacceptable Failure Modes

ASTM D 3039/D 3039M recommends

• In case of Grip/Tab Failures—re-examine the means of load introduction into the material if a significant fraction of failures in a sample population occur within one specimen width of the tab or grip. Factors considered should include the tab alignment, tab material, tab angle, tab adhesive, grip type, grip pressure, and grip alignment.

<table>
<thead>
<tr>
<th>First Character</th>
<th>Code</th>
<th>Second Character</th>
<th>Code</th>
<th>Third Character</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Type</td>
<td></td>
<td>Failure Area</td>
<td></td>
<td>Failure Location</td>
<td></td>
</tr>
<tr>
<td>Angled</td>
<td>A</td>
<td>Inside grip/tab</td>
<td>I</td>
<td>Bottom</td>
<td>B</td>
</tr>
<tr>
<td>edge Delamination</td>
<td>D</td>
<td>At Grip/tab</td>
<td>A</td>
<td>Top</td>
<td>T</td>
</tr>
<tr>
<td>Grip/tab</td>
<td>G</td>
<td>1 W from grip/tab</td>
<td>W</td>
<td>Left</td>
<td>L</td>
</tr>
<tr>
<td>Lateral</td>
<td>L</td>
<td>Gage</td>
<td>G</td>
<td>Right</td>
<td>R</td>
</tr>
<tr>
<td>Multi-mode</td>
<td>M</td>
<td>Multiple Areas</td>
<td>M</td>
<td>Middle</td>
<td>M</td>
</tr>
<tr>
<td>Long Splitting</td>
<td>S</td>
<td>Various</td>
<td>V</td>
<td>Various</td>
<td>V</td>
</tr>
<tr>
<td>eXplosive</td>
<td>X</td>
<td>Unknown</td>
<td>U</td>
<td>Unknown</td>
<td>U</td>
</tr>
<tr>
<td>Ohter</td>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LIT GAT LAT
Tensile Testing, Typical Stress-Strain Response

ASTM D 3039/D 3039M recommends to record:

**Tensile Stress/Tensile Strength.**

**Tensile Strain/Ultimate Tensile Strain**
Tensile Testing, Typical Stress-Strain Response

ASTM D 3039/D 3039M recommends to record:

- **Tensile Chord Modulus of Elasticity**
  
  \[ E_{\text{chord}} = \frac{\Delta \sigma}{\Delta \varepsilon} \]

  where:

  \( E_{\text{chord}} \) = tensile chord modulus of elasticity, GPa [psi];
  \( \Delta \sigma \) = difference in applied tensile stress between the two strain points of 1000\( \mu \varepsilon \) and 3000\( \mu \varepsilon \), MPa [psi]; and
  \( \Delta \varepsilon \) = difference between the two strain points of (2000\( \mu \varepsilon \)).
Tensile Testing, Poisson’s Ratio

ASTM D 3039/D 3039M recommends to record:

- Poisson’s ratio
  \[ \nu = \frac{\Delta \varepsilon_t}{\Delta \varepsilon_l} \]

where:
  \( \nu \) = Poisson’s ratio;
  \( \Delta \varepsilon_t \) = difference in lateral strain between the two longitudinal strain points; and
  \( \Delta \varepsilon_l \) = difference in longitudinal strain between the two longitudinal strain points of 1000 \( \mu \varepsilon \) and 3000 \( \mu \varepsilon \) (2000 \( \mu \varepsilon \)).
Open-Hole Tensile Test of Composite Materials
Open-Hole Tensile Test of Composite Materials

### Need for this test:
- To investigate the effect of hole on strength (notch sensitivity)

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS EN ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5766</td>
<td></td>
</tr>
</tbody>
</table>

**Test Specimen Preparation:**
- Specimen preparation is same with ASTM D3039 (except opening hole)
- Ratio of specimen width to hole diameter to should be: $w/D=6$.
- Preferred ratio of hole diameter to thickness of the specimen is $1.5 \leq D/t \leq 3$ unless the influence of this effect is investigated.
- End tabs are recommended.
- Drilling composite materials demands more care than metallic materials.
  - Delamination around hole region, uncut fibres within hole should be avoided.
  - Specimen and hole region should be fixed between metal plates where top plate should contain a hole in required diameter.

**Procedure:**
Test procedure is same with ASTM D3039.
Open-Hole Tensile Test of Composite Materials: Failure Modes

- [+45/90/-45/0]s (pull-out)
- [-45/0/+45/90]s (delamination)
- [0/+45/90/-45]s (fibre failure)
- [90/-45/0/+45]s (matrix failure)
Compression Tests

\[ E_1, \nu_{12}, X_c \]

\[ E_2, Y_c \]

(transverse direction)

(fibre direction)
Compression Tests

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS EN ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 3410</td>
<td>14126:1999</td>
</tr>
</tbody>
</table>

Fibre-reinforced plastic composites — Determination of compressive properties in the in-plane direction

Desulation: D3410/D3410M – 03 (Reapproved 2008)

Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading¹
Other Compression Test Methods:

• D695 where compressive force is transmitted into the specimen by end-loading,
• D6641/D6641M where compressive force is transmitted by combined shear and end loading,
• D5467/D5467M where compressive force is transmitted by subjecting a honeycomb core sandwich beam with thin skins to four-point bending.
Compression Testing, Specimen Geometry

- According to ASTM D 3410

  - Minimum specimen thickness is determined with respect to the gage length, Young’s modulus and expected compression strength (Table 3). Typically 1-4.38 mm for 10 mm gage length.
  - Two strain gages should be bonded on opposite faces.
  - This is used to check buckling, which is not an acceptable failure mode.
  - Quantitatively, buckling can be detected by a rapid increase in percent bending:

\[ B_y = \text{Percent Bending} = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \times 100 \]
Plain Compression Test of Composite Materials

**Need for this test:**
- To determine:
  - Elastic moduli ($E_1^C, E_2^C$), Tensile Strengths ($\sigma_1^C, \sigma_2^C$)
  - Poisson’s ratio ($\nu_{12} - \nu_{21} - \nu_{23}$)

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS EN ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 3410</td>
<td>14126:1999</td>
</tr>
</tbody>
</table>

**Test Specimen Preparation:**
- Dimensions of the specimen can be prepared as needed.
- Gauge length of compression test specimens are smaller than tension test specimens to prevent buckling during testing.
- In order to see if the specimen is buckled during testing, strain gauges should be placed on each surfaces of the specimen.
- Grips and end tabs are larger than the ones used for tension tests. An example:
Compression Testing, Specimen Geometry

- According to BS EN ISO 14126:1999

![Diagram of Compression Testing Specimens]

**Table 1 — Specimen dimensions**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Symbol</th>
<th>Type A specimen</th>
<th>Type B1 specimen</th>
<th>Type B2 specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length (minimum)</td>
<td>$l_0$</td>
<td>$110 \pm 1$</td>
<td>$110 \pm 1$</td>
<td>$125 \pm 1$</td>
</tr>
<tr>
<td>Thickness</td>
<td>$h$</td>
<td>$2 \pm 0.2$</td>
<td>$2 \pm 0.2$</td>
<td>$\geq 4$</td>
</tr>
<tr>
<td>Width</td>
<td>$b$</td>
<td>$10 \pm 0.5$</td>
<td>$10 \pm 0.5$</td>
<td>$25 \pm 0.5$</td>
</tr>
<tr>
<td>Distance between end tabs/grips</td>
<td>$L$</td>
<td>10</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Length of end tabs (minimum)</td>
<td>$l_t$</td>
<td>50</td>
<td>50 (if required)</td>
<td>50 (if required)</td>
</tr>
<tr>
<td>Thickness of end tabs</td>
<td>$d_t$</td>
<td>1</td>
<td>$0.5$ to $2$ (if required)</td>
<td>$0.5$ to $2$ (if required)</td>
</tr>
</tbody>
</table>
Test Fixture
ASTM D 3410 (ITTRI)
BS EN ISO 14126:1999 Method 1
Test Fixture
Compression Test

**Procedure:**

- *Displacement/Load controlled* tests are available. Static tests are generally displacement controlled.
- *Test speed* for displacement controlled test is recommended to be 1.5 mm/min.
- There is no need to apply *Preload*.
- For accurate *strain*, *modulus* and *Poisson’s ratio* measurements, strain gages should be used. Video extensometer seems more appropriate for compression tests.
  - Modulus and Poisson’s ratio calculations are recommended to be done in 0.1%-0.3% strain range.

---

Compression Testing, Acceptable Failure Modes

ASTM D 3410 recommends

- To record the mode, area, and location of failure for each specimen by choosing a standard failure identification code based on the three-part code.

<table>
<thead>
<tr>
<th>First Character</th>
<th>Second Character</th>
<th>Third Character</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Failure Type</strong></td>
<td><strong>Failure Area</strong></td>
<td><strong>Failure Location</strong></td>
</tr>
<tr>
<td>Angled</td>
<td>Inside grip/tab</td>
<td>Bottom</td>
</tr>
<tr>
<td>Brooming</td>
<td>At Grip/tab</td>
<td>Top</td>
</tr>
<tr>
<td>end-Crushing</td>
<td>1 W from grip/tab</td>
<td>Left</td>
</tr>
<tr>
<td>Delamination</td>
<td>Gage</td>
<td>Right</td>
</tr>
<tr>
<td>Euler buckling</td>
<td>Multiple Areas</td>
<td>Middle</td>
</tr>
<tr>
<td>tThrough-thickness</td>
<td>Various</td>
<td>Various</td>
</tr>
<tr>
<td>Kink bands</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>long Splitting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse shear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>eXplosive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Compression Testing, Unacceptable Failure Modes

ASTM D 3410 recommends

- All of the failure modes are acceptable with the exception of end-crushing or Euler buckling.

<table>
<thead>
<tr>
<th>First Character</th>
<th>Failure Type</th>
<th>Code</th>
<th>Second Character</th>
<th>Failure Area</th>
<th>Code</th>
<th>Third Character</th>
<th>Failure Location</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angled</td>
<td>A</td>
<td></td>
<td>Inside grip/tab</td>
<td>I</td>
<td></td>
<td>Bottom</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Brooming</td>
<td>B</td>
<td></td>
<td>At Grip/tab</td>
<td>A</td>
<td></td>
<td>Top</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>end-Crushing</td>
<td>C</td>
<td></td>
<td>1 W from grip/tab</td>
<td>W</td>
<td></td>
<td>Left</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Delamination</td>
<td>D</td>
<td></td>
<td>Gage</td>
<td>G</td>
<td></td>
<td>Right</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Euler buckling</td>
<td>E</td>
<td></td>
<td>Multiple Areas</td>
<td>M</td>
<td></td>
<td>Middle</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Through-thickness</td>
<td>H</td>
<td></td>
<td>Various</td>
<td>V</td>
<td></td>
<td>Various</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Kink bands</td>
<td>K</td>
<td></td>
<td>Unknown</td>
<td>U</td>
<td></td>
<td>Unknown</td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td>L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-mode</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Splitting</td>
<td>S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse shear</td>
<td>T</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eXplosive</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Typical Failure Modes in Compression

- An Euler buckling failure mode cannot be determined by visual inspection of the specimen during or after the test, therefore it must be determined through inspection of the stress-strain or force-strain curves when back-to-back strain indicating devices are used.
Compressive Testing, Typical Stress-Strain Response

ASTM D 3410 recommends to record:

- Compressive Stress/Compressive Strength.
- Compressive Strain/Ultimate Compressive Strain

\[ F_{cu} (= X_c) = \frac{P_{max}}{A} \]
\[ \sigma_{ic} = \frac{P_i}{A} \]

where:
\[ F_{cu} (= X_c) \] = compressive strength, MPa [psi],
\[ P_{max} \] = maximum force before failure, N [lbf],
\[ P_i \] = force at \( i \)th data point, N [lbf],
\[ A \] = cross-sectional area at test section, mm\(^2\) [in.\(^2\)], and
\[ \sigma_{ic} \] = compressive stress as the \( i \)th data point, MPa [psi].
Compressive Testing, Typical Stress-Strain Response

ASTM D 3410 recommends to record:

- Compressive Chord Modulus of Elasticity

\[ E_{chord} = \frac{\Delta \sigma}{\Delta \varepsilon} \]

where:

\( E_{chord} \) = Compressive chord modulus of elasticity, GPa [psi];

\( \Delta \sigma \) = difference in applied tensile stress between the two strain points of 1000\( \mu \varepsilon \) and 3000\( \mu \varepsilon \), MPa [psi]; and

\( \Delta \varepsilon \) = difference between the two strain points of (2000\( \mu \varepsilon \)).
Tensile Testing, Typical Stress-Strain Response

ASTM D 3410 recommends to record:

- Poisson’s ratio

\[ \nu^c = \frac{\Delta \varepsilon_t}{\Delta \varepsilon_l} \]

where:

- \( \nu^c \) = Poisson’s ratio in compression;
- \( \Delta \varepsilon_t \) = difference in lateral strain between the two longitudinal strain points; and
- \( \Delta \varepsilon_l \) = difference in longitudinal strain between the two longitudinal strain points of 1000\( \mu \varepsilon \) and 3000\( \mu \varepsilon \) (2000\( \mu \varepsilon \)).
Open-hole Compression Test of Composite Materials

Need for this test:
- To investigate the effect of hole on compressive strength (notch sensitivity)

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS/ISO/EN</th>
<th>DIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6484</td>
<td>12817:2013</td>
<td></td>
</tr>
</tbody>
</table>

Test Specimen Preparation:
- Ratio of specimen width to hole diameter should be: \( w/d = 6 \),
- Preferred hole diameter to specimen thickness is: \( 1.5 \leq D/h \leq 3 \).
- End tabs are not used for this test.
- Drilling is very important as in ASTM D5766. There should not be any pre-failure on specimen before test.

Procedure:
- Test procedure is similar with ASTM 3410, where the fixture is different.
In-plane shear stress/shear strain response by the ± 45° tension test method
Determination of the in-plane shear stress/shear strain response by the ± 45° tension test method

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS/ISO/EN</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3518</td>
<td>14129</td>
</tr>
</tbody>
</table>

**Need for this test:**
- To determine:
  - In-plane Shear Modulus ($G_{12}$),
  - In-plane Shear Strength ($\tau_{12}$)

**Test Specimen Preparation:**
- Recommended specimen width is 25 mm,
- [+45/-45]$_n$s laminates where:
  - $4 \leq n \leq 6$ for UD tapes, prepregs
  - $2 \leq n \leq 4$ for woven fabrics
- End tabs are required for this test as in ASTM D3039.
Determination of the in-plane shear stress/shear strain response by the ± 45° tension test method

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS/ISO/EN</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3518</td>
<td>14129</td>
</tr>
</tbody>
</table>

**Procedure:**

- Perform a tension test accordance with Test Method D 3039/D 3039M,
- Normal strain is measured in both longitudinal (x) and transverse (y) directions and load-normal strain data are recorded continuously.
- If ultimate failure does not occur within 5 % shear strain, the data shall be truncated to the 5 % shear strain mark.
- This 5 % shear strain point shall be considered the maximum shear stress.
**Procedure:**

- Perform a tension test accordance with Test Method D 3039/D 3039M,
- Normal strain is measured in both longitudinal (x) and transverse (y) directions and load-normal strain data are recorded continuously.
- If ultimate failure does not occur within 5% shear strain, the data shall be truncated to the 5% shear strain mark.
- This 5% shear strain point shall be considered the maximum shear stress.
Determination of the in-plane shear stress/shear strain response by the ± 45° tension test method

Shear chord modulus of elasticity:

\[ G_{chord}^{12} = \frac{\Delta \tau_{12}}{\Delta \gamma_{12}} \]

- \( G_{chord}^{12} \) = shear chord modulus of elasticity, GPa [psi];
- \( \Delta \tau_{12} \) = difference in applied shear stress between the two shear strain points, MPa [psi]; and
- \( \Delta \gamma_{12} \) = difference between the two shear strain points (nominally 0.004).

Translate the shear chord modulus of elasticity line along the strain axis from the origin by 0.2% and extend this line until it intersects the stress-strain curve.

Determine the shear stress that corresponds to the intersection point and report this value as the offset shear strength, \( F_{12}^o \).
Shear Properties by V-Notched Rail Shear Method
Shear Properties of Composite Materials by V-Notched Rail Shear Method

<table>
<thead>
<tr>
<th>ASTM</th>
<th>ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 7078</td>
<td></td>
</tr>
</tbody>
</table>

Test Specimen Preparation:
- V-notched specimen loaded in rail shear fixture.
- Provides the best shear response of the standardized methods.
- Provides shear modulus and strength.
- Produces a relatively pure and uniform shear stress state.
Shear Properties of Composite Materials by V-Notched Rail Shear Method

<table>
<thead>
<tr>
<th>ASTM</th>
<th>ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 7078</td>
<td></td>
</tr>
</tbody>
</table>
Shear Properties of Composite Materials by V-Notched Rail Shear Method

<table>
<thead>
<tr>
<th>ASTM</th>
<th>ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 7078</td>
<td></td>
</tr>
</tbody>
</table>

**Test Specimen Preparation:**

- V-notched specimen loaded in rail shear fixture.
- Provides the best shear response of the standardized methods.
- Provides shear modulus and strength.
- Produces a relatively pure and uniform shear stress state.

Diagram with dimensions:
- $d_1 = 31.0$ mm [1.20 in.]
- $d_2 = 12.7$ mm [0.50 in.]
- $h = \text{as required}
- L = 76.0$ mm [3.0 in.]
- $r = 1.3$ mm [0.05 in.]
- $w = 56.0$ mm [2.20 in.]
Test Specimen Preparation:

- the $[0/90]_{ns}$ specimen has been found to provide a more accurate elastic modulus determination, shows less variation in the strength results, and is generally preferred over either the $[0]_n$ or the (not recommended) $[90]_n$ specimens.
- Strain gages in $+45^\circ$ and $-45^\circ$ should be bonded to the specimens on the front and back faces to measure the strains in these directions,
Orientations

- h=as required
- h=56 mm
- h=76 mm
Failure modes
Shear Properties of Composite Materials by V-Notched Rail Shear Method

Shear Strain at any point $i$:
$$\gamma_i = |\epsilon_{+45}| + |\epsilon_{+45}|$$

Maximum Shear Strain:
$$\gamma^u = \min \left\{ \gamma \quad \text{at max shear stress} \right\}$$

- $\gamma_i = $ shear strain at $i$-th data point, $\mu \epsilon$;
- $\epsilon_{+45} = +45$ normal strain at $i$-th data point, $\mu \epsilon$;
- $\epsilon_{-45} = -45$ normal strain at $i$-th data point, $\mu \epsilon$; and
- $\gamma^u = $ maximum shear strain, $\mu \epsilon$.

Shear Stress at any point $i$:
$$\tau_i = \frac{P_i}{2A}$$

Shear stress versus shear strain graph
Shear Properties of Composite Materials by V-Notched Rail Shear Method

Maximum Shear Stress:

\[ F^u = S = P^u / 2A \]

- \( F^u \) = maximum in-plane shear stress, MPa [psi];
- \( P^u \) = maximum load at or below 5 % shear strain, N [lbf];
- \( \tau_i \) = shear stress at \( i \)-th data point, MPa [psi];
- \( P_i \) = load at \( i \)-th data point, N [lbf]; and
- \( A \) = cross-sectional area
Shear Properties of Composite Materials by V-Notched Rail Shear Method

Draw a chord on the linear section of the curve:

Shear chord modulus of elasticity:

\[ G_{\text{chord}} = \frac{\Delta\tau}{\Delta\gamma} \]

- \( G_{\text{chord}} \) = shear chord modulus of elasticity, GPa [psi];
- \( \Delta\tau \) = difference in applied shear stress between the two shear strain points, MPa [psi]; and
- \( \Delta\gamma \) = difference between the two shear strain points (nominally 0.004).

Translate the shear chord modulus of elasticity line along the strain axis from the origin by 0.2% and extend this line until it intersects the stress-strain curve.

Determine the shear stress that corresponds to the intersection point and report this value as the offset shear strength, \( F^O \).
Short Beam Shear (SBS) Test
Short Beam Shear Test

**Need for this test:**
- To determine:
  - Short beam shear strength (ILSS: Interlaminar Shear Strength)

**Test Specimen Preparation:**
Short Beam Strength may be related to interlaminar shear strength, but the stress state is quite mixed, and so results are not recommended as an assessment of shear strength due to stress concentrations and high secondary stresses at loading points. Shear modulus cannot be measured.

<table>
<thead>
<tr>
<th>ASTM</th>
<th>ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2344</td>
<td>14130</td>
</tr>
</tbody>
</table>

**Typical specimen thickness assumed:**
- $t = 2.5 \text{ mm/0.100 inch}$
- Support span = $s$
- Specimen overhang = specimen thickness

**a) Current Test Configuration**
- $s/t = 4$
- Loading cylinder diameter = 6 mm/0.250 inch
- Support cylinder diameters = 3 mm/0.125 inch
Short Beam Shear Test

Need for this test:
- To determine:
  - Short beam shear strength (ILSS: Interlaminar Shear Strength)

Test Specimen Preparation:
- Span Length to thickness should be 4.
- Thickness of the test specimen must be: 2 mm ≥ t.
- Specimen Length: \( L = 6 \times t \)
- Specimen width: \( w = 2 \times t \)
- Flexural (tensile and compressive stresses should be minimized and induced shear stress must be maximized

\[
F^{sbs} = 0.75 \times \frac{P_m}{b \times h}
\]

\( F^{sbs} \) = short-beam strength, MPa (psi);
\( P_m \) = maximum load observed during the test, N (lbf);
\( b \) = measured specimen width, mm (in.), and
\( h \) = measured specimen thickness, mm (in.).
Flexural Tests
**Flexural Tests**

**Need for this test:**
- To determine:
  - Flexural Properties of flat rectangular composite laminates:
    - Flexural Strength
    - Flexural Modulus
    - Flexural Strain-Stress Response

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS ISO EN</th>
</tr>
</thead>
<tbody>
<tr>
<td>D790</td>
<td>14125</td>
</tr>
<tr>
<td>D6272</td>
<td></td>
</tr>
<tr>
<td>D7264</td>
<td></td>
</tr>
</tbody>
</table>

- **ASTM D790**
  - ASTM D7264 Method A
  - BS ISO EN 14125 Method A

- **ASTM D6272**
  - ASTM D7264 Method B
  - BS ISO EN 14125 Method B
Flexural Tests

<table>
<thead>
<tr>
<th>ASTM</th>
<th>BS ISO EN</th>
</tr>
</thead>
<tbody>
<tr>
<td>D790</td>
<td>14125</td>
</tr>
<tr>
<td>D6272</td>
<td>178</td>
</tr>
<tr>
<td>D7264</td>
<td></td>
</tr>
</tbody>
</table>

Test Specimen Preparation:
- Test specimens can be cut from larger plates to desired dimensions.
- Specimen geometry should be flat and rectangular.
- Specimens should be cut from large plates with respect to span length to thickness ratio.

Procedure:
- *Displacement/Load controlled* tests are available. Static tests are generally displacement controlled.
- *Test speed* for displacement controlled test is recommended to be 1.0 mm/min.
- *Deflection* and *load* are measured by LVDT (the motion of crosshead) and load cell respectively.
Flexural Tests

<table>
<thead>
<tr>
<th>Standard</th>
<th>ASTM D 790</th>
<th>ASTM D 6272</th>
<th>ASTM D 7264</th>
<th>ISO 14125</th>
<th>ISO 178¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of Loading 3- and/or 4-Point</td>
<td>3 pt</td>
<td>4 pt</td>
<td>3 &amp; 4</td>
<td>3 &amp; 4</td>
<td>3 pt</td>
</tr>
<tr>
<td>Quarter-Point or Third-Point Loading</td>
<td>n/a</td>
<td>both</td>
<td>quarter</td>
<td>third</td>
<td>n/a</td>
</tr>
<tr>
<td>Specimen Length (mm)</td>
<td>-</td>
<td>128</td>
<td>100⁻²⁰⁴/₄</td>
<td>80±2</td>
<td></td>
</tr>
<tr>
<td>(inch)</td>
<td>-</td>
<td>5.12</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Specimen Thickness (mm)</td>
<td>≥1.6²</td>
<td>4</td>
<td>2±0.2</td>
<td>4±0.2</td>
<td></td>
</tr>
<tr>
<td>(inch)</td>
<td>≥0.625</td>
<td>0.16</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Support Span Length/Specimen Thickness 16±1⁸</td>
<td>32⁹</td>
<td>40</td>
<td>16 ±1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen Width (mm)</td>
<td>see note¹⁰</td>
<td>13</td>
<td>15±0.5</td>
<td>10±0.2²^n</td>
<td></td>
</tr>
<tr>
<td>(inch)</td>
<td>see note¹⁰</td>
<td>0.50</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support Radius (mm)</td>
<td>5.0±0.1¹</td>
<td>3</td>
<td>5±0.2³</td>
<td>5±0.2³</td>
<td></td>
</tr>
<tr>
<td>(inch)</td>
<td>0.197±0.004⁴</td>
<td>0.125</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading Radius (mm)</td>
<td>5.0±0.1¹</td>
<td>3</td>
<td>5±0.2</td>
<td>5±0.1</td>
<td></td>
</tr>
<tr>
<td>(inch)</td>
<td>0.197±0.004⁴</td>
<td>0.125</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ For plastics, and composites with fiber lengths ≤7.5 mm.
² EN 603:1977 is identical.
³ ≥0.2 mm for specimen thickness ≤3 mm.
⁴ For a nonstandard specimen thickness, the width can vary as stated in the standard.
⁵ Minimum of 3.2 mm (0.125 inch) for both loading and support radii; for specimens 3.2 mm or thicker, the support radii may be up to 1.6 times the thickness; the maximum radius of the loading nose shall be no more than 4 times the specimen thickness.
⁶ Shal not exceed one-fourth of support span for specimens thinner than 3.2 mm; specimens 3.2 mm (0.125 inch) or thinner shall be 12.7 mm (0.50 inch) wide.
⁷ For specimens ≤1.6 mm (0.0625 inch) thick, specimen shall be 50.8 mm (2 inch) long by 12.7 mm (0.50 inch) wide, tested on a 25.4-mm (1-inch) support span.
⁸ Can be increased, if it is necessary to minimize shear deformation effects, to 32, 40 or 60.
⁹ Optional ratios are 16, 20, 40 and 60.
¹⁰ For high-modulus unidirectional composites. For lower-modulus composites, ratios of 16, 20 or 25 are specified.

• An example of 4 point bending test for AS4/8552 (CFRP) with respect to ASTM D6272:
  • Span Length: L=96 mm
  • Specimen thickness: t=3mm (L/t=32)
  • Specimen width: w=24 mm (There is no obligation about width of composite specimen)
Flexural Tests

- An example of 4 point bending test for AS4/8552 (CFRP) with respect to ASTM D790:
  - Span Length: L=320 mm
  - Specimen thickness: t=20mm (L/t=16)
  - Specimen width: w=24 mm
ASTM D7264 indicates that to obtain valid flexural strength, it is necessary that the specimen failure occurs on either one of its outer surfaces, without a preceding interlaminar shear failure or a crushing failure under a support or loading nose.
Flexural Tests

BS ISO EN 14125 indicates acceptable failure modes by a Figure.

![Diagram of flexural tests showing various failure modes such as tensile fracture of fibre, tensile fracture at outermost layer, compressive fracture, tensile fracture (including interlaminar shear), and interlaminar shear fracture.](image)

**Figure 6 — Examples of possible failure modes**
(Tensile-initiated and compression-initiated, remote from the loading points, are acceptable failure modes. Failures initiated by interlaminar shear are not acceptable.)
Flexural Tests

Maximum Flexural Stress

The flexural strength is equal to the maximum stress at the outer surface corresponding to the peak applied force prior to failure.

\[ \sigma = \frac{3PL}{2bh^2} \]

\[ \sigma = \frac{3PL}{4bh^2} \]

\(\sigma\) = stress at the outer surface in the load span region, Mpa [psi],
\(P\) = applied force, N [lbf],
\(L\) = support span, mm [in.],
\(b\) = width of beam, mm [in.], and
\(h\) = thickness of beam, mm [in.].
Flexural Tests

Flexural Modulus

The flexural strength is equal to the maximum stress at the outer surface corresponding to the peak applied force prior to failure.

\[
E_f^{\text{secant}} = \frac{L^3m}{4bh^3}
\]

\[
E_f^{\text{secant}} = \text{flexural secant modulus of elasticity, MPa [psi],}
\]

\[
L = \text{support span, mm [in.],}
\]

\[
b = \text{width of beam, mm [in.],}
\]

\[
h = \text{thickness of beam, mm [in.],}
\]

\[
m = \text{slope of the secant of the force-deflection curve.}
\]
Measurement of Thermal Expansion Coefficients

• Most materials change their dimensions as the temperature is changed.

• Thermal expansion is defined as the change of dimensions of a body or material as a result of a temperature change.

• This is very important in the application of composite materials in structures that undergo temperature changes, such as aerospace structures, since change in dimensions may cause extra stresses in addition to the stresses due to applied loads.

• The material property constant describing this phenomenon is the coefficient of thermal expansion (CTE), indicated by the symbol $\alpha$, and is defined as:

$$\alpha = \frac{\Delta \varepsilon}{\Delta T}$$
Coefficients of Thermal Expansion (CTEs)

• Most composites have different dimensional changes, hence different CTEs in the three material directions:

\[ \alpha_1 = \frac{\Delta \varepsilon_1}{\Delta T} \]
\[ \alpha_2 = \frac{\Delta \varepsilon_2}{\Delta T} \]
\[ \alpha_3 = \frac{\Delta \varepsilon_3}{\Delta T} \]

In most UD composites, the transverse and thickness direction CTEs are much higher than the fibre direction CTE, due to higher CTE of the resin as compared to the fibres.

\[ \alpha_1 \ll \alpha_2 \]
\[ \alpha_1 \ll \alpha_3 \]

For transversely isotropic materials

\[ \alpha_2 = \alpha_3 \]
Coefficients of Thermal Expansion (CTEs)

Following standards propose using a vitreous silica dilatometer or thermomechanical analysis (TMA) apparatus for materials with CTE values as small as $5 \times 10^{-6}/\degree C$.

- ASTM Standard E 228-95, Test Method for Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer
- ASTM Standard D 696-98, Test Method for Coefficient of Linear Thermal Expansion of Plastics between –300C and 30C
- ASTM Standard E 831-00, Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
Thermal Expansion Coefficients of Composites

Strain Gages can be used to measure CTE values in composites.

• The test specimen used for determining the CTEs of a unidirectional lamina or woven fabric ply using strain gages should be a flat panel.

• a commonly used specimen size is 50 mm × 50 mm

• The thickness of the panel is commonly about 1 mm.

• Biaxial strain gages are bonded to the surface of a specimen in the fibre and transverse directions by using high temperature adhesives to prevent the softening of the adhesive at elevated temperatures and viscoelastic creep or stress relaxation effects
Thermal Expansion Coefficients of Composites

In non-isothermal applications of strain gages, the performance of the gage may change due to the following effects of temperature:

• The gage dimensions change with temperature.

• The resistance of the gage changes with temperature.

• Transverse strain sensitivity of the gage will induce an error in the measurements.

• The gage factor may change with temperature.
Thermal Expansion Coefficients of Composites

Solution:

- Use a pair of compensation gages bonded to a near-zero CTE sample, like titanium silicate or quartz ($\alpha_r = 5 \times 10^{-6}/\degree\text{C}$)
- The output voltage of the bridge is directly proportional to the difference ($\varepsilon_c - \varepsilon_r$)

where:

$\varepsilon_c = $ strain of composite

$\varepsilon_r = $ strain of the quartz sample

- Thus, the CTE of the composite is

$$\alpha_c = \alpha_r + \frac{(\varepsilon_c - \varepsilon_r)}{\Delta T}$$
Strain vs. Temperature Plot

Slope = CTE $\mu \varepsilon / ^\circ C$

Tomasz Garstka Separation of Process Induced Distortions in Curved Composite Laminates, PhD Thesis, University of Bristol, Bristol, UK September 2005
Conclusions
Summary

• Mechanical properties of composites are reviewed.
• Preparation of test specimens, cutting, tab bonding, strain gage installation is explored in detail.
• Testing standards and methods to measure the thermoelastic and strength properties are explored.
Typical Properties of Various Types of Polymer Matrix Unidirectional Composites*

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$ (GPa)</td>
<td>31</td>
<td>43</td>
<td>52</td>
<td>76</td>
<td>134</td>
<td>138</td>
<td>172</td>
<td>240</td>
<td>325</td>
</tr>
<tr>
<td>$E_2$ (GPa)</td>
<td>3.4</td>
<td>9.7</td>
<td>11.7</td>
<td>5.5</td>
<td>10.1</td>
<td>10.3</td>
<td>10.0</td>
<td>18.6</td>
<td>6.2</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>1.4</td>
<td>6.2</td>
<td>7.6</td>
<td>2.1</td>
<td>5.9</td>
<td>6.9</td>
<td>6.2</td>
<td>6.6</td>
<td>5.2</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.32</td>
<td>0.26</td>
<td>0.28</td>
<td>0.34</td>
<td>0.28</td>
<td>0.30</td>
<td>0.29</td>
<td>0.23</td>
<td>0.26</td>
</tr>
<tr>
<td>$X_1^T$ (MPa)</td>
<td>1100</td>
<td>1070</td>
<td>1590</td>
<td>1380</td>
<td>2140</td>
<td>2275</td>
<td>2760</td>
<td>1590</td>
<td>760</td>
</tr>
<tr>
<td>$X_2^T$ (MPa)</td>
<td>8</td>
<td>38</td>
<td>41</td>
<td>30</td>
<td>80</td>
<td>52</td>
<td>50</td>
<td>60</td>
<td>26</td>
</tr>
<tr>
<td>$X_1^C$ (MPa)</td>
<td>83</td>
<td>870</td>
<td>1050</td>
<td>275</td>
<td>1105</td>
<td>1590</td>
<td>1540</td>
<td>2930</td>
<td>705</td>
</tr>
<tr>
<td>$X_2^C$ (MPa)</td>
<td>48</td>
<td>185</td>
<td>234</td>
<td>138</td>
<td>200</td>
<td>207</td>
<td>152</td>
<td>200</td>
<td>70</td>
</tr>
<tr>
<td>$S_6$ (MPa)</td>
<td>24</td>
<td>72</td>
<td>90</td>
<td>43</td>
<td>120</td>
<td>131</td>
<td>124</td>
<td>108</td>
<td>27</td>
</tr>
<tr>
<td>$\alpha_1$ (10^{-6}/°C)</td>
<td>−11.0</td>
<td>6.4</td>
<td>6.2</td>
<td>−2.0</td>
<td>−0.1</td>
<td>−0.1</td>
<td>−0.4</td>
<td>4.5</td>
<td>−0.5</td>
</tr>
<tr>
<td>$\alpha_2$ (10^{-6}/°C)</td>
<td>120</td>
<td>16</td>
<td>16</td>
<td>57</td>
<td>29</td>
<td>18</td>
<td>18</td>
<td>20</td>
<td>18</td>
</tr>
</tbody>
</table>

References

• D2344/D2344M Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates
• D3039/D3039M Test Method for Tensile Properties of Polymer Matrix Composite Materials
• D3410/D3410M Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading
• D3518/D3518M Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate
• D4255/D4255M Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method
• D5379/D5379M Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method
References

• D5467/D5467M Test Method for Compressive Properties of Unidirectional Polymer Matrix Composite Materials Using a Sandwich Beam
• D5766/D5766M Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates
• D6484/D6484M Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates
• D6641/D6641M Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture
• D7264/D7264M Test Method for Flexural Properties of Polymer Matrix Composite Materials
• D790 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
• D6272 Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending
References

• ASTM Standard E 228-95, Test Method for Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer
• ASTM Standard D 696-98, Test Method for Coefficient of Linear Thermal Expansion of Plastics between –300C and 30C
• ASTM Standard E 831-00, Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
• VISHAY MICRO-MEASUREMENTS, Application Note VMM-1: Strain Gage Measurements on Plastics and Composites
# Structure

This presentation consists of 5 sections:

<table>
<thead>
<tr>
<th>Sections</th>
<th>Section number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
</tr>
<tr>
<td>2</td>
<td>Need for Regulation, Codes and Standards</td>
</tr>
<tr>
<td>3</td>
<td>Role of the Regulators</td>
</tr>
<tr>
<td>4</td>
<td>Role of Classification Societies</td>
</tr>
<tr>
<td>5</td>
<td>Role of Standardisation Bodies</td>
</tr>
</tbody>
</table>
Introduction
What is a composite?

A material which is made up of two or more distinct macroscopic, and not microscopic, materials.

Concrete comprises aggregate and cement.

Plywood is used widely in construction.

Composite sandwich structural panel.
**History**

Composites are not new

- Plywood in ancient Mesopotamia at around 3400 B.C.
- Straw reinforced bricks in ancient Egypt and Mesopotamia at around 1500 B.C.

Recently

- High interest in designing materials for specific applications
- Rise to a range of industries producing materials with a wide spectrum of properties
Our focus
Polymer matrix reinforced composite materials

Carbon Fibre #4 – Brett Jordan CC-BY-2.0
Important considerations

- Composites challenge conventional materials in many applications
- Originally over sold as the ultimate solution for structural applications
- Led to inappropriate use of the material and poor design
- Main difficulty is the black aluminium approach used in early designs
**Important considerations**

High strength carbon fibres developed at RAE, Farnborough in 1960’s

- Development of RB211 Hyfil blade
- Catastrophically failed during bird-strike test
- Led to bankruptcy of Rolls-Royce

Reasons for failure

- Black aluminium approach to design
- Poor understanding of criticality of transverse stresses
- Poor control of defects (fibre waviness, local variation of $V_p$, etc.)

More detailed approach is being used now
Why use a composite?

- **Composites Standards & Certification**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Density (kg m(^{-3}))</th>
<th>Young's Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porous ceramics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubbers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood and wood products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals and alloys</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Graphical Representation**

  - Young's modulus (GPa) on the y-axis
  - Density (kg m\(^{-3}\)) on the x-axis
  - Various materials groups such as Composites, Ceramics, Metals and alloys, etc., plotted on the graph.
Why use a composite?

- **Polymers**
- **Ceramics**
- **Metals and alloys**
- **Composites**
- **Glasses**
- **Porous ceramics**
- **Polymers**
- **Wood and wood products**
- **Foams**
- **Rubbers**
Why use a composite?

![Diagram showing the Young's modulus (GPa) vs. cost (£/kg) for various materials including metals and alloys, ceramics, glasses, composites, porous ceramics, wood and wood products, polymers, rubbers, and foams.](image)
What is a Polymer Matrix Composite?

- Polymer composites are plastics within which there are embedded fibres or particles.
- The plastic is known as the **matrix**, and the fibres or particles, dispersed within it, are known as the **reinforcement**.
Polymer composites

- Such a material is said to be anisotropic i.e. different properties in different directions
- At a microscopic level, the properties of these composites are determined by the orientation and distribution of the fibres, as well as by the properties of the fibre and matrix materials
Why are reinforcements needed?

Carry most of the load (provide stiffness and strength)

- Transfers load between reinforcement fibres
- Supports reinforcement against compressive buckling
- Provides toughening when individual reinforcement might break
- Protects reinforcement from wear and environment

Cannot function alone

Hence, the matrix...
Most Common Types of Fibres for Structural Applications

- Aramid fibres
- Glass fibres
  - E-glass
  - S-glass
- Carbon fibres
  - High strength (HS) carbon
  - High modulus (HM) carbon
Fibre architectures

- Knitted
- Woven
- Unidirectional
- Non-crimp
- Braided
- Random
- 3D woven
Matrix materials

- Metallic
- Ceramic
- Polymeric: Most widely used to manufacture composites because they are easy to infiltrate in the fibre perform and present limited cost
  - Thermosets (Resins)
  - Thermoplastics

![Thermoplastic](Image)
![Elastomer](Image)
![Thermoset](Image)
Applications

**Civil Aerospace**
Airbus A320 – Andy Mitchell CC BY-SA 2.0

**Automotive**
Lamborghini Aventador chassis – J.Smith831 CC BY-SA 2.0

**Renewables**
Wind turbine – Ian Munroe CC BY-SA 2.0

**Oil and gas**
HOBAS pipe – HOBAS CC BY-SA 3.0

**Rail**
High speed train – Hikosaemon CC BY-SA 2.0
What sets composites apart?

- Lightweight
- Strong
- Durable
Need for Regulation, Codes and Standards
Definitions

Regulations

• Obligation to meet certain performance and safety requirements
• Legal document
  ➢ e.g. Construction Products Regulation (No 305/2011) for construction works and products that bear the CE Marking
**Definitions**

**Codes**

- Document giving specific instructions for technical aspects
- Addressing a Regulation
  - e.g. EN Eurocodes are a series of 10 European Standards, EN 1990 - EN 1999, providing a common approach for the design of buildings and other civil engineering works and construction products.
  - e.g. EN 40-3-1:2013 Lighting columns. Design and verification. Specification for characteristic loads
Definitions

Standards

• Voluntary documentation that has been accepted and validated for a test method or specification
• Addressing a business need
Why do we need standards?

- Safety and reliability
- Interoperability
- Business
Why do we need standards?

Safety and reliability

• Creation of products and services that are safe, reliable and of good quality safeguarding consumers and end-users
Why do we need standards?

Interoperability

• The ability of devices to work together relies on products and services complying with standards
Why do we need standards?

Business benefits

• Helping businesses increase productivity while minimising errors and waste
• Enabling products from different markets to be directly compared they facilitate companies entering new markets and assist on development of global trade
Performance-based or material specific standards?

Case Study

• EN 124:1994 - Gully tops and manhole tops for vehicular and pedestrian areas

• Allowed manhole covers to be marketed using a range of materials based on performance levels of the end product
Revision

The revised EN 124:2015 includes higher test and accreditation requirements for composites compared to metallic or concrete covers!!!

<table>
<thead>
<tr>
<th>Test</th>
<th>Cast Iron</th>
<th>Steel/Al</th>
<th>Concrete</th>
<th>Composite</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Creep</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Vehicle Fuels</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Impact</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Action

Following representation by UK manufacturers and NPL, led by Composites UK, to EU authorities

- EN 124: 2015 has not been cited in the official journal, cannot be harmonised and therefore cannot be used for regulatory purposes
- The EU authorities instructed that the standard be revised as a performance based document
Lessons Learnt

This case highlights:

• Reverting from performance-based standards to material specific standards can disrupt the market and distort competition

• The need for Standards Developing Organisation committees to have adequate and appropriate representation across material sectors to aid drafting of open performance-based standards
Role of the Regulators
Role of Regulators

• A regulatory agency (also regulatory authority, regulatory body or regulator) is a public authority or government agency responsible for exercising autonomous authority over some area of human activity in a regulatory or supervisory capacity

  ➢ An independent regulatory agency is a regulatory agency that is independent from other branches or arms of the government

• Regulatory authorities are commonly set up to enforce safety and standards, and/or to protect consumers in markets where there is a lack of effective competition or the potential for the undue exercise of market power
Role of Regulators

- **A regulatory body** is like a professional body but it is not a membership organisation and its primary activity is to protect the public
  - Unlike professional bodies, it is established on the basis of legal mandate
How do Regulators function

• In some instances, regulators have powers to require that organisations operating within a particular industry adhere to standards or deliver expected outputs

• This type of regulation is common in the provision of public utilities which are subject to economic regulation

• Regulatory bodies in this area will:
  ➢ require individuals, companies or organisations entering the industry to obtain a license
  ➢ set price controls and require the provision of particular service levels.
How do Regulators function

• In most cases, regulators have powers to:
  ➢ require transparency of information & decision-making on part of the regulated organisation;
  ➢ monitor performance & compliance of the regulated organisation, with the regulator publishing the findings of its investigations;
  ➢ require that administrators give reasons explaining their actions, and have followed principles that promote non-arbitrary & responsive decisions;
  ➢ undertake enforcement action e.g. directing the company to comply through orders, the imposition of financial penalties and/or the revocation of a license to operate
  ➢ review administrative decisions by courts or other bodies such as competition authorities
Regulation in the Aerospace Sector

- Most aviation regulation & policy is harmonised globally to ensure consistent levels of safety & consumer protection

- Global safety regulations are set by the **International Civil Aviation Organisation (ICAO)**

- National regulations for UK aerospace industry are based on rules developed by ICAO

- ICAO imposes obligations on member States with respect to the safe operation and airworthiness of registered Aircraft however, it cannot prescribe legally binding technical standards
Regulation in the Aerospace Sector

- In Europe the **European Aviation Safety Agency (EASA)** is responsible for safety regulations (EASA is an Agency of the EU)

- EASA is a body governed by European public law; it is distinct from the Community Institutions (Council, Parliament, Commission, etc.) and has its own legal personality

- EASA was set up by a Council and Parliament regulation (Regulation (EC) 1592/2002 repealed by Regulation (EC) No 216/2008 and amended by Regulation (EC) 1108/2009) and was given specific regulatory and executive tasks in the field of civil aviation safety and environmental protection
Regulation in the Aerospace Sector

- The Civil Aviation Authority is the UK's specialist aviation regulator
- It is a public corporation, established by Parliament in 1972 as an independent specialist aviation regulator
- The UK Government requires that the CAA’s costs are met entirely from charges to those who they provide a service to or regulate
- It’s remit is to ensure that:
  - the aviation industry meets the highest safety standards
  - consumers have choice
  - the environmental impact of aviation on local communities is effectively managed and CO2 emissions are reduced
  - value for money
  - are protected and treated fairly when they fly
  - airspace is used efficiently
  - the aviation industry manages security risks effectively
Regulation in the Marine Sector

- The shipping industry is regulated by various UN agencies - primarily the International Maritime Organization (IMO), which develops & maintains the framework of global maritime safety regulations.
- Maritime regulations also originate from EU legislation and UK legislation.
- IMO has adopted a comprehensive framework of detailed technical regulations, in the form of international diplomatic conventions which govern the safety of ships & protection of the marine environment.
- National governments, which form the membership of IMO, are required to implement & enforce these international rules, and ensure that the ships which are registered under their national flags comply.
- The level of ratification & enforcement of IMO Conventions is generally very high in comparison with international rules adopted for shore based industries.
Regulation in the Marine Sector

- Responsibility for enforcing IMO regulations concerning ship safety & environmental protection sits with the flag states i.e. countries in which merchant ships are registered.

- Flag states enforce IMO requirements through inspections of ships conducted by network of international surveyors.
  - Much of this work is delegated to bodies called classification societies e.g. Lloyd’s Register, Stiftelsen Det Norske Veritas.
Regulation in the Marine Sector

• Flag state enforcement is supplemented by what is known as Port State Control, whereby officials in any country which a ship may visit can inspect foreign flag ships to ensure that they comply with international requirements.

• Port State Control officers have the power to detain foreign ships in port if they do not conform to international standards. As a consequence, most IMO regulations are enforced on a more or less global basis.
Regulation in the Marine Sector

• The **Maritime & Coastguard Agency (MCA)** is responsible for implementing the UK Government’s maritime safety policy in the UK on behalf of the Department for Transport (DfT) as one of its executive agencies

• The MCA works closely with national and international partners in the shipping industry to promote the safe construction, operation and navigation of ships
Regulation in the Automotive Sector

• In the 1950s, cars were easily differentiated from one another by make and model

• Designs varied wildly year to year, and the creativity of these designs were part of their sales appeal. However, these designs also differed greatly from one another in terms of safety

• In 1952, there was a huge step towards globally harmonized regulations on vehicles with the creation of the WP.29 (now the World Forum for Harmonization of Vehicle Regulations, a working party of the United Nations)
  ➢ Came about after formation of United Nations Economic Commission for Europe (UNECE) was set up in 1947 by ECOSOC
Regulation in the Automotive Sector

- UNECE aims to establish a global market for vehicles while ensuring a high level of environmental protection and safety.

- Common technical requirements, like those under the UNECE, reduce development costs and prevent the duplication of administrative procedures.

- They are also an important tool to avoid technical barriers to the trade of automotive products.
Regulation in the Automotive Sector

- Harmonisation within the EU is based on the Whole Vehicle Type-Approval System (EU WVTA) and enables manufacturers to benefit from the EU Single Market

- Under the WVTA, a manufacturer can obtain certification for a vehicle type in one EU country and then market it EU-wide without the need for further tests. This system significantly contributes to the completion of single market in automotive products

- The European Commission is responsible for EU legislation on motor vehicles, providing rules for safety and environmental protection, as well as the conditions under which vehicles can be put on the EU market
Regulation in the Automotive Sector

- European Commission Directive 2007/46/EC was established to provide a framework for the approval of motor vehicles

- The European Commission is also involved with:
  - harmonisation process - through its active participation in the harmonisation process, the EU ensures coherence between its regulatory activities and those of UNECE;
  - bilateral contacts - the Commission maintains bilateral contacts with authorities in China, Japan, South Korea, and the USA to seek common solutions to regulatory issues
Role of Classification Societies
Classification Societies

Maritime Industry

• Provide classification and statutory services and assistance to the maritime industry and regulatory bodies regarding maritime safety and pollution prevention
Objective

- Verify the structural strength and integrity of essential parts of the ship’s hull and its appendages

- Verify the reliability and function of the propulsion and steering systems, power generation and those other features and auxiliary systems which have been built into the ship in order to maintain essential services on board
History

• Second half of the 18th century, marine insurers, based at Lloyd’s coffee house in London, developed a system for the independent technical assessment of the ships presented to them for insurance cover.

• Result → Lloyd’s Register Book for the years 1764-65-66.

• The condition of the hull was classified A, E, I, O or U, according to the excellence of its construction and its adjudged continuing soundness.

• The concept of classification slowly spread to other countries and insurance markets.
How it is done

• A technical review of the design plans

• Attendance at the construction of the vessel in the shipyard by a Classification Society surveyors

• Attendance by a Classification Society surveyors at the relevant production facilities that provide key components

• Attendance by a Classification Society surveyors at the sea trials
  ➢ If satisfied, approval of assignment of class and a certificate of classification issued;

• Once in service, the owner must submit the vessel to a clearly specified programme of periodical class surveys
Role of Standardisation Bodies
ISO – International Organization for Standardization

ISO is an established network of national standards bodies:

“Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges”

• **Full members**, influence ISO standards development and strategy
• **Correspondent members**, observe the development of ISO standards and strategy
• **Subscriber members**, keep up to date with ISO’s work but cannot participate in it
Standards and trade

- The World Trade Organization’s (WTO) recognizes the vital contribution of international standards to improve productivity and facilitate international trade
ISO standards development

• International standards are developed by ISO technical committees (TC) and subcommittees (SC) by a process of six steps:
  - Stage 1: Proposal stage
  - Stage 2: Preparatory stage
  - Stage 3: Committee stage
  - Stage 4: Enquiry stage
  - Stage 5: Approval stage
  - Stage 6: Publication stage

• The TCs/SCs may set-up working groups (WG) of experts. SCs can have several WGs which can have several sub groups (SG).
ISO standards development

• ISO deliverables created by committees
ISO deliverables

- An **International Standard** provides rules, guidelines or characteristics for activities or for their results, aimed at achieving the optimum degree of order in a given context.

- A **Technical Specification** addresses work still under technical development, or where it is believed that there will be a future, but not immediate, possibility of agreement on an International Standard.

- A **Technical Report** contains information of a different kind from that of the previous two publications.
ISO deliverables

- A Publicly Available Specification is published to respond to an urgent market need, representing either the consensus of the experts within a working group, or a consensus in an organization external to ISO.

- An International Workshop Agreement is a document developed outside the normal ISO committee system to enable market players to negotiate in an “open workshop” environment.
European Committee for Standardisation (CEN)

- The CEN Technical Board steers the standardisation activities of CEN, while standards are developed by Technical Committees (TCs)

- TCs work on the basis of national participation by CEN Members, where delegates represent the respective national point of view

- A Subcommittee (SC) can be established within a TC in case of a large programme of work

- Standards development in reality is undertaken by Working Groups (WGs) where expert for the CEN members are speaking on a personal capacity
British Standards Institute (BSI)

- UK National Standards Body and the first national standards body

- As such represents UK economic and social interests across all European and international standards organizations
# Structure

This presentation consists of 5 sections:

<table>
<thead>
<tr>
<th>Sections</th>
<th>Section number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Standards Creation and Pre-Standardisation Work</td>
</tr>
<tr>
<td>2</td>
<td>Interlaboratory Validation of Test Methods</td>
</tr>
<tr>
<td>3</td>
<td>Composite Materials Test Standards</td>
</tr>
<tr>
<td>4</td>
<td>Interpretation of Materials Test Standards</td>
</tr>
<tr>
<td>5</td>
<td>Specifications and Design Codes</td>
</tr>
</tbody>
</table>
Standards Creation and Pre-Standardisation Work
Developing the RCS Infrastructure

- It is easiest to introduce a material when a well established Regulations, Codes and Standards infrastructure exists, particularly in code regulated industries (e.g. Eurocodes in construction)
- Standards help the innovation and adoption processes for emerging material as well as trade and usage of mature technologies
Composites RCS Infrastructure

For composites to be used successfully a supporting infrastructure is needed to cover the following needs:

• Design / Materials Selection
• Approval / Certification / Design
• Specification / Purchasing
• Handling / Installation
• Maintenance / Repair
• Recycling / Re-use
Development of international standards

New Work Item Proposal from Member Body

‘Proposal’ stage

‘Project’ stage

Consensus amongst experts

Working Draft

Final Draft

First Committee Draft

Final Committee Draft

Draft International Standard

‘Enquiry’ stage

‘Approval’ stage

Consensus amongst all ISO members

Published as International Standard

Composites Standards & Certification
Role of experts

• Nominated by the members of the Standards Organisation that wish to participate in the project
• Nominated for their expertise and act as individuals not as representatives of their nominating body or their employer
• Work with the Project Leader to develop the draft (submitted with the NWIP or subsequently) into a consensus Final Working Draft within about 12 months
• Need to participate actively, both by taking part in meetings, if possible, and by timely response to drafts for comment
Essential elements of a standard

- **Title** – must reflect the ‘scope’ and usually has three elements
  - An introductory element indicating the general field to which the document belongs (typically title of TC)
  - A main element indicating the principal subject treated within that general field
  - A complementary element indicating the particular aspect of the principal subject or giving details that distinguish the document from other documents, or other parts of the same document
Essential elements of a standard

- **Foreword** – formal element not prepared by the project group and not voted on during ballots
- **Scope** – must reflect the title
  - Defines without ambiguity the subject of the document and the aspects covered, indicating the limits of applicability of the document or particular parts of it. It does not contain requirements
- All other elements are conditional upon the type of document and information to be provided in the standard
Conditional and discretionary elements of a standard

• Introduction
  ➢ discretionary element
  ➢ provides background information
  ➢ puts the document in context
  ➢ Must not contain requirements or recommendations

• Normative references – conditional
• Terms and definitions – conditional
• Symbols – conditional
Conditional and discretionary elements of a standard

• For test methods – conditional
  a) Principle
  b) Reagents and/or materials
  c) Apparatus
  d) Preparation and preservation of test samples and test pieces
  e) Procedure
  f) Expression of results, including method of calculation, precision of the test method, and the measurement uncertainty
  g) Test report
Conditional and discretionary elements of a standard

- Normative annex(es) – conditional
- Informative annex(es) – conditional
  - Must not contain requirements
- Notes, examples, footnotes – conditional
  - All informative hence must not contain requirements
Normative VS informative elements of the text

• Normative elements contain requirements:
  ➢ Must be met in order to comply with the standard
  ➢ Usually indicated by the use of the word ‘shall’ or by being written in the imperative.
  ➢ Must be verifiable

• Informative elements are for information only and must not contain requirements
  ➢ Must not use the word ‘shall’.
Versailles Project on Advanced Materials and Standards (VAMAS)

- Promote world trade by innovation and adoption of advanced materials

- Platform for international collaborations providing the technical basis for harmonisation of measurement methods, leading to best practices and standards
Benefits in engaging with VAMAS

• Pre-standards technical work
• Development of reference materials, test methods and procedures
• Increased proficiency of laboratories
• Precision data statements
ILC to assess the method performance characteristics

- To use a 'real-life' material
- To use a material that is sufficiently homogeneous and stable
  - Sufficiently homogeneous to be able to expose the differences between laboratories
  - Stability depends on the time period foreseen between activities
- To provide enough material for ≥ 2 measurements per lab
  - The contributions of method repeatability (within laboratories) and reproducibility (between laboratories) to the variance of the results.
  - To work with qualified test laboratories
- To agree and impose a clear and unambiguous test protocol similar to a draft standard
ILC to assess the method performance characteristics

To work with qualified test laboratories
  • Only expert laboratories will lead to overestimation of the method reproducibility

To agree and impose a clear and unambiguous test protocol similar to a draft standard
  • Assess the method reproducibility all labs have to strictly implement the method
ILC to assess laboratory proficiency

- To use a real-life, homogeneous and stable (reference) material.
- To provide enough material for $\geq 2$ measurements per lab.
- Contrary to the ILC for method validation, the participation should be open to all interested laboratories, within the resource limits of the organiser.
- Whether the test protocol must be flexible or strict depends on the measurand.
Proficient tests metrics

\[ z = \frac{x - X}{s} \quad \zeta = \frac{x - X}{\sqrt{u_x^2 - u_X^2}} \]

- \( z \) = z-score (should be < 2)
- \( x \) = participant’s result
- \( X \) = assigned value
- \( s \) = appropriate measure of variability

- \( \zeta \) = zeta-score (should be < 2)
- \( x \) = participant’s result
- \( X \) = assigned value
- \( u_x \) = laboratory’s estimate of standard uncertainty of \( x \)
- \( u_X \) = standard uncertainty of the assigned value \( X \)
ILC to characterise a reference material

To use a real-life, homogeneous material, sufficiently stable for the longer term use as a reference material.

- To provide ≥ 2 samples or units per lab.
- To work with qualified test laboratories (labs with demonstrated expertise in the particular field)

Whether the test protocol can be flexible or must be strict depends on the measurand
Further reading

VAMAS Guidelines for the Design and Operation of Interlaboratory Comparisons (ILCs)
Gert Roebben

VAMAS Report No 50
May 2017

VAMAS
www.vamas.org
Interlaboratory Validation of Test Methods
Interlaboratory Comparison (ILC)

• An interlaboratory comparison is the organization, performance and evaluation of measurements or tests on the same or similar items by two or more laboratories in accordance with predetermined conditions

• Also known as round-robin, inter-comparison exercise, accuracy experiment, precision or trueness experiment

• Typically undertaken to:
  ➢ Assess method performance characteristics
  ➢ Assess laboratory proficiency
  ➢ Characterise a reference material
Available guidance for ILCs

- VAMAS Guidelines for the Design and Operation of Interlaboratory Comparisons (ILCs), Report No 50
- ISO 5725 Accuracy (trueness and precision) of measurement methods and results
  - Part 1: General principles and definitions
  - Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method
  - Part 3: Intermediate measures of the precision of a standard measurement method
  - Part 4: Basic methods for the determination of the trueness of a standard measurement method
  - Part 5: Alternative methods for the determination of the precision of a standard measurement method
  - Part 6: Use in practice of accuracy values
Introducing trueness and precision

- “Trueness” – Closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value
- “Precision” – Closeness of agreement between test results

**Improving Trueness**
(Decreasing systematic errors)

**Improving Precision**
(Decreasing random errors)

**Improving Accuracy**
Decreasing Uncertainty
Sources of variability

Many different factors contribute to variability of results

- the operator
- the equipment used
- the calibration (or not!) of the equipment
- the environment – temperature, humidity
- the time elapsed between measurements
- the test method
- the test material
- ...

Composites Standards & Certification
Describing variability

- General term for variability between repeated measurements is precision.

- Two conditions of precision useful for describing variability of a measurement method:
  - repeatability – within site scatter
    - operator, equipment, calibration, environment and time between measurements – **constant**
  - reproducibility – between site scatter
    - operator, equipment, calibration, environment and time between measurements – **vary**

- Terms describe extremes of precision: repeatability (minimum scatter) and reproducibility (maximum scatter).
Describing variability

- Precision is normally expressed in terms of standard deviations
- Intermediate conditions between extreme limits of repeatability and reproducibility are possible – i.e. one or more factors are allowed to vary e.g. operator
### ISO 5725 definitions

<table>
<thead>
<tr>
<th><strong>OBSERVED VALUE</strong></th>
<th><strong>LEVEL OF THE TEST IN A PRECISION EXPERIMENT</strong></th>
<th><strong>ACCEPTED REFERENCE VALUE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>“Value of a characteristic obtained as the result of a single observation”</td>
<td>“General average of test results from all laboratories for one particular material or specimen tested”</td>
<td>“A value that serves as an agreed-upon reference for comparison:”</td>
</tr>
<tr>
<td><strong>TEST RESULT</strong></td>
<td><strong>CELL IN A PRECISION EXPERIMENT</strong></td>
<td><strong>LABORATORY BIAS</strong></td>
</tr>
<tr>
<td>“Value of a characteristic obtained by carrying out a specified test method”</td>
<td>“Test results at a single level obtained by one laboratory”</td>
<td>“Difference between the expectation of the test results from a particular laboratory and an accepted reference value”</td>
</tr>
<tr>
<td><strong>ACCURACY</strong></td>
<td><strong>BIAS</strong></td>
<td><strong>REPRODUCIBILITY</strong></td>
</tr>
<tr>
<td>“Closeness of agreement between test result &amp; the accepted reference value”</td>
<td>“Difference between the expectation of the test results and an accepted reference value”</td>
<td>“Precision under reproducibility conditions”</td>
</tr>
<tr>
<td><strong>TRUENESS</strong></td>
<td><strong>PRECISION</strong></td>
<td></td>
</tr>
<tr>
<td>“Closeness of agreement between average value obtained from a large series of test results and an accepted reference value”</td>
<td>“Closeness of agreement between independent test results obtained under stipulate conditions”</td>
<td></td>
</tr>
<tr>
<td><strong>REPEATABILITY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Precision under repeatability conditions”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Practical implications for an interlaboratory comparison

• Standard measurement method
  ➢ ensures measurements are made the same way
  ➢ written document describing in full detail how the measurement should be made

• Accuracy experiment
  ➢ accuracy measures determined from a series of test results reported by participating laboratories
  ➢ organized by panel of experts established specifically for purpose
  ➢ considered as practical test of adequacy of standard measurement method
Practical implications for an interlaboratory comparison

• Identical test items
  ➢ distributed to participating laboratories from central point of origin
  ➢ samples should be identical when dispatched
  ➢ remain so during transit

• Short intervals of time
  ➢ measurements should be made under constant operating conditions
  ➢ equipment should not be recalibrated between measurements unless required by test
  ➢ tests should be conducted in as short a time as possible
For estimating accuracy of a measurement method, it is useful to assume that every result, \( y \), is the sum of three components:

\[
y = m + B + e
\]

- **general mean** (expectation) e.g. a tensile strength
- **laboratory component of bias under repeatability conditions** (constant)
  \[ var(B) = \sigma^2_L \]
  between-lab variance
- **random error occurring in every measurement under repeatability conditions**
  \[ var(e) = \sigma^2_W \]
  within-lab variance
Between and within lab variance

\[ \sigma^2_L \]
- between lab-variance includes the between-operator and between-equipment variabilities
- can be considered as the sum of both random and systematic components
- expected to have different values in different labs due to differences such as skill of operator
- for a properly standardized method the differences between labs should be small
- justifiable to establish a common value of within-lab variance for all labs using the measurement method
- this value is estimated as the arithmetic mean of within-lab variances – repeatability variance

\[ \sigma^2_W \]

\[
\sigma^2_r = \overline{\text{var}(e)} = \sigma^2_W
\]
Repeatability and reproducibility

- The two quantities required as measures of precision and that are derived from an interlaboratory exercise are:

  Repeatability standard deviation: \( \sigma_r = \sqrt{\text{var}(e)} \)

  Reproducibility standard deviation: \( \sigma_R = \sqrt{\sigma_L^2 + \sigma_r^2} \)
Planning an ILC: Standard measurement method

• The measurement method under investigation shall be standardized
• Must be robust – small variations in procedure should not lead to large variations in results
• The document setting out the measurement method should be unambiguous and complete
• All operations shall be included
• Manner of calculating results should be precisely specified including number of significant figures
Planning an ILC

• Important considerations include:
  ➢ Is a standard available for the measurement method?
  ➢ How many labs should participate?
  ➢ How should labs be recruited?
  ➢ What is the range of levels encountered in practice?
  ➢ How many levels should be covered by the experiment?
  ➢ What are suitable materials to use and how should they be prepared?
  ➢ How many replicates?
  ➢ Time-frame?
  ➢ ...

Composites Standards & Certification
Example: ILC for ISO 20144

- ILC conducted on 6 test methods contained within *ISO 20144 Fibre-reinforced plastic composites - Standard qualification plan (SQP) for composite materials, including reduced qualification plan (RQP) and extended qualification plan (EQP) schemes*

- Tests selected dependent on importance of data, likelihood of error in testing, availability of previous data

- Analysis of results to ISO 5725

- Organisations were encouraged to assess at an early stage the use of the SQP in their operations
ILC for ISO 20144: materials and specimens

- Two materials studied were sourced from industry and typical of materials covered by ISO 20144

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Fibre type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>913 Carbon-T300J-5-35%</td>
<td>T300J (12k)</td>
</tr>
<tr>
<td>2</td>
<td>SE84LV/HSC/300/300/37±3%</td>
<td>T700 (24k)</td>
</tr>
</tbody>
</table>

- Test panels manufactured at one site according to
  - ISO 1268 Part 4 – Preparation of fibre-reinforced, resin bonded, low-pressure, laminated plates or panels for test purposes
- Unidirectional specimens machined from 1 and 2 mm thick panels
- Specimens extracted following
  - ISO 2818 – Preparation of test specimens by machining
## ILC for ISO 20144: testing methods

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Properties measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>BS EN ISO 527-1 and -5</td>
<td>$\sigma_{mt11}$, $E_{t11}$, $v_{12}$</td>
</tr>
<tr>
<td>Compression</td>
<td>BS EN ISO 14126</td>
<td>$\sigma_{mc11}$, $E_{c11}$</td>
</tr>
<tr>
<td>Flexure</td>
<td>BS EN ISO 14125</td>
<td>$\sigma_{mf11}$, $E_{f11}$</td>
</tr>
<tr>
<td>Interlaminar shear (ILSS)</td>
<td>BS EN ISO 14130</td>
<td>$\tau_{m1}$</td>
</tr>
<tr>
<td>DMA</td>
<td>ISO/CD 6721-11</td>
<td>$T_g$, $T_{onset}$, $T_{loss}$, $T_{tandelta}$</td>
</tr>
</tbody>
</table>

Mechanical tests – 6 specimens, DMA – 3 specimens
## ILC for ISO 20144: properties measured

<table>
<thead>
<tr>
<th>Site</th>
<th>Tension</th>
<th>Compression</th>
<th>Flexure</th>
<th>ILSS</th>
<th>DMA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{M11}$</td>
<td>$E_{t11}$</td>
<td>$v_{12}$</td>
<td>$\sigma_{Mc11}$</td>
<td>$E_{c11}$</td>
</tr>
<tr>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>8</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>9</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>
ILC for ISO 20144: analysis

- ISO 5725-2 - Accuracy (trueness and precision) of measurement methods and results -- Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method

1. Initial check of “as-received” data
2. Mandel’s $h$ and $k$ statistics
3. Cochran and Grubb tests for outliers and stragglers
4. Calculation of repeatability and reproducibility
ILC for ISO 20144: check of “as-received” data

- **Tensile strength**
- **Tensile modulus**
- **Compression strength**
ILC for ISO 20144: Mandel’s $h$ and $k$ consistency statistics

Tensile modulus - example of normal pattern
ILC for ISO 20144: Mandel’s $h$ and $k$ consistency statistics

Flexural modulus - example of abnormal pattern
ILC for ISO 20144: Cochran and Grubb tests

- Cochran test – site variances

- Grubb test – site means and outlying observations

- Following ISO 5725:
  - Outliers discarded
  - Stragglers retained

- On basis of statistical tests some further data discarded
ILC for ISO 20144: tension results

- Explosive fracture
- Various deflection measurement methods used
- Good repeatability and reproducibility after removal of erroneous data
ILC for ISO 20144: compression results

- Acceptable failure modes achieved
- Only 1 site checked for bending
- High values of repeatability and reproducibility for strength
- Few sites able to undertake tests
ILC for ISO 20144: Flexure results

- Acceptable failure modes achieved
- Various deflection measurement methods used
- Various test speeds used
- Systematic errors in measurement observed for 2 sites
- Good repeatability and reproducibility after removal of erroneous data
ILC for ISO 20144: ILSS results

- Failure modes unacceptable for all sites and both materials
- Data analysed as purpose of this round-robin was not to generate precision data
- Good repeatability and reproducibility after removal of erroneous data
ILC for ISO 20144: DMA results

- Double peaks reported on $T_{\text{tandelta}}$ plots for material 1 – not fully cured
- Some difficulties specifying onset and loss modulus peaks
- Very low repeatability
- Higher reproducibility due to:
  - Deficiencies in temperature measurement
  - Various methods for temperature calibration
## ILC for ISO 20144: Repeatability and reproducibility

<table>
<thead>
<tr>
<th>Property</th>
<th>Value as a percentage of mean, %</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Repeatability conditions</td>
<td>Reproducibility conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_r$</td>
<td>$r$</td>
<td>$S_R$</td>
</tr>
<tr>
<td>Tension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{Mt11}$</td>
<td>4.27</td>
<td>12.00</td>
<td>5.45</td>
</tr>
<tr>
<td>$E_{t11}$</td>
<td>2.46</td>
<td>6.88</td>
<td>5.09</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>5.95</td>
<td>17.00</td>
<td>7.14</td>
</tr>
<tr>
<td>Compression</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{Mc11}$</td>
<td>8.18</td>
<td>22.90</td>
<td>15.50</td>
</tr>
<tr>
<td>$E_{c11}$</td>
<td>9.10</td>
<td>25.50</td>
<td>9.10</td>
</tr>
<tr>
<td>Flexure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{Mf11}$</td>
<td>5.81</td>
<td>16.30</td>
<td>8.05</td>
</tr>
<tr>
<td>$E_{f11}$</td>
<td>2.57</td>
<td>7.21</td>
<td>3.97</td>
</tr>
<tr>
<td>ILSS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{M1}$</td>
<td>2.98</td>
<td>8.36</td>
<td>5.72</td>
</tr>
<tr>
<td>DMA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_g$</td>
<td>0.96</td>
<td>2.67</td>
<td>3.76</td>
</tr>
<tr>
<td>$T_{onset}$</td>
<td>1.68</td>
<td>4.70</td>
<td>8.50</td>
</tr>
<tr>
<td>$T_{loss}$</td>
<td>0.85</td>
<td>2.37</td>
<td>7.24</td>
</tr>
<tr>
<td>$T_{\tan \delta}$</td>
<td>1.10</td>
<td>3.07</td>
<td>9.05</td>
</tr>
</tbody>
</table>
ILC for ISO 20144: Repeatability and reproducibility

Repeatability CoV - Material 1
Repeatability CoV - Material 2
Reproducibility CoV - Material 1
Reproducibility CoV - Material 2

- Tension
- Compression
- Flexure
- ILSS
- DMA

Percentage of general mean (%)

\[ \sigma_{M1}, \ E_{f1}, \ v_{12}, \ \sigma_{Mc11}, \ E_{c11}, \ \sigma_{Mf11}, \ E_{f11}, \ \tau_{M1}, \ T_g, \ T_{onset}, \ T_{loss}, \ T_{tandelta} \]
Composite Materials Test Standards
Composites Standardisation Committees

- ISO TC61/SC13 (Composites)
  - WG1 – Fibre and Fibre Products (mats, fabrics etc.)
  - WG2 – Laminates and Compounds
  - WG3 – Joined systems (bolted, bonded, electro-chemical interaction)
- CEN TC 249/SC2/WG15, also WG23 often adopted ISO standards as ENs
- ASD EN Aerospace – D4/WG8 Composites
- BSI Committees
  - PRI 42 Composites
  - PRI 21 Plastics
  - ISO and CEN product committees
- ASTM - D30 Composites / D20 Plastics
- VAMAS (pre-normalisation and validation)
  - TWA5 Polymer Composites
## Materials Level Standardisation

<table>
<thead>
<tr>
<th>Standard Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 1887</td>
<td>Textile glass – Determination of combustible-matter content</td>
</tr>
<tr>
<td>ISO 1888</td>
<td>Textile glass – Staple fibres or filaments – Determination of average diameter</td>
</tr>
<tr>
<td>ISO 1889</td>
<td>Reinforcement yarns – Determination of linear density</td>
</tr>
<tr>
<td>ISO 1890</td>
<td>Reinforcement yarns – Determination of twist</td>
</tr>
<tr>
<td>ISO 2078</td>
<td>Textile glass – Yarns – Designation</td>
</tr>
<tr>
<td>ISO 3341</td>
<td>Textile glass – Yarns – Determination of breaking force and breaking elongation</td>
</tr>
<tr>
<td>BS 4045</td>
<td>Specification for Epoxide Resin Pre-Impregnated Glass Fibre Fabrics</td>
</tr>
<tr>
<td>ISO 1268</td>
<td>Fibre-reinforced plastics – Parts 1 – 3 and 5 – 11</td>
</tr>
<tr>
<td>ISO 9163</td>
<td>Textile glass – Rovings – Manufacture of test specimens and determination of tensile strength of impregnated rovings</td>
</tr>
<tr>
<td>ISO 10119</td>
<td>Carbon fibre – Determination of density</td>
</tr>
<tr>
<td>ISO 10548</td>
<td>Carbon fibre – Determination of size content</td>
</tr>
<tr>
<td>ISO 11566</td>
<td>Carbon fibre – Determination of the tensile properties of single-filament specimens</td>
</tr>
<tr>
<td>ISO 11567</td>
<td>Carbon fibre – Determination of filament diameter and cross-sectional area</td>
</tr>
<tr>
<td>ISO 10618</td>
<td>Carbon fibre – Determination of tensile properties of resin-impregnated yarn</td>
</tr>
<tr>
<td>ISO 13002</td>
<td>Carbon fibre – Designation system for filament yarns</td>
</tr>
<tr>
<td>BS ISO 10371</td>
<td>Fibre reinforced plastics. Braided tapes for composite materials reinforcement. Basis for a specification</td>
</tr>
<tr>
<td>BS EN 13003</td>
<td>Para-aramid fibre filament yarns</td>
</tr>
<tr>
<td>BS EN 13417</td>
<td>Specifications for woven fabrics – Parts 1 – 3</td>
</tr>
<tr>
<td>BS EN 13473</td>
<td>Specifications for multi-axial multi-ply fabrics (NCFs) – Parts 1 – 3</td>
</tr>
<tr>
<td>BS EN 14020</td>
<td>Specification for textile glass rovings – Parts 1 – 3</td>
</tr>
<tr>
<td>BS EN 14118</td>
<td>Specifications for textile glass mats – Parts 1 – 3</td>
</tr>
<tr>
<td>ISO/DIS 15039</td>
<td>Textile-glass rovings – Determination of solubility of size</td>
</tr>
<tr>
<td>ISO/DIS 15100</td>
<td>Plastics – Reinforcement fibres – Chopped strands – Determination of bulk density</td>
</tr>
</tbody>
</table>
CEN Work Programme

EN 16245 Fibre-reinforced plastics composites - Specifications for raw materials

- Part 1: General declaration/order document
- Part 2: Additional declaration for resin products
- Part 3: Additional declaration for fibre products
- Part 4: Additional declaration for fabric products
- Part 5: Additional declaration for core products

Certificate of Analysis (CoA)

- The purpose of the CoA is to verify that material properties and quality conform to the declared values
Prepreg/Moulding Compounds

Physical Properties
- ISO 10352  Mass per unit area prepreg and moulding compound
- ISO 11667  Fibre content – digestion method – carbon fibres

Processing properties
- ISO 12114  curing characteristics (SMC)
- ISO 12115  flow, maturation, shelf life (SMC)
- ISO 15040  gel-time (epoxy prepgregs)
- ISO 15034  resin flow (‘’)
- EN 1832    flowability (GMT)

Specification standards
- EN 13677/14598  GMT / SMC, DMC
- EN 2833    Aerospace - Glass-fibre pre-pregs
### ISO 1268 – Test Panel Manufacture

<table>
<thead>
<tr>
<th>Part</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>General conditions</td>
</tr>
<tr>
<td>2</td>
<td>Hand and Spray Lay-up</td>
</tr>
<tr>
<td>3</td>
<td>Wet press moulding</td>
</tr>
<tr>
<td>4</td>
<td>Moulding of pre-impregnates**</td>
</tr>
<tr>
<td>5</td>
<td>Filament winding</td>
</tr>
<tr>
<td>6</td>
<td>Pultrusion</td>
</tr>
<tr>
<td>7</td>
<td>RTM</td>
</tr>
<tr>
<td>8</td>
<td>SMC (press)</td>
</tr>
<tr>
<td>9</td>
<td>GMT/STC</td>
</tr>
<tr>
<td>10</td>
<td>BMC (injection; multi-purpose)</td>
</tr>
<tr>
<td>11</td>
<td>BMC (injection; small plates)</td>
</tr>
</tbody>
</table>

*covers all main material types and process routes*
Constituent Materials Test Methods

Fibres
• Physical testing
  ➢ Density, Thermal Properties
• Mechanical testing
  ➢ Tension

Matrix
• Thermal/Physical testing
  ➢ Density, Electrical Resistivity, Thermal Expansion Coefficient
• Mechanical testing
  ➢ Tension, Compression, Shear
Fibre Characterisation Tests

Physical Testing: For constituent content
- Fibre diameter
- Fibre density (ASTM D3800)

Mechanical Testing
- Tensile properties
- Single fibre (ASTM D3379)
- Tow tests (ASTM D4018)

Optical micrographs of (a) carbon and (b) glass fibres under 200 \( \times \) magnification
Matrix Characterisation Tests

Thermal Analysis
• Glass Transition Temperature, Tg
• Thermal expansion properties

Physical Testing
• Matrix density
  ➢ (ASTM D792 or D1505)

Mechanical Testing
• Tensile properties (ASTM D638)
• Compression, shear, flexure
Prepreg Characterisation Tests

- Main focus is placed in properties of the uncured prepreg
- Fibre and resin content
  - Resin extraction (ASTM C613)
- Resin flow, gel time
- Surface tack, drape
Physical Test Methods for Composites

- Density (ASTM D792)
- Constituent content (i.e. fibre, matrix, void content)
  - Matrix digestion (ASTM D3171)
  - Ignition loss (ASTM D2584)
  - Image analysis
- Flammability
- Thermal cycling micro-cracking
- EMI shielding effectiveness
Physical Test Methods for Composites

- Glass Transition Temperature, Tg
  A temperature induced change in the matrix material from the glassy to the rubbery state during heating or cooling. A change in matrix stiffness of two or three orders of magnitude occurs during the glass transition
  - Dynamic Mechanical Analysis (DMA)
  - Most common method
  - Forced oscillation measurement
  - Thermo-Mechanical Analysis (TMA)
  - Measures changes in thermal expansion
  - Differential Scanning Calorimetry (DSC)
  - Measure changes in heat capacity associated with glass transition
  - Well suited for neat resin specimens, more difficult with composites

Diagram: Dynamic mechanical analysis identification of glass transition
CFRP - DMA Reference Specimen

- First batch of reference specimens manufactured (NPL Autoclave)
- Indium encased in CFRP, tin version now requested to give 2-point calibration
- Interlaboratory test exercise completed, VAMAS 30 + world activity underway
- Procedure proposed as ISO 6721-11
Mechanical Test Methods for Composites

• Unique aspects of testing composite materials
  ➢ Orthotropic i.e. different stiffness and strength in different directions
  ➢ Minimum thickness flat plates for testing
  ➢ Properties not always the same in tension and compression
Elastic Properties

- Isotropic materials (metals, plastics, ceramics etc)
  - $E$, $\nu$, $G$

- Composite lamina (or layer, ply)
  - $E_1$, $E_2$, $E_3$
  - $\nu_{12}$, $\nu_{13}$, $\nu_{23}$
  - $G_{12}$, $G_{13}$, $G_{23}$

- Composite lamina (or layer, ply)
  - $E_2 = E_3$
  - $\nu_2 = \nu_3$
  - $G_{12} = G_{13}$

\[
G = \frac{E}{2(1 + \nu)}
\]

\[
G_{23} = \frac{E_2}{2(1 + \nu_{23})}
\]
Strength Properties

- 3 axial tensile strengths:
  - $X_t, Y_t, Z_t$

- 3 axial compressive strengths:
  - $X_c, Y_c, Z_c$

- 3 shear strengths:
  - $S_{12}, S_{13}, S_{23}$

- Transverse isotropy results in:
  - $Y_{t.c} = Z_{t.c}$
  - $S_{12} = S_{13}$
Laminate Test Method Standards

- BS EN ISO 527 - 4  Tension - "Isotropic materials"
- BS EN ISO 527 - 5  Tension - "Unidirectional materials"
- BS EN ISO 14125  Three and four point flexure
- BS EN ISO 14126  Compression
- BS EN ISO 14129  In-plane shear by $\pm 45^\circ$ tension
- BS EN ISO 14130  Interlaminar (short beam) shear
- ISO 13003  Fatigue – General Principle
- ISO 15024/15114  Mode I / II Fracture Toughness
- ISO 15310  In-plane Shear Modulus (Plate Twist)
- ISO 6721-11  Glass transition by DMA
- ISO 11357-1  Glass transition by DSC
- ISO 75-3  DTUL / HDT
- ISO 10350-2  Database - Single Point
- ISO 11340 (3 parts)  Database - Multipoint
- ISO 14127  CFRP – Volume fractions
Tensile Tests (ASTM D3039)

- Parallel-sided specimens
- 25mm wide, ~ 250mm long
- Adhesively bonded end-tabs
- Strain gages (or extensometer) to measure axial and transverse strain for $E$, $v_{12}$
- Requires valid gauge section failure
Tensile Tests (ASTM D3039)

- Large variety of failure modes, but only some are valid
- Failures in the middle of the gauge length are valid
- Failures close to the end-tab or within the end-tab are invalid
- Delamination failure at any location is invalid
Tabbing of Composite Tension Specimens

- Tab material
  - G10 or G11 glass/epoxy circuit board material
- Tab geometry
  - 1 mm to 2 mm thickness
  - 5° to 30° taper angle
- Adhesive
  - High strength
  - 0.25 mm to 1 mm bondline

Tensile Failure – Transverse to the Fibre Direction
Through Thickness Tensile Failure
Compression Testing of Composites

- Shear loading methods
  - IITRI compression test (ASTM D 3410)
- End loading methods
  - Modified ASTM D695
- Combined loading methods
  - Combined Loading Compression (ASTM D6641)

Shear failure area

a) Dogboned (width-tapered) specimen
b) Thickness-tapered specimen
c) Tabbed, straight-sided specimen
Common Compression Test Methods

- Shear loading, (ASTM D 3410)
  - 140 mm long specimen
  - 12.7 mm gage length
  - Versatile
  - Heavy and expensive
- End loading (ASTM D695)
  - 80 mm long specimen
  - 5 mm gauge length
  - Separate tests for modulus and strength
Common Compression Test Methods

• Combined loading (ASTM D6641)
  ■ 140 mm long specimen
  ■ 12.7 mm gage length
  ■ Adjustable loading ratio via bolt torque
Compressive Failure
Shear Testing – Flat Composite Plates

- In-plane shear testing
  - $G_{12}, S_{12}$
- Out-of-plane shear testing
  - $G_{13}, S_{13}$
  - $G_{23}, S_{23}$
Common In-plane Shear Test Methods

- **Iosipescu Shear (ASTM D5379)**
  - 75 mm × 20 mm specimen
  - Edge loaded
- **V-Notched Rail Shear (ASTM D7078)**
  - 75 mm × 55 mm specimen
  - Face loaded
  - Recommended by CMH-17
Common Out-of-plane Shear Test Methods

• Short Beam Shear (ASTM D2344)
  ➢ Shear strength only
  ➢ Combined stress state
  ➢ Small specimen
  ➢ Simple and affordable test
Through–Thickness Test Methods

- Part 1 – RARDE specimen tension and Compression
- Part 2 – Effective volume Flexure tests
Double Beam Shear (DBS)

- Developed by Gang Zhou, Loughborough University,
- NPL drafted standard and organised RR (7 sites and 4 samples),
- Published as ISO 19927:2018

Comparison between DBS and SBS methods and between 2 mm and 4 mm thick specimens.
Other composite material test methods

- Notched Laminate Testing
- Bearing Testing
- Compression After Impact Testing
- Fracture Mechanics Testing
Notched laminate testing

- Notch means hole
- Laminate test, i.e. does not yield a material property
- Tests in tension or compression with or without a fastener (“open” or “filled”)
  - Open-hole tension
  - Filled-hole tension
  - Open-hole compression
  - Filled-hole compression
- Used to provide design values
  - Mechanically fastened joints
  - Effects of manufacturing anomalies and small damage areas
- Governed by ASTM standards (i.e. ASTM D5766, ASTM D6484)
Open-Hole Compression Testing

- 300 mm long × 38 mm wide specimen
- 6.35 mm diameter centre hole
- Face supported
- Clamped in hydraulic grips or end loaded
- Staggered V-shaped joints in both sides of the fixture
- Guide plates to maintain alignment
Bearing strength testing

Laminate test

- Utilizes specified bolted joint configuration
  - Single shear: One bolt, two bolt
  - Double shear

Used to compare materials and provide design values

- Not meant to be representative of actual joint designs
- Yield and ultimate bearing strength
- Governed by ASTM D5961
Impact resistance and damage tolerance

- Charpy impact tests commonly used to characterise rigid plastics
- Composites are susceptible to low velocity / energy impacts
- Drop weight impact tests
Impact resistance and damage tolerance

- Impact induced delamination
Compression after impact (CAI) strength

- Compressive strength can reduce significantly due to impact induced damage
- Testing is governed by ASTM D7137 as well as industry standards
Fracture mechanics testing

• Determine propagation characteristics of existing cracks/delaminations
• Considers three modes of crack growth
  ➢ Mode I, opening or peeling
  ➢ Mode II, shearing
  ➢ Mode III, tearing

Mode I   Mode II   Mode III
Fracture mechanics testing methods

• Mode I
   Double Cantilever Beam (DCB) specimen (ASTM D5528)
• Mode II
   End-notch Split (ELS) specimen – No standard
Fracture mechanics testing methods

- Mixed Mode I/II
  - Mixed Mode Bending (MMB)
  - Test (ASTM D 6671)
Fracture morphology: Mode I

Fibre bridging
- Nesting of fibres during consolidation promotes bridging

Matrix cleavage
- Textured micro-flow: granular structure with flow direction
- Scarps: sharp steps between two adjacent crack planes
Fracture morphology: Mode II

Cusps

• Appear as inclined platelets on the fracture surface
Mechanical test methods for sandwich composites

- Flatwise Tension (ASTM C297)
- Flatwise Compression (ASTM C365)
- Sandwich Panel Shear (ASTM C273)
- Sandwich Panel Flexure (ASTM C393)
- Climbing Drum Peel (ASTM D1781)
Mechanical test methods for sandwich composites

- Mode I Fracture Mechanics (Single Cantilever Beam)
- Climbing Drum Peel (ASTM D1781)
Full scale testing of composite wind turbine blades

- Full scale testing is not as trivial as coupon testing
- Also very expensive and the most critical loading scenario needs to be examined only
Interpretation of Materials Test Standards
Example: BS EN ISO 14126

Indicates harmonised British, European & International standard

Number : year of revision

BS EN ISO 14126:1999

Fibre-reinforced plastic composites –

Introductory element often based on committee title

Determination of compressive properties in the in-plane direction

Main element – principal subject of the standard
Structure

Foreword
Introduction
1. Scope
2. Normative references
3. Definitions
4. Principle
5. Apparatus
   5.1 Test machine
      5.1.1 General
      5.1.2 Speed of testing
      5.1.3 Indication of load
   5.2 Strain measurement
   5.3 Micrometer
   5.4 Loading fixtures
      5.4.1 General
      5.4.2 Method 1: shear loading
      5.4.3 Method 2: end loading
6. Test specimens
   6.1 Shape and dimensions
      6.1.1 Type A specimen
      6.1.2 Type B specimen
   6.2 Preparation
      6.2.1 General
      6.2.2 End-tab material
      6.2.3 Application of end tabs
      6.2.4 Machining the specimens
   6.3 Checking
7. Number of test specimens
8. Conditioning
9. Procedure
10. Expression of results
11. Precision
12. Test Report
13. Annexes (either normative or informative in nature)
Foreword

- Unnumbered but may be subdivided with subheadings
- Administrative information, using standard wording, including:
  - Committee/subcommittee
  - Supersession
  - Relationship with other publications (e.g. other parts in series, used in conjunction with other standards)
  - Information about document (e.g. if a revision, principal changes from previous edition)
  - Hazard warnings and use of document
  - Contractual and legal considerations (e.g. compliance statement)
- No provisions (requirements or recommendations)
ISO 14126: Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 14126 was prepared by ISO/TC 61, Plastics, Subcommittee SC 13, Composites and reinforcement fibres.

This first edition cancels and replaces ISO 8515:1991, which dealt only with glass-fibre-reinforced plastic composites.

Annex A forms a normative part of this International Standard. Annex B to Annex D are for information only.
Introduction

• Provides specific detail on the technical content which is considered necessary for the application of the standard
• Not compulsory to include
• Usually unnumbered (but if numbered, is clause 0 and may be subdivided)
• Follows the foreword on a separate page
• Does not contain requirements or recommendations
ISO 14126: Introduction

Contains information on:

• Supersession of ISO 8515 (GFRP)
• Source documents consulted e.g. ASTM D 3410, ASTM D 695, prEN2850, CRAG 400, DIN 65380 and JIS K 7076
• Compression jigs referenced in source documents

• Rationale for ISO 14126
  ➢ Focus on quality of compression test - limit on buckling strain at failure
  ➢ Allows any jig design as long as buckling strain limit is not exceeded
  ➢ Two specimen designs standardized
1. Scope

- Numbered as Clause 1
- Provides an unambiguous definition of:
  - Subject of standard, e.g. two methods (shear and end-loading) for determining compressive properties
  - Limits of applicability, e.g. methods are suitable for fibre-reinforced thermoplastic and thermosetting plastic composites, fibres > 7.5 mm long
- Should be concise
2. Normative references

• List of separate standards that are referred to and which without you could not use the standard
• If referencing a specific clause in another standard then it should be dated
• Always appears in an ISO standard as Clause 2 even if no other standards are referenced
ISO 14126: Normative references

- ISO 291:1997 Plastics – Standard atmospheres for conditioning and testing
- ISO 1268:1974 Plastics – Preparation of glass fibre reinforced, resin bonded, low-pressure laminated plates or panels for test purposes (under revision)
- ISO 5893:1993 Rubber and plastics test equipment – Tensile, flexural and compression types (constant rate of traverse) – Description
3. Definitions

• Terms are defined (definitions):
  ➢ if they are not self-explanatory, commonly known or routinely used outside of the standard
  ➢ if the interpretation of a term could be different depending on the context in which it used
• Commonly used terms are only defined if they are used in the standard with a specific meaning
• There is always a Definitions clause (Clause 3) even if no terms are defined
• Example of a definition in ISO 14126:
  3.1
  compressive stress
  the compressive force experienced by the test specimen at any particular moment divided by the initial cross-sectional area of the parallel-sided portion of the specimen. It is expressed in megapascals
4. Principle

- A concise summary of the measurement method prescribed within the standard
- Example of principle given in ISO 14126:
  
  An axial force is applied to the unsupported length of a rectangular specimen held in a loading fixture, while the applied load and strain in this area are monitored. The test method concentrates on the quality of the axial deformation experienced by the specimen. Any loading fixture can be used, provided specimen failure occurs below a 10% bending strain in the specimen.

  The compressive load is applied to the material:

  - either by shear through end tabs (method 1);
  - or by direct end loading of the specimen (method 2)

  Method 2 using a tabbed specimen results in load introduction into the test area by a combination of direct compression and shear through the tabs
5. Apparatus – test machine

- Conformity to BS ISO 5893 Rubber and plastics test equipment – Tensile, flexural and compression types (constant rate of traverse) – Specification
- ISO 5893 covers requirements for:
  - Designation of machine class according to accuracy (force & elongation)
  - Design features (size, construction, axial alignment, tensile grips, drive characteristics, jigs for compression, shear and flexural loading)
  - Types of force-measuring system
  - Steady state and dynamic machine accuracy
  - Measurement of elongation (deflection)
  - Rate of displacement of driven grip
  - Machine stiffness
  - Stability (temperature range, supply voltage etc.)
  - Certificate of verification
5. Apparatus – test machine

• Speed of testing
  ➢ Checks should be made to ensure that the test machine to be used is capable of maintaining the required speed of testing
  ➢ The speed of testing will usually be stipulated in a sub-clause in the Procedure clause

• Indication of load
  ➢ The error on the indicated load should not exceed a certain percentage, typically ± 1%
  ➢ Load cells should be calibrated on the machine on which they will be used
  ➢ Typically load cells are calibrated annually
  ➢ However, if the test machine is moved, relocated, disturbed etc then re-calibration should be undertaken
5. Apparatus – test machine

• Strain measurement
  ➢ Recommendations are given as to appropriate strain measurement devices
  ➢ Typically, bonded strain gauges or extensometers
  ➢ Calibration required
  ➢ Crosshead displacement not recommended unless it is appropriate to perform compliance compensation
  ➢ Consideration given to active length of strain gauges and gauge-length of extensometer re. specimen geometry, material format etc
  ➢ Error in indicated strain $\leq \pm 1\%$

• Micrometers, veniers
  ➢ Measurement of specimen dimensions
  ➢ Standard will stipulate what device should be used for measurement of which dimensions and to what accuracy level
  ➢ Prescribes the type of faces for the measurement device
5. Apparatus – loading fixtures

- Strain measurement
  - Recommendations are given as to appropriate strain measurement devices
  - Typically, bonded strain gauges or extensometers
  - Calibration required
  - Crosshead displacement not recommended unless it is appropriate to perform compliance compensation
  - Consideration given to active length of strain gauges and gauge-length of extensometer re. specimen geometry, material format etc
  - Error in indicated strain ≤ ± 1 %

- Micrometers, veniers
  - Measurement of specimen dimensions
  - Standard will stipulate what device should be used for measurement of which dimensions and to what accuracy level
  - Prescribes the type of faces for the measurement device
5. Apparatus – loading fixtures

- Guidance provided as to fixtures appropriate to the loading mode
- Level of prescription relating to jigs varies depending on the measurement method
- Some examples:

- Through-thickness tension (ISO/NP 20975-1)
- Interlaminar shear (BS EN ISO 14130)
- Double V-notch beam shear
- End-loading compression jig (ISO 14126)
## 6. Test specimens

Shape and dimensions of specimens prescribed

Example of allowable specimen types & sizes from ISO 14126:

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Symbol</th>
<th>Type A specimen</th>
<th>Type B1 specimen</th>
<th>Type B2 specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length (minimum)</td>
<td>$l_0$</td>
<td>$110 \pm 1$</td>
<td>$110 \pm 1$</td>
<td>$125 \pm 1$</td>
</tr>
<tr>
<td>Thickness</td>
<td>$h$</td>
<td>$2 \pm 0.2$</td>
<td>$2 \pm 0.2$ to $10 \pm 0.2$</td>
<td>$\geq 4$</td>
</tr>
<tr>
<td>Width</td>
<td>$b$</td>
<td>$10 \pm 0.5$</td>
<td>$10 \pm 0.5$</td>
<td>$25 \pm 0.5$</td>
</tr>
<tr>
<td>Distance between end tabs/grips</td>
<td>$L$</td>
<td>$10$</td>
<td>$10$</td>
<td>$25$</td>
</tr>
<tr>
<td>Length of end tabs (minimum)</td>
<td>$l_t$</td>
<td>$50$</td>
<td>$50$ (if required)</td>
<td>$50$ (if required)</td>
</tr>
<tr>
<td>Thickness of end tabs</td>
<td>$d_t$</td>
<td>$1$</td>
<td>$0.5$ to $2$ (if required)</td>
<td>$0.5$ to $2$ (if required)</td>
</tr>
</tbody>
</table>

Tolerances given on length, thickness and width
6. Test specimens – panel preparation

ISO typically recommends panels be prepared in accordance with:

  - Part 1 - General conditions
  - Part 2 - Contact and spray-up moulding
  - Part 3 - Wet compression moulding
  - Part 4 - Moulding of prepregs
  - Part 5 - Filament winding
  - Part 6 - Pultrusion moulding
  - Part 7 - Resin transfer moulding
  - Part 8 - Compression moulding of SMC and BMC
  - Part 9 - Moulding of GMT/STC
  - Part 10 - Injection moulding of BMC and other long-fibre compounds. General principles and moulding of multipurpose test specimens
  - Part 11 - Injection moulding of BMC and other long-fibre moulding compounds. Small plates
6. Test specimens – panel preparation

- ISO 9353 Glass-reinforced plastics. Preparation of plates with unidirectional reinforcements by bag moulding
- Other agreed procedure
6. Test specimens – end-tabbing

- End-tabs applied to specimens where ends of the specimen need reinforcement i.e. to protect against damage from gripping.
- Typically end-tabs should be made from 0°/90° GFRP cross-ply laminate or fabric with fibre axes set at ±45° to the specimen axis.
- Usually, tab angle is 90° but in some ASTM standards the tabs can be tapered.
- Other end-tab materials can be used as long as fit-for-purpose.
- End-tab thickness: typically 0.5 mm to 2 mm.
- Surface preparation essential.
- Selection of correct adhesive.
6. Test specimens: machining

- Specimens from fibre-reinforced plastic composite panels should be machined using saws fitted with diamond grit coated blades.
- Liquid coolants are recommended to avoid build-up of heat in the specimen.
- Abrasive water-jet cutting can also be used.
- Specimens should be dried immediately after machining.
- All cut surfaces should be free from machining defects.
- Subsequent machining operations may involve grinding to ensure tolerances on squareness and parallelism are met.
- Solid carbide drills should be used for hole drilling.
- Checks should be made to ensure specimens meet tolerances and are free from damage.
7. Number of test specimens

- Typically a minimum of 5 specimens should be tested
- Performed in each direction of test
- If a greater degree of precision of the mean value if required then more specimens should be tested
- This can be determined from the confidence interval (ISO 2602)
- Additional specimens should be tested if unacceptable failure modes are obtained
8. Conditioning

• Specimens should be conditioned as per the standard that is being used
• If this information is not provided then select the most appropriate set of conditions from ISO 291 Plastics – Standard atmospheres for conditioning and testing
• Or, at conditions as agreed upon by all interested parties
9. Procedure

• Specimens should be tested in accordance with the detailed procedure contained within the standard

• The procedure will typically contain guidance on:
  ➢ measurement of specimen dimensions
  ➢ attachment of strain gauges or extensometers
  ➢ alignment or bending criteria
  ➢ test control i.e. load, displacement or strain control
  ➢ cross-head speed or loading rate
  ➢ acceptable failure modes
  ➢ what should be measured during the test
  ➢ ...
10. Expression of results

- Explicit instructions on calculation of properties
- For example, in ISO 14126:
  - Calculate the components strength $\sigma_{cM}$, expressed in megapascals, using the equation
    \[ \sigma_{cM} = \frac{F_{\text{max}}}{bh} \]
    Where:
    - $F_{\text{max}}$ is the maximum load, in newtons;
    - $b$ is the width, in millimetres, of the test specimen;
    - $h$ is the thickness, in millimetres, of the test specimen.
  - Calculate the compressive modulus $E_c$, expressed in megapascals, using the equation
    \[ E_c = \frac{\sigma_{c''} - \sigma_{c'}'}{\varepsilon_{c''} - \varepsilon_{c'}'} \]
    Where:
    - $\sigma_{c''}$ is the compressive stress at $\varepsilon_{c''} = 0.0025$, expressed in megapascals;
    - $\sigma_{c'}'$ is the compressive stress at $\varepsilon_{c'}' = 0.0005$, expressed in megapascals.
11. Precision data

- A precision data clause is included whether data are available or not
- Precision data, generated from an interlaboratory comparison exercise, will be included in this clause if available
- Used to evidence the repeatability and reproducibility of the test standard
Specifications and Design Codes
Examples of specifications and codes

• EN 13706: Reinforced Plastic Composites - Specification for Pultruded Profiles
• DNVGL-RP-F119 Thermoplastic composite pipes
• TR 55 Design guidance for strengthening concrete structures using fibre composite materials
EN 13706: Reinforced plastic composites - specification for pultruded profiles

- Part 1: Designation
- Part 2: Methods of test and general requirements
- Part 3: Specific requirements
The need

• Each pultruder uses a different laminate construction with different properties
• Large variation on profile properties make it difficult for structural designers and specifiers who are not always specialist in composites
• Standards give confidence in the products
Real life application

- Source: Exel Composites UK Deep Ocean Environmental Long Term Observatory System (DELOS) constructed, in part, from pultruded structural profiles. Its two large ocean floor platforms accommodate researcher's underwater data-collection systems
Part 1 – Designation

- A coding system that incorporates all types of structural profiles
- Can be used as a product code
- Potential for materials database

EN 13706 - BGV, IF, E23
- B: box section
- G: glass-fibre
- V: surface veil
- I: isophthalic polyester
- F: fire retardant
- E23: modulus 23 GPa
Part 2 – Methods of test and general requirements

- All parameters in the specification except mechanical properties
- Dimensional tolerances not specific profile dimensions
- Visual and workmanship

Appendices

- A: Visual defects
- B: Tolerances
- C: Workmanship
- D: Effective flexural modulus
- E: Pin bearing strength
- F: Other test methods
- G: Section stiffness tests (flexure, shear and torsion)
Part 3 – Test specification

- Two grades, E23 and E17, initially proposed for glass-fibre based systems
- Mandated test methods for
  - Properties to be achieved
  - Other properties that may be reported
- Recommended test methods for other properties (impact and long term mechanical, thermal, chemical and environmental, electrical, fire)
- Additional requirements (defects, tolerances)
## Part 3 – Test specification

Table 1: Minimum Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full section test</td>
<td>GPa</td>
<td>E23 23</td>
</tr>
<tr>
<td>Tension modulus – axial</td>
<td>GPa</td>
<td>E17 17</td>
</tr>
<tr>
<td>Tension modulus – transverse</td>
<td>GPa</td>
<td>7</td>
</tr>
<tr>
<td>Tension strength – axial</td>
<td>MPA</td>
<td>240</td>
</tr>
<tr>
<td>Tension strength – transverse</td>
<td>MPA</td>
<td>50</td>
</tr>
<tr>
<td>Pin-bearing – axial</td>
<td>MPA</td>
<td>150</td>
</tr>
<tr>
<td>Pin-bearing – transverse</td>
<td>MPA</td>
<td>70</td>
</tr>
<tr>
<td>Flexural strength – axial</td>
<td>MPA</td>
<td>240</td>
</tr>
<tr>
<td>Flexural strength – transverse</td>
<td>MPA</td>
<td>100</td>
</tr>
<tr>
<td>Interlaminar Shear strength</td>
<td>MPA</td>
<td>25</td>
</tr>
</tbody>
</table>
### Part 3 – Test specification

Table 2: Material properties that may be reported

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression strength-axial, MPa</td>
<td>EN ISO/DIS 14126</td>
</tr>
<tr>
<td>Compression strength-transverse, MPa</td>
<td>EN ISO/DIS 14126</td>
</tr>
<tr>
<td>Fibre content by weight, %</td>
<td>ISO 1172 (glass-fibre)</td>
</tr>
<tr>
<td></td>
<td>ISO 14127 (carbon-fibre)</td>
</tr>
<tr>
<td>Density, kg/m$^3$</td>
<td>ISO 1183</td>
</tr>
<tr>
<td>Poisson's Ratio-axial</td>
<td>EN ISO 527-4</td>
</tr>
<tr>
<td>Poisson's Ratio-transverse</td>
<td>EN ISO 527-4</td>
</tr>
<tr>
<td>Thermal expansion-axial $10^{-6}/^\circ C$</td>
<td>ISO 11359-2</td>
</tr>
<tr>
<td>Thermal expansion-transverse $10^{-6}/^\circ C$</td>
<td>ISO 11359-2</td>
</tr>
</tbody>
</table>
Annex on fire testing

Reaction to Fire (EN 13501-1)
- Single burning item and small burner
- Classes B to D for composites, wood, PVC
- Smoke density included
- Smoke toxicity not included

Resistance to Fire (EN 13501-2)
- Very expensive furnace tests
- Load bearing, Insulation and integral resistance

EU Fire Standard
- Challenge → standard developed for flat materials, not suitable for linear elements!!!
Recommended practice – an example

DNVGL-RP-F119 Thermoplastic composite pipes

Thick walled HD-PE pipes for slurry – Gordon J CC BY-SA 4.0
Thermoplastic composite pipes

This recommended practice (RP) describes requirements for flexible thermoplastic composite pipes (TCP) for offshore applications

It is intended for:

- Suppliers of TCP for offshore service and suppliers of raw materials for such pipes who seek market access for their products
- Operators, contractors and others seeking acceptance for using TCP in offshore operations
- Suppliers and recipients of TCP who need a common technical basis for contractual reference
Real life application

Replace bespoke steel connection between the wellhead and skid
What is covered in RP

1. General
2. Design Philosophy
3. Design basis
4. Materials
5. Failure mechanisms and design criteria
6. Analysis methodology
7. Design criteria pipe body
8. Design criteria end fittings
9. Performance based qualification – full scale testing only
10. Prototype test requirements – full scale samples
11. Safety factors
12. Operational phase: inspection, maintenance, repair
13. Production QA test requirements
14. Marking and packaging
15. Documentation
Design considerations

Cross section of the body of a bonded thermoplastic composite pipe.
Relationships to standards

Section 1.2.11 Relationship of this recommended practice to other standards

Failure pipe for offshore use

- Metal based
  - Unbonded
    - API 17J Specification for unbonded flexible pipe
  - Bonded
    - API 17K Specification for bonded flexible pipe

- Composite based
  - Unbonded
  - Bonded
    - DNVGL-RP-F119 Thermoplastic composite pipes

Relationship of this RP to other standards on flexible pipes. No standard exists for unbonded composite pipes, but API17J covers this subject partially.
Relationships to standards

Section 1.3 Referenced standards and codes

1.3.2 DNV GL standards

<table>
<thead>
<tr>
<th>Document code</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNV-OS-1.303</td>
<td>Composite Components, Rev.20, 2013</td>
</tr>
<tr>
<td>DNV-OS-1.304</td>
<td>Laminar Pipe Systems</td>
</tr>
<tr>
<td>DNV-OS-1.305</td>
<td>Dynamic Risers</td>
</tr>
</tbody>
</table>

1.3.3 DNV GL recommended practices

<table>
<thead>
<tr>
<th>Document code</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNV-RP-F102</td>
<td>Composite Booms, Rev.20, 2013</td>
</tr>
<tr>
<td>DNV-RP-F103</td>
<td>Keel Interference</td>
</tr>
<tr>
<td>DNV-RP-F106</td>
<td>On-Bottom Stabilisation of Laminar Pipelines</td>
</tr>
</tbody>
</table>

1.3.4 DNV classification notes

<table>
<thead>
<tr>
<th>Document code</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNV Classification Note No. 38.1</td>
<td>Structural reliability analysis of marine structures</td>
</tr>
</tbody>
</table>

1.3.5 Other standards and codes

<table>
<thead>
<tr>
<th>Document code</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>API 15E</td>
<td>Qualification of Submarine Pneumatically Actuated Valves, 1st edition, March 2003</td>
</tr>
<tr>
<td>API TR 79 / ISO 15131-1</td>
<td>Recommended Practice for Flexible Pipelines</td>
</tr>
<tr>
<td>API RP 17P</td>
<td>Specification for Flexible Permanent Pipelines</td>
</tr>
<tr>
<td>API RP 17J</td>
<td>Design of Sheets for Flexible Pneumatic Systems (FPSs) and Tension-Leg Platforms (TLPs)</td>
</tr>
<tr>
<td>API RP 21C</td>
<td>Standard Practice for Composite Linepipe</td>
</tr>
</tbody>
</table>
Section 2: Design philosophy

Section 2.2.3 Safety classes and service classes

Safety classes are based on the consequences of failure while Service classes are based on the frequency of service interruptions or restrictions

Safety class low:
- Where failure implies low risk of human injury and minor environmental and economic consequences

Safety class medium:
- For conditions where failure implies risk of human injury, significant environmental pollution or very high economic or political consequences

Safety class high:
- For operating conditions where failure implies high risk of human injury, significant environmental pollution or very high economic or political consequences
Section 4: Materials

This section specifies which material properties shall be obtained as a minimum and it describes how the properties shall be obtained.
## Section 4: Materials

High level test program complimented by very detailed testing requirements and conditions at all levels of complexity

<table>
<thead>
<tr>
<th>Test program description</th>
<th>UD flt laminate</th>
<th>UD ring or pipe</th>
<th>Multiaxial flt laminate</th>
<th>Multiaxial pipe</th>
<th>TCP samples</th>
<th>TCP assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short term testing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-term tests to obtain ply properties</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-term tests to obtain laminate properties from laminates or pipes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Confirmation testing – static testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Long term testing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long-term tests for TCP laminates</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confirmation testing on TCP – long-term properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Inter-face testing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Short term test requirements for interfaces</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long term test requirements for interfaces</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Proto-type testing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Prototype test requirements – full scale samples (not just laminate)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Composites Standards & Certification
Testing only vs Design calculation

• This RP also gives the option to qualify the TCP, end fittings or components completely by testing. This would be an alternative to the design calculation based approach given in Sec.5, Sec.6, Sec.7 and Sec.8

• However, a qualification by testing only will only be valid for the conditions tested, typically severely limiting the range conditions under which the TCP can be used
**Full scale testing**

Full scale testing is specified to:

- verify performance under the main loading conditions
- verify the design analysis

1. Burst test
2. Burst test under bending
3. Cyclic fatigue survival testing
4. Stress rupture survival testing
5. External pressure test
6. Torsional balance
7. Gauge test
8. Impact Test
# Fatigue testing

Test temperature, conditioning and load are selected based on the Safety class

<table>
<thead>
<tr>
<th></th>
<th>Safety class high</th>
<th>Safety class medium</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Axial fatigue</strong></td>
<td>2 survival tests at $N_{test} = 10^5$ cycles each</td>
<td>1 survival test at $N_{test} = 10^5$ cycles each</td>
</tr>
<tr>
<td>if the TCP experiences axial loads fatigue loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bending fatigue</strong></td>
<td>2 survival tests at $N_{test} = 10^5$ cycles each</td>
<td>1 survival test at $N_{test} = 10^5$ cycles each</td>
</tr>
<tr>
<td>testing shall be performed if the TCP experiences bending fatigue loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Internal pressure</strong></td>
<td>2 survival tests at $N_{test} = 10^5$ cycles each</td>
<td>1 survival test at $N_{test} = 10^5$ cycles each</td>
</tr>
<tr>
<td>testing shall be performed if the TCP experiences internal pressure fatigue loads</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Gauge testing

Pipeline inspection gauge capsule with different types of sensor carriers mounted

Sensors – Basel CC-BY-4.0
Design Guidance – an example

- TR 55 Design guidance for strengthening concrete structures using fibre composite materials. 3rd edition 2012
- Published by the Concrete Society
- TR 55 should be read in conjunction with TR 57 Strengthening concrete structures using fibre materials: acceptance, inspection and monitoring.
Real life application

- Flexural reinforcement of concrete bridge deck reinforced by CFRP sheet
What is covered in TG

1. Introduction
2. Background
3. Material types and properties
4. Review of applications
5. Structural design of strengthen members
6. Design of members in flexure
7. Shear strengthening
8. Column design
9. Workmanship and installation
10. Long-term inspection and monitoring
Appendix B: Systems Available in the UK

- Sheets and FRP plates
- Properties of carbon fibre composite plate materials
- Properties of fibre composite sheet materials
- Properties of epoxy adhesives
- Properties of laminating resins
## Properties of fibre composite sheet materials

<table>
<thead>
<tr>
<th>Trade</th>
<th>Fibre</th>
<th>Strength (N/mm²)</th>
<th>Modulus (kN/mm²)</th>
<th>Area weight (g/m²)</th>
<th>Effective thickness * (mm)</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DML Composites</td>
<td>Carbon</td>
<td>4900</td>
<td>230</td>
<td>150, 300, 900</td>
<td>-</td>
<td>300, 500, 1500</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>3400</td>
<td>70</td>
<td>200, 250, 1200</td>
<td>-</td>
<td>350, 500</td>
</tr>
<tr>
<td></td>
<td>Aramid</td>
<td>2800</td>
<td>115</td>
<td>200, 300</td>
<td>-</td>
<td>340</td>
</tr>
<tr>
<td>Kevlar Structural Reinforcement Systems</td>
<td>Aramid</td>
<td>2100</td>
<td>120</td>
<td>280, 420</td>
<td>0.193, 0.286</td>
<td>100, 300, 500</td>
</tr>
<tr>
<td>Enforce</td>
<td>Carbon</td>
<td>3900</td>
<td>240</td>
<td>200</td>
<td>0.117</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Carbon</td>
<td>2650</td>
<td>640</td>
<td>400</td>
<td>0.235</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>1700</td>
<td>65</td>
<td>350</td>
<td>0.135</td>
<td>680</td>
</tr>
<tr>
<td></td>
<td>Aramid</td>
<td>2900</td>
<td>120</td>
<td>290, 420</td>
<td>0.2, 0.29</td>
<td>300</td>
</tr>
</tbody>
</table>
Appendix C: Quality Control of materials

The manufacturer should supply characteristic values of the mechanical properties to be used for design purposes which should be taken as the mean value minus 2 standards deviations. Sufficient test should be carried out at regular intervals to ensure that this is statistically valid.

• What if testing suggests that less than 2 StDev could be subtracted from the mean value?
Appendix C: Quality Control of materials

High level specification for:

Strengthening Materials
- Fabric materials
- Pultruded plates
- Prepreg plates
- Shells

Site Requirements
- Plates
- Wet lay-up laminates
Composites Standards & Certification

3
Structure

This presentation consists of 4 sections:

<table>
<thead>
<tr>
<th>Sections</th>
<th>Section number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Certification Pyramid</td>
</tr>
<tr>
<td>2</td>
<td>Acceptable Means of Compliance (AMC)</td>
</tr>
<tr>
<td>3</td>
<td>Statistical Interpretation of Qualification Test Data</td>
</tr>
<tr>
<td>4</td>
<td>Role of Numerical Simulation in the Certification</td>
</tr>
</tbody>
</table>
Certification Pyramid
Introduction

• This section is largely based on the Composite Materials Handbook 17 (CMH-17) and therefore is directly applicable to aerospace but equally valid to any composite structure.
Building Block Approach

- Analysis alone is generally not considered adequate for validation of composite structural designs
- Instead the building-block approach to design development testing is used in concert with analysis
The need for a Building Block Approach

• Essential to the certification of composite structures due to the sensitivity of composites to out-of-plane loads the multiplicity of composite failure modes the lack of standard analytical methods

• Impractical to conduct full scale tests under the actual environmental conditions (e.g. moisture and temperature)
  ➢ Used to establish environmental compensation values applied to full-scale tests at room-temperature ambient environment
The need for a Building Block Approach

• One major purpose of employing this approach is to reduce program cost and risk while meeting all technical, regulatory, and customer requirements
History

- The Building Block approach has been used in aircraft structures development programs long before the application of composites.
Building Block Approach: Steps 1-4

1. Generate material basis values and preliminary design allowables
2. Based on the design/analysis of the structure, select critical areas for subsequent test verification
3. Determine the most strength-critical failure mode for each design feature
4. Select the test environment that will produce the strength-critical failure mode
   - Special attention to (a) matrix-sensitive failure modes (b) potential hot-spots caused by out-of-plane loads
Building Block Approach: Steps 5-6

5. Design and test a series of test specimens, each one of which simulates a single selected failure mode and loading condition, compare to analytical predictions, and adjust analysis models or design allowables as necessary.

6. Design and conduct increasingly more complicated tests that evaluate more complicated loading situations with the possibility of failure from several potential failure modes. Compare to analytical predictions and adjust analysis models as necessary.
Building Block Approach: Step 7

7. Design (including compensation factors) and conduct, as required, full-scale component static and fatigue testing for final validation of internal loads and structural integrity. Compare to analysis.
The pyramid of tests
Test levels and data uses

- Constituent Testing
  - evaluates the individual properties of fibres, fibre forms, matrix materials, and fibre-matrix preforms
- Lamina Testing
  - evaluates the properties of the fibre and matrix together in the composite material form
- Laminate Testing
  - characterizes the response of the composite material in a given laminate design
Test levels and data uses

• Structural Element Testing
  ➢ Evaluates the ability of the material to tolerate common laminate discontinuities

• Structural Subcomponent (or higher) Testing
  ➢ Evaluates the behaviour and failure mode of increasingly more complex structural assemblies
Test levels and data uses
Data application categories

- Screening Testing
- Material Qualification Testing
- Acceptance Testing
- Equivalence Testing
- Structural Substantiation Testing
Test levels and data uses

- Screening Testing
  - Assessment of material candidates for a given application. Initial evaluation of new material systems under worst-case environmental and loading test conditions

- Material Qualification Testing
  - Proves the ability of a given material/process to meet the requirements of a material specification
  - Establishes the original specification requirement values
Test levels and data uses

• Acceptance Testing
  ➢ Verifies material consistency through periodic sampling of material product and evaluation of key material properties

• Equivalence Testing
  ➢ Assesses the equivalence of an alternate material to a previously characterized material, often for the purpose of utilizing an existing material property database

• Structural Substantiation Testing
  ➢ Assesses the ability of a given structure to meet the requirements of a specific application
## Test programme definition

<table>
<thead>
<tr>
<th>Structural complexity level</th>
<th>Material Screening</th>
<th>Material Qualification</th>
<th>Material Acceptance</th>
<th>Material Equivalence</th>
<th>Structural Substantiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constituent</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lamina</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Laminate</td>
<td>-</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Structural Element</td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Structural Subcomponent</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9</td>
</tr>
</tbody>
</table>
The building block approach

Group A: Material property development
- Block 1: Material screening and selection
- Block 2: M&P specification development
- Block 3: Allowable development
- Block 4: Structural element test
- Block 5: Sub-component tests
- Block 6: Component tests

Group B: Design value development
- Block 1

Group C: Analysis verification
- Block 1
Specific applications: Business and private aircraft

- Risk and cost reduction are the main justifications for a building block approach
- Material tests allow alternate materials to be specified
- Element tests can identify allowable intrinsic manufacturing defects
- The scope of full scale static and fatigue testing can be reduced with a program of analysis supported by smaller tests
## Typical building block programme

### Typical matrix: Material Lamina Tests

<table>
<thead>
<tr>
<th>Property</th>
<th>Number of batches (6 tests EA batch)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTD</td>
</tr>
<tr>
<td><strong>Tension 0</strong></td>
<td></td>
</tr>
<tr>
<td>Strength, modulus, and Poisson’s</td>
<td>1</td>
</tr>
<tr>
<td><strong>Compression 0</strong></td>
<td></td>
</tr>
<tr>
<td>Strength and modulus</td>
<td>1</td>
</tr>
<tr>
<td><strong>Tension 90</strong></td>
<td></td>
</tr>
<tr>
<td>Strength and modulus</td>
<td>1</td>
</tr>
<tr>
<td><strong>Compression 90</strong></td>
<td></td>
</tr>
<tr>
<td>Strength and modulus</td>
<td>1</td>
</tr>
<tr>
<td><strong>In-plane shear</strong></td>
<td></td>
</tr>
<tr>
<td>Strength and modulus</td>
<td>1</td>
</tr>
</tbody>
</table>
## Typical building block programme

### Typical matrix: Material Laminate Tests

<table>
<thead>
<tr>
<th>Property</th>
<th>Number of batches (6 tests EA batch)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTD</td>
</tr>
<tr>
<td>Bearing strength</td>
<td>1</td>
</tr>
<tr>
<td>Compression after impact</td>
<td>1</td>
</tr>
<tr>
<td>Open hole tension strength</td>
<td>1</td>
</tr>
<tr>
<td>Open hole compression strength</td>
<td>1</td>
</tr>
<tr>
<td>Fluid exposure</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>-</td>
</tr>
<tr>
<td>Deice fluid</td>
<td>-</td>
</tr>
<tr>
<td>Hydraulic fluid</td>
<td>-</td>
</tr>
<tr>
<td>Cleaning solvent</td>
<td>-</td>
</tr>
</tbody>
</table>
## Typical building block programme

### Typical element test matrix: Critical laminates

<table>
<thead>
<tr>
<th>Property</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTD</td>
</tr>
<tr>
<td>Tension strength</td>
<td></td>
</tr>
<tr>
<td>Virgin</td>
<td>3</td>
</tr>
<tr>
<td>Impact damage</td>
<td>3</td>
</tr>
<tr>
<td>Detectable</td>
<td>3</td>
</tr>
<tr>
<td>Compression strength</td>
<td></td>
</tr>
<tr>
<td>Virgin</td>
<td>3</td>
</tr>
<tr>
<td>Impact damage</td>
<td>3</td>
</tr>
<tr>
<td>Detectable</td>
<td>3</td>
</tr>
<tr>
<td>Shear strength</td>
<td></td>
</tr>
<tr>
<td>Virgin</td>
<td>3</td>
</tr>
<tr>
<td>Impact damage</td>
<td>3</td>
</tr>
<tr>
<td>Detectable</td>
<td>3</td>
</tr>
<tr>
<td>Tension flaw growth</td>
<td></td>
</tr>
<tr>
<td>From impact damage</td>
<td>3</td>
</tr>
<tr>
<td>From detectable damage</td>
<td>3</td>
</tr>
<tr>
<td>Compression flaw growth</td>
<td></td>
</tr>
<tr>
<td>From impact damage</td>
<td>3</td>
</tr>
<tr>
<td>From detectable damage</td>
<td>3</td>
</tr>
<tr>
<td>Shear flaw growth</td>
<td></td>
</tr>
<tr>
<td>From impact damage</td>
<td>3</td>
</tr>
<tr>
<td>From detectable damage</td>
<td>3</td>
</tr>
</tbody>
</table>
# Typical building block programme

## Typical test matrix: Joint and critical details

<table>
<thead>
<tr>
<th>Property</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTD</td>
</tr>
<tr>
<td><strong>Tension strength</strong></td>
<td></td>
</tr>
<tr>
<td>Virgin</td>
<td>3</td>
</tr>
<tr>
<td>Max bond line</td>
<td>3</td>
</tr>
<tr>
<td>Bond voids</td>
<td>3</td>
</tr>
<tr>
<td>Lighting damage</td>
<td></td>
</tr>
<tr>
<td><strong>Bending strength</strong></td>
<td></td>
</tr>
<tr>
<td>Virgin</td>
<td>3</td>
</tr>
<tr>
<td>Max bond line</td>
<td>3</td>
</tr>
<tr>
<td>Bond voids</td>
<td>3</td>
</tr>
<tr>
<td>Lighting damage</td>
<td></td>
</tr>
<tr>
<td><strong>Bolts alone strength</strong></td>
<td></td>
</tr>
<tr>
<td>Virgin</td>
<td>3</td>
</tr>
<tr>
<td>Max gap</td>
<td>3</td>
</tr>
<tr>
<td>Min e/d</td>
<td>3</td>
</tr>
<tr>
<td>Miss-aligned</td>
<td>3</td>
</tr>
<tr>
<td><strong>Tension flaw growth</strong></td>
<td></td>
</tr>
<tr>
<td>Max bond line</td>
<td></td>
</tr>
<tr>
<td>Bond voids</td>
<td></td>
</tr>
<tr>
<td><strong>Bending flaw growth</strong></td>
<td></td>
</tr>
<tr>
<td>Max bond line</td>
<td></td>
</tr>
<tr>
<td>Bond voids</td>
<td></td>
</tr>
</tbody>
</table>
## Typical building block programme

### Typical sub component tests

<table>
<thead>
<tr>
<th>Sub component</th>
<th>Test type</th>
<th>Loading</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing or stabilizer box</td>
<td>Static</td>
<td>Bending/torsion</td>
<td>RTD and ETW</td>
</tr>
<tr>
<td></td>
<td>D&amp;DT</td>
<td>2 lifetimes</td>
<td>RTD</td>
</tr>
<tr>
<td></td>
<td>Res Strength</td>
<td>Bending/torsion</td>
<td>RTD</td>
</tr>
<tr>
<td>Wing or stabilizer box</td>
<td>Static</td>
<td>Bending/torsion</td>
<td>RTD</td>
</tr>
<tr>
<td>Pressure bulkhead installation</td>
<td>Static</td>
<td>Operating and ultimate pressure</td>
<td>RTD</td>
</tr>
<tr>
<td></td>
<td>D&amp;DT</td>
<td>2 lifetimes</td>
<td>RTD</td>
</tr>
<tr>
<td></td>
<td>Res Strength</td>
<td>Operating and ultimate pressure</td>
<td>RTD</td>
</tr>
</tbody>
</table>
Typical building block programme

Full scale tests—static

- Extent of full scale testing can be reduced based on the test results from lower levels of testing and validation of analytical methods by comparison to those results
- Thus, a limited number full scale test load cases will be tested, and tested under ambient temperature/moisture only
- The other temperature/moisture conditions can be cleared by analysis or by direct comparisons of strain data to element test results
- Similarly, other load cases can be cleared by analysis
Typical building block programme

Full scale tests—durability and damage tolerance tests

- Full scale testing of composite structure to demonstrate tolerance of in-service repeated loads both in the as-manufactured condition and after inflicted damage is the industry norm in aero structures.
- Usually a load enhancement factor of 1.15 is applied to enable two test lifetimes to represent one service lifetime.
Acceptable means of compliance (AMC)
Why AMC documents are important?

- Provide a clear way, although not the only way, to satisfy regulatory requirements
- Guide the manufacturer on what needs to done in order to meet regulations during the certification of a safety critical structure
- Prescribe detailed practices and a broad framework for using new materials
AMC 20-29 Composite Aircraft Structure

- We will look into the AMC 20-29 Composite Aircraft Structure document and how this prescribes detailed practices and testing procedures for composite aircraft structures
Purpose

• AMC 20-29 Composite Aircraft Structure

“provides an acceptable means, but not the only means, for airworthiness certification of composite aircraft structures”

• The objective of the document is to standardise recognised good design practices common to composite aircraft structure
Applicability of the document

- This AMC provides Acceptable Means of Compliance with the provisions of CS-23, CS-25, CS27 and CS-29
  - CS-23 Airworthiness Code for Normal, Utility, Aerobatic and Commuter Aeroplanes
  - CS-25 Airworthiness Code for Large Aeroplanes
  - CS-27 Airworthiness Code for Small Rotorcraft
  - CS-29 Airworthiness Code for Large Rotorcraft

- The technical content of AMC 20-29 is harmonised with FAA Advisory Circular AC 20-107B
Airworthiness Code CS-23

- Requirement

CS 23.603 Materials and workmanship  
(See AMC 23.603)

(a) The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must –

   (1) Be established by experience or tests;

   (2) Meet approved specifications that ensure their having the strength and other properties assumed in the design data; and

   (3) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.

(b) Workmanship must be of a high standard.
"To provide an adequate design database, environmental effects on critical properties of the material systems and associated processes should be established. In addition to testing in an ambient environment, variables should include extreme service temperature and moisture content conditions and effects of long-term durability. Qualification tests for environmental effects and long-term durability are particularly important when evaluating the materials, processes, and interface issues associated with structural bonding."

- Paragraph 6a (c) provides details on how the requirement in the airworthiness code can be met and suggests action.
- Stresses the need for quantifying the environmental effects on the selected materials.
Airworthiness Code CS-23

- Requirement

CS 23.305  **Strength and deformation**

(a) The structure must be able to support limit loads without detrimental, permanent deformation. At any load up to limit loads, the deformation may not interfere with safe operation.

(b) The structure must be able to support ultimate loads without failure for at least three seconds, except local failures or structural instabilities between limit and ultimate load are acceptable only if the structure can sustain the required ultimate load for at least three seconds. However, when proof of strength is shown by dynamic tests simulating actual load conditions, the three second limit does not apply.
AMC 20-29; 7. Proof of Structure - Static

7c “The component static test may be performed in an ambient atmosphere if the effects of the environment are reliably predicted by building block tests and are accounted for in the static test or in the analysis of the results of the static test”

• Provisions are made for the static test of the component and in particular the environmental conditions that the test should take place and how to account for the effects of the environment
AMC 20-29; 7. Proof of Structure - Static

7d “The static test articles should be fabricated and assembled in accordance with production specifications and processes so that the test articles are representative of production structure including defects consistent with the limits established by manufacturing acceptance criteria”

- Provisions are made on how the test article should be manufactured
- Test article should be representative (manufacturing tolerances, defects etc.) of the real structure
AMC 20-29; 8. Proof of Structure – Fatigue and Damage Tolerance

- The composite structure’s evaluation must show that catastrophic failure due to fatigue, environmental effects, manufacturing defects or accidental damage will be avoided throughout the aircrafts’ operational life
AMC 20-29; 8. Proof of Structure – Fatigue and Damage Tolerance

8a(1) “Damage tolerance evaluation starts with identification of structure whose failure would reduce the structural integrity of the aircraft. A damage threat assessment must be performed for the structure to determine possible locations, types, and sizes of damage considering fatigue, environmental effects, intrinsic flaws, and foreign object impact or other accidental damage (including discrete source) that may occur during manufacture, operation or maintenance”

- Provisions for performing damage threat assessments
- Structure details, elements and sub-components must be tested thereafter under repeated loads to assess susceptibility to damage growth
AMC 20-29; Other considerations

- Deals with **Continued Airworthiness** establishing detailed maintenance, inspection and repair practices
- Deals with **Fire Protection, Flammability and Thermal Issues** where there is a requirement that “a composite design, including repair and alterations, should not decrease the existing level of safety relative to metallic structure”
- Also deals with **Lightning Protection** since a lightning strike can result in structural failure or large area damage
Statistical interpretation of qualification test data
Material Qualification Testing

- Proves the ability of specific materials/processes to meet the requirements of a material specification
- Quantitative assessment of the variability of key material properties
- Analysis of qualification data leads to various statistics that can be used to establish:
  - Material acceptance
  - Equivalence
  - Quality control
  - Design basis values
Material Qualification Testing

- Composite material qualification testing differs from metals or unreinforced plastics
- Requires consideration of:
  - Test matrices
  - Material sampling and pooling
  - Statistical calculations
  - Test method selection
  - Material and processing variation
  - Conditioning and non-ambient testing
  - Variations on coupon configurations
  - Data normalisation and documentation
  - Application specific testing
Definitions

• Population - The set of measurements about which inferences are to be made or the totality of possible measurements which might be obtained in a given testing situation

• Sample - The collection of measurements (sometimes referred to as observations) taken from a specified population

• Sample size - The number of measurements in a sample
Definitions

- Population mean – The average of all potential measurements in a given population weighted by their relative frequencies in the population. The population mean is the limit of the sample mean as the sample size increases.
- Sample mean – The average of all observations in a sample and an estimate of the population mean.
- If the notation $x_1, x_2, \ldots, x_n$ is used to denote the $n$ observations in a sample, then the sample mean is defined by:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$
Definitions

- Sample variance—The sum of the squared deviations from the sample mean, divided by \( n - 1 \), where \( n \) denotes the sample size.

- The sample variance is defined by:

\[
s^2 = \frac{1}{n - 1} \sum_{i=1}^{n} (x_i - \bar{x})^2
\]

- Sample standard deviation—The square root of the sample variance. The sample standard deviation is denoted by \( s \).
Design basis values

• Design values must be chosen to minimise the probability of structural failure due to material variability.

• Compliance is typically shown by selecting design values that ensure material strength with the following probability:
  
  ➢ A-basis value: Where applied loads are eventually distributed through a single member within an assembly, the failure of which would result in loss of structural integrity of the component; 99 percent probability with 95 percent confidence interval (A-basis value)
  
  ➢ B-basis value: For redundant structure, in which the failure of individual elements would result in applied loads being safely distributed to other load carrying members; 90 percent probability with 95 percent confidence interval (B-basis values)
Design basis values

In statistical terms:

- **A-basis value**: A statistically-based material property; 95% confidence that 99% of the tested material samples will exceed this value
  
  \[ A - basis\ value = \bar{x} - (K_A) \cdot s \]

- **B-basis value**: A statistically-based material property; a 95% confidence that 90% of the tested material samples will exceed this value
  
  \[ B - basis\ value = \bar{x} - (K_B) \cdot s \]

- Basis values are not material properties – minimum value of a property expected to be used for design and analysis of a structure

- They are not fixed values because they depend on the number of specimens you test........
Effect of sample size on $K_A$ and $K_B$

Standard deviations can be very unstable when sample size is small (<30); resulting in very erratic basis values, unless pooling method is used.
Effect of sample size on the calculated B-basis value

• For very large sample sizes, the B-basis (ten percentile) value for this example would be 87.2
Procedure for calculating B-basis value

Procedure for calculating B-basis design allowables for properties measured from tests on 30 specimens from a minimum of 3 batches of material.

The approach is based on the methods given in CMH-17-1G. The flow chart provides a step by step guide to the statistical analysis process for B-basis design allowables.
Validity and consistency of failure modes

- For a particular strength property, the failure modes observed should be valid and consistent for a given environmental condition.
- Specimens observed to fail in non-acceptable modes (in accordance with the relevant test standard) should not be included in the data set.
- In addition, if a range of acceptable failure modes are observed within a data set, then the data should be further examined to see if there is a correlation between strength and the mode of failure.
- Should such a correlation exist then investigation of specimen manufacturing and preparation, as well as testing parameters should be undertaken to determine the cause of the different failure modes.
Investigation and removal of bad data

- Should physical evidence be identified that invalidates a test result (e.g. incorrect failure mode), then this result should be deemed a bad data point and removed from the data set

Failure within end-tab region of a compression coupon
Quantity of data

• Basis value calculation is strongly dependent on the sample size
• Smaller sample populations are obviously less costly to test, however, **as the population size decreases, so does the calculated basis value**
• In accordance with the guidance provided in CMH-17 statistically robust B-basis values should only be derived from data groups consisting of at least 18 specimens sampled from at least 3 material batches
• For A-basis the minimum number of specimens is typically 55 – higher cost and increased effort
• For those properties measured from a single batch of material (i.e. 10 specimens), the statistical analysis of these data should be limited to calculation of mean and standard deviation
Test for outliers within each batch

- Each data set shall be examined for the presence of outliers
- First step is to calculate the mean and standard deviation:

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i
\]

Mean of data set \( \bar{x} \) \( \leftrightarrow \) Measured values

\( n \) \( \rightarrow \) Number of measurements in a data set

\[
s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2
\]

Variance of data set \( s^2 \) \( \leftrightarrow \) \( \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \)

Where \( s \) is the standard deviation of data set
Test for outliers within each batch

- The maximum normed residual (MNR) method can be used for screening of outliers:

\[
\text{MNR} = \frac{\max_i |x_i - \bar{x}|}{s} \quad i = 1, 2, ..., n
\]

- MNR calculated for each measurement in each data set
- Resulting values compared to a critical value calculated for a data set size, \(n\),

\[
C = \frac{n - 1}{\sqrt{n}} \sqrt{\frac{t^2}{n - 2 + t^2}}
\]

Where: \(t\) is the \([1 - \alpha/2n]\) quantile of the t-distribution with \(n - 2\) degrees of freedom; and \(\alpha\) is the significance level (\(\alpha = 0.05\) for the MNR test).

The maximum absolute deviation from the data set mean divided by the data set standard deviation.
Treatment of outliers detected by MNR method

- If MNR values calculated are greater than C, then the largest value of MNR should be declared an outlier and can be rejected from the data set.
- Outliers are not automatically removed; cause needs to be identified first.
- Considerations:
  - Material or one of its constituents out of specification
  - Panel/specimen preparation outside of tolerance range
  - Incorrect test specimen dimensions and/or orientation
  - Defect detected
  - Incorrect specimen preconditioning
  - Errors in test machine / fixture set up
  - Incorrect test parameters used e.g. test speed
  - Issues with specimen gripping
  - Failure mode, bending
  - Incorrect normalisation of data
- If outlier is removed then the MNR process is repeated until no more outliers are detected.
Test for between data set variability

- For grouped or structured data, each data value will belong to a particular group and there will generally be more than one value within each data group.

- Double subscripts used to identify observations.
  - Data denoted by $x_{ij}$ for $i = 1, \ldots, k$ and $j = 1, \ldots, n_i$, where $i$ is the group and $j$ is the observation within that group.
  - If there are $n_i$ data values in the $i^{th}$ of $k$ groups, then total number of observations is $n = n_1 + n_2 + \ldots + n_k$.

- The $k$-sample Anderson-Darling test should be used to test whether the populations from which two or more groups of data were drawn are identical. The test requires that each group be an independent random sample from a population.
The k-sample Anderson-Darling statistic is given by:

\[ ADK = \frac{n - 1}{n^2(k - 1)} \sum_{i=1}^{k} \left[ \frac{1}{n_j} \sum_{j=1}^{L} h_j \frac{(nF_{ij} - n_i H_j)^2}{(n - H_j) - nh_j/4} \right] \]

Where:

- \( h_j \) is the number of values in the combined samples equal to \( z_{(j)} \)
- \( H_j \) is the number of values in the combined samples less than \( z_{(j)} \) plus one half the number of values in the combined samples equal to \( z_{(j)} \)
- \( F_{ij} \) is the number of values in the \( i^{th} \) group which are less than \( z_{(j)} \) plus one half the number of values in this group which are equal to \( z_{(j)} \)
Test for between data set variability

- Under the hypothesis of no difference in the populations, the mean and variance of ADK are approximately 1 and:

\[
\sigma^2_n = \text{Var}(ADK) = \frac{an^3 + bn^2 + cn + d}{(n - 1)(n - 2)(n - 3)(k - 1)^2}
\]

With:
\[
a = (4g - 6)(k - 1) + (10 - 6g)S \\
b = (2g - 4)k^2 + 8Tk + (2g - 14T - 4)S - 8T + 4g - 6 \\
c = (6T + 2g - 2)k^2 + (4T - 4g + 6)k + (2T - 6)S + 4T \\
d = (2T + 6)k^2 - 4Tk
\]

Where:
\[
S = \sum_{i=1}^{k} \frac{1}{n_i} \quad g = \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \frac{1}{(n-i)j} \quad T = \sum_{i=1}^{n-1} \frac{1}{i}
\]
Test for between data set variability

- If the critical value (ADC) is less than the ADK statistic then it can be concluded that the groups were drawn from different populations

\[ ADC = 1\sigma_n \left( 1.96 + \frac{1.149}{\sqrt{k-1}} - \frac{0.391}{k-1} \right) \]

- Otherwise, the hypothesis that the groups were selected from identical populations is not rejected, and the data may be considered a simple random sample
Treatment of between data set variability

- If statistically significant between-batch variability is not detected via the k-sample Anderson-Darling test, then all batch data can be pooled into a single data set.

- Statistical analysis can then continue to testing for outliers within this single data set using the MNR method described previously.

- If significant variability between batches is found, then the analysis should be terminated as it will not be possible to calculate B-basis values.
Observed significance level (OSL) for normal distribution of data

• In order to calculate a B-basis value for a normally distributed population, the population mean and standard deviation should be calculated.

• The goodness-of-fit for the assumed normal distribution should first be tested, let:

\[ Z(i) = \frac{x(i) - \bar{x}}{s} \]

\[ i = 1, 2, ..., n \]

Where \( x(i) \) is the \( i^{th} \) smallest observation, \( \bar{x} \) is the sample mean, and \( s \) is the sample standard deviation.
Observed significance level (OSL) for normal distribution of data

- The Anderson-Darling test statistic is:

\[
AD = \sum_{i=1}^{n} \frac{1 - 2i}{n} \{ln[F_0(z_i)] + ln[1 - F_0(z_{(n+1-i)})]\} - n
\]

Where \( F_0 \) is the cumulative distribution function of the standard normal distribution. The observed significance level (OSL) is given by:

\[
OSL = \frac{1}{\{1 + \exp[-0.48 + 0.78 \ln(AD^*) + 4.58AD^*]\}}
\]

Where:

\[
AD^* = \left[1 + \frac{4}{n} - \frac{25}{n^2}\right]AD
\]
Observed significance level (OSL) for normal distribution of data

- If the OSL is greater than 0.05 then the population can be considered normally distributed
- If the OSL value is less than or equal to 0.05, then the population can not be considered to be normally distributed
- In this instance, procedures for analysing Weibull or lognormal distributions should be evaluated (not detailed here)
Calculation of B-basis value for normal distribution

- If the OSL is greater than 0.05 then the population can be considered normally distributed
- The B-basis value can then be calculated from the following:

\[ B = \bar{x} - k_B s \]

Where \( \bar{x} \) is the sample mean, \( s \) is the sample standard deviation and \( k_B \) is the one-sided tolerance-limit factor given by:

\[ k_B \approx 1.282 + \exp\{0.958 - 0.520 \ln(n) + 3.19/n\} \]
Role of numerical simulation in the certification
Role of analysis

- Analysis, whether performed by closed form solutions or numerical models is useful in design and certification of composite structures.
- The state of the art is such that analysis cannot stand by itself but can be useful in directing and analysing test results and expanding test data to untested configurations by semiempirical methods.
- Analysis helps reducing the reliance on physical experiments, hence reducing the cost of the certification process.
Challenges

• Composites are inhomogeneous and anisotropic (fibres, matrix, nano-enhancements)
• Multiple and complex failure modes (fibre and matrix failure, delamination, interfacial failure)
• Composites can have a multitude of manufacturing imperfections at varying degrees (fibre waviness, porosity, geometric tolerances)
Common analysis & simulation types

- Constitutive modelling
  - e.g. modelling material behaviour, failure non-linearities etc.
- Strength and stiffness analysis
  - e.g. effect of manufacturing or in-service defects on strength and stiffness
- Stability
  - e.g. numerical and/or semi-analytical buckling analysis
- Fatigue analysis
  - e.g. progressive damage modelling under repeated loads
Strength and stiffness analysis

• Voids have detrimental effect on both stiffness and strength
• Production defects can not be avoided, unless production costs increase significantly
• Predicting material properties of imperfect laminates is the basis for economic design
Approach

- Replace experimental knock-down values by accurate numerical predictions

- Void size, shape and location
- Material model with progressive failure
- Macroscale parameters (strength & stiffness)
Strength and stiffness analysis

- In-service defects like foreign object impact have detrimental effect on the structural performance of composite structures
- Combination of testing and numerical simulation to evaluate performance and approve structures for safe operations
Quantifying damage

• Damage in the form of delamination, matrix cracks and fibre breakage will be distributed through the thickness of the composite

Glass fibre / epoxy composite subjects to impact
Predicting stiffness and strength

Fatigue analysis

- Delamination growth under fatigue is huge issue in composite structures
- Delamination can initiate from ply drop-offs, around holes, on sharp corners, structural discontinuities as well and due to in-service overloads
- Validating numerical tools to predict its growth is key in understanding and certifying structural performance
Fatigue analysis

Delamination growth prediction on ply drop-offs using a combination of analytical models and numerical simulation while utilising experimentally measured material properties.
Certification of Aircraft components

- Demonstrate compliance with the applicable regulations
- Sometimes in a single step and can be part of certification at aircraft level
- Oftentimes, articles approved to an industry standard, then compliance to the applicable regulation is later demonstrated
- **Generally compliance through physical testing!**
Why certification by analysis?

- Aircraft manufacturers are under strong pressure to reduce costs and development cycles
- For example, the development of aircraft interiors is driven by individualized customer demands → increasingly complex products and ever shorter innovation cycles
- To remain competitive, aircraft manufacturers must employ state-of-the-art computational tools and processes to reduce the amount of physical testing, certification costs and product development cycles
Certification by Analysis

- The authorities approve the data, not the analytical technique
- The authorities don’t hold a list of acceptable analyses, approved computer codes, or formulas
- The applicants must show the data are valid
- The authorities must find the data accurate and applicable, and that the analysis does not violate the assumptions of the problem
Incorporation into the certification process

• Example: Seats
Advisory Circular (AC) 20-146A

- Methodology for Dynamic Seat Certification by Analysis for Use in Parts 23, 25, 27, and 29 Airplanes and Rotorcraft

“This AC includes guidance for certifying seats by computer modelling analysis techniques that are validated by dynamic tests. This AC defines the acceptable applications, limitations, validation processes, and minimum documentation requirements involved when substantiation by computer modelling is used to support a seat certification program”
Applicability

- The material in this AC is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for showing compliance with the applicable regulations.
Verification of Explicit Codes

The process of verification determines that the computational model represents the mathematical model and its solution accurately

- Code verification
  - i.e. the process determining that the numerical algorithms are correctly implemented in the computer code

- Calculation verification
  - i.e. process of determining the solution accuracy of a particular calculation
Computer model validation

The validation process determines the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model

- The model should be validated against the original dynamic tests (paragraph 8.2.1)
- The level of correlation required should not be more stringent than the level of accuracy of the test data, which is dependent on the test instrumentation (8.2.4)
Also...

The AC 20-146A describes in detail how to

- Apply computer modelling in **support** of dynamic testing
- Apply computer modelling **instead** of dynamic testing
A clear certification plan

- Familiarise the authorities with the project
- Discuss the details of the design
- Identify applicable certification compliance paragraphs
- Negotiate where computer modelling will be used, and specify the intent and purpose of the analysis
- Establish means of compliance either by test, computer modelling, or both, with respect to the certification requirements
- Establish the validation criteria for the computer model
- Prepare and obtain approval of the certification plan
Documentation requirements

• Overview of a Validation and Analysis Report
• Purpose of Computer Model
• Validation Criteria
• Overview of Seating System
  ➢ Seat structure
  ➢ Restraint system
  ➢ Unique energy absorbing features in the installation
• Software and hardware overview
Documentation requirements ... continued

Description of Computer Model

- Engineering Assumptions
- Modelling of the Physical Structure
- Material Models
- Constraints
- Load Application
- Occupant Simulation
- General Analysis Control Parameters
Documentation requirements ...
continued

• Result Interpretation
  ➢ Energy Balance
  ➢ Data Output
  ➢ Data Filtering

• Ultimate Margin of Safety
Devise a basic qualification programme for a deep-water composite riser

Task:
You are going to work in small groups aiming to design a qualification programme for a composite riser.

Similar to pipelines, risers transport produced hydrocarbons, as well as production materials, such as injection fluids, control fluids and gas lift from/to a sea vessel to/from the seafloor. You are going to consider the case of a flexible riser. Flexible risers can withstand both vertical and horizontal movement, making them ideal for use with floating facilities (as shown below):

At the end of this exercise each group will present their approach and main assumptions to the rest of the class.

Procedure:
Before you DO anything, you should:
- Familiarize yourself with the DNVGL-RP-F119 Recommended Practice for Thermoplastic Composite Pipes

The sketch above provides the basic parts of the system (seafloor, vessel at sea level and a connecting flexible riser) and the forces typically acting on a riser.

For typical operational conditions the temperature difference between the inside of the riser and the environment is 80 °C – 100 °C. A 12” external diameter composite pipe with a 2 mm think liner and a 40 mm thick monolithic laminate was designed to fulfil the loading requirements. The layup of the monolithic
composite laminate is \([\{0^\circ\}, / (\pm\theta^\circ), / (90^\circ)\}^n\].ns.

Before you formulate the qualification programme it is important to consider the main loads acting upon the composite riser and how these translate to loading (short- and long-term) locally at a composite section. Use your engineering knowledge and skills and prepare sketches that show the critical loading conditions.

You will then have to consult the DNVGL-RP-F119 Recommended Practice for Thermoplastic Composite Pipes and prepare a test qualification plan covering all levels of the test pyramid, with attention to:

- What would be the safety and service class of the construction?
- How would you obtain test specimens?
- How would you replicate the environmental conditions in a laboratory?
- What would be the critical properties to be measured at a constituent and lamina level?
- How would you propose to quantify the performance at a laminate and pipe level?
- What are the most critical failure modes that need to be accounted for while executing the qualification plan?
- How many full scale tests will you suggest performing and under what loading scenarios?

**Reflection:**

The purpose of this exercise is to make you familiar with a Recommended Practice and the requirements this prescribes for, in this instance, offshore thermoplastic pipes. Through discussion with your peers during the class you should utilise general engineering and specific composite materials knowledge to devise a simple yet effective plan for qualifying the pipe structure. Only the general principles are required, rather than a detailed programme.
Devise a basic qualification programme for a deep-water composite riser

Resourcing:
You will need:

- A copy of DNVGL-RP-F119 Recommended Practice for Thermoplastic Composite Pipes
- A class with flip charts (one per 4 – 5 learners)
- A digital projector and laptop

Trainer’s Notes:
Try to maximize the learners’ decision-making in this practical. Create groups of 4 – 5 learners and encourage teamwork and the sharing of ideas.

Encourage learners to assign roles and responsibilities from the start of the exercise and decide how they will present their outcome to the rest of the group.

It is important that the learners:

- Identify the critical loading conditions before starting the device a qualification programme
- Make full use of the Recommended Practice and reference back to the document in their approach and decisions

The purpose of the exercise is for the learners to understand how to utilise accepted documentation to make decisions and present the outcomes to their peers.
Calculation of B-basis values for longitudinal compression strength of a carbon epoxy pre-preg material

Task:
You are going to plan a qualification test programme for characterising the B-basis compression strength (\(\sigma_{11}^c\)) design allowable for a unidirectional carbon epoxy pre-impregnated composite. The test programme requires you to measure the compression strength in accordance with ISO 14126 Fibre-reinforced plastic composites — Determination of compressive properties in the in-plane direction. The material you will be testing will be approximately 2 mm thick. Once the test is complete, you will derive the B-basis value using real data-sets provided to you.

N.B. You will undertake actual testing of compression coupons within a separate laboratory exercise as part of this training course.

Procedure:
Before you DO anything, you should:

- List the reasons why a material qualification programme is undertaken and what needs to be considered in its planning (10 mins)
- Outline the definitions for A- and B-basis design values (5 mins)
- For a single test environment, decide how many specimens should be tested and from how many batches of material to provide sufficient data-sets and measurements for the derivation of a B-basis design value (10 mins)

Activity 1: Test considerations

- Read through a copy of ISO 14126 and familiarize yourself with the procedures it contains (20 mins)
- Decide which specimen geometry you should use and produce a marked-up sketch indicating dimensions and tolerances (10 mins)
- List the equipment and procedure you will use to measure the in-plane compression strength (10
Decide upon the key factors that need to be considered and adhered to in order to minimize the uncertainty in your results (5 mins)

What are the factors that determine whether the tests you have undertaken are valid? (5 mins)

**Activity 2: Calculation of B-basis value:**

Analyze the data supplied to you according to the supplied procedure; assume that the data has a normal distribution. A set of specimens has been supplied to you which you can examine to aid judgement of the treatment of data. By the end of this session you should have calculated a B-basis design value.

- Did you identify any outliers in the data? If so, what was your thought process when deciding how to treat the outliers? Did you reject any outlier data points?
- Did you detect any variability between data sets?
- If the level of variability between data-sets was found to be low enough to justify pooling of data across data sets, did the check for outliers on the pooled data set indicate any outliers?
- If outliers were detected in, and rejected from, the pooled data set, did subsequent checks indicate that the data distribution was normal?

**Reflection:**

By the end of this exercise you will have:

- An appreciation of why and how qualification test programmes are carried out
- A basic understanding of a statistical approach used for deriving B-basis design values
- Experience of using your engineering judgement when dealing with outliers
Calculation of B-basis values for longitudinal compression strength of a carbon epoxy pre-preg material

**Resourcing:**
You will need:

- A copy of ISO 14126
- A copy of the B-basis derivation procedure and accompanying Excel spreadsheet
- A set of compression specimens containing specimens with incorrect dimensions/tolerances and failure modes

**Trainer’s Notes:**
Try to maximise the learners' autonomy and decision-making in this practical. However, teamwork and sharing of ideas can be improved by allowing them to work in pairs.

As you will be in a laboratory you will need to check the learners follow the Health & Safety procedures at all times.

It is important the learners identify the outliers in the data provided and provide appropriate reasoning.
This document is the software quality documentation for the Anderson-Darling spreadsheet. The associated software quality plan is qf-59_AndersonDarling.docx

User requirements:
The software has integrity level 2. The calculations are simple and will be cross-checked against a Matlab implementation, which will itself be checked against Matlab’s internal implementation of the normality test. The software will be used by external people but only within a training environment.

The software is required to implement a series of calculations to evaluate the k-sample Anderson-Darling test for sample consistency, and the Anderson-Darling test for sample normality on the pooled data.

The software will take in user-supplied data, generate the relevant statistics, and state clearly whether tests are passed or failed.

The software will be an Excel Spreadsheet created in version 15.0.5067.1000. The calculations are largely simple arithmetic and cell location commands with some use of the inverse normal distribution and are unlikely to be affected by version changes of Excel.

The acceptance criteria are defined as that the tests in the Testing section below are all passed. The software will be maintained on demand.

Functional requirements:
The inputs of the software are up to 10 samples, collectively totaling at most 100 data points.

Let the data points be \( \{x_{ij}, i = 1, 2, \ldots, k, j = 1, 2, \ldots, n_i\} \), where \( k \) is the number of samples and \( n_i \) is the number of points in the \( i \)th sample. Let \( n_1 + n_2 + \cdots + n_k = n \) be the total number of points. Then the outputs of the software are:

1. The \( k \)-sample Anderson-Darling statistic:

   \[
   ADK = \frac{n - 1}{n^2(k - 1)} \sum_{i=1}^{k} \left[ \sum_{j=1}^{N} \frac{(nF_{ij} - n_iH_j)^2}{H_j(n - H_j) - nh_j/4} \right],
   \]

   where \( h_{ij} \) is the number of values in the combined samples equal to \( x_{ij} \), \( H_j \) is the number of values in the combined samples less than \( x_{ij} \), plus half of the number of values in the combined samples equal to \( x_{ij} \), and \( F_{ij} \) is the number of values in the \( i \)th sample that are less than \( x_{ij} \) plus half of the number of values in the \( i \)th sample that are equal to \( x_{ij} \). Note that this formulation is not exactly that given in the slides, but it is mathematically equivalent. The extension of the sum from 1 to \( N \) is balanced by the removal of the multiplying factor \( h_j \).

2. The variance of \( ADK \):

   \[
   \sigma_{ADK}^2 = \frac{an^3 + bn^2 + cn + d}{(n - 1)(n - 2)(n - 3)(k - 1)^2},
   \]
Where:

\[ a = (4g - 6)(k - 1) + (10 - g)S \]  
(3)

\[ b = (2g - 4)k^2 + 8Tk + (2g - 14T - 4)S - 8T + 4g - 6 \]  
(4)

\[ c = (6T + 2g - 2)k^2 + (4T - 4g + 6)k + (2T - 6)S + 4T \]  
(5)

\[ d = (2T + 6)k^2 - 4Tk \]  
(6)

\[ S = \sum_{i=1}^{k} \frac{1}{n_i} \]  
(7)

\[ g = \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \frac{1}{(n - i)j} \]  
(8)

\[ T = \sum_{i=1}^{n-1} \frac{1}{i} \]  
(9)

3. The critical value, \( ADC \):

\[ ADC = 1 + \sigma^2 \left( 1.96 + \frac{1.149}{\sqrt{k - 1}} - \frac{0.391}{k - 1} \right) \]  
(10)

4. The Anderson-Darling test statistic for normality of the pooled data:

\[ AD = \sum_{i=1}^{n} \frac{1 - 2i}{n} \left( \ln(F_0[z_{(i)}]) + \ln(1 - F_0[z_{(n+1-i)}]) \right) - n \]  
(11)

Where the data have now been pooled to be \( \{x_i, i = 1, 2, ..., n\} \), and:

\[ z_i = \frac{x_i - \bar{x}}{s} \]  
(12)

\[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \]  
(13)

\[ s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2} \]  
(14)

5. The observed significance level:

\[ OSL = \frac{1}{1 + \exp(-0.48 + 0.78 \ln(AD^*) + 4.58AD^*)} \]  
(15)

\[ AD^* = \left( 1 + \frac{4}{n} - \frac{25}{n^2} \right) AD \]  
(16)

6. Cell defining whether each test is passed or failed.
The functions in different columns will carry out each of those calculations. Calculation of $S$, $g$, and $T$ (equations (7) to (9)) will be held on a separate locked sheet as they do not vary with sample values.

Performance is not a vital factor.

Usability will be addressed by providing a separate instruction sheet and using the same terminology as the associated training course.

Security of the sheet will be ensured by locking the majority of the cells.

The sheet will run on a standard NPL Windows laptop.

**Software design:**

Unless otherwise stated, all terms are on the sheet titled “Calculation”.

The user inserts the data in columns B and C and is told how to do so on the instruction sheet.

The calculations for each sum are carried out in the following cells:

1. The $k$-sample Anderson-Darling statistic:

   $$ADK = \frac{n - 1}{n^2(k - 1)} \sum_{i=1}^{k} \left[ \frac{1}{n_i} \sum_{j=1}^{N} \frac{(nF_{ij} - n_iH_j)^2}{H_j(n - H_j) - nh_j/4} \right],$$

   - $h_j$ is calculated in column N using countif and offset commands.
   - $H_j$ is calculated in column O using countif and offset commands.
   - $F_{ij}$ is calculated in columns P ($i = 1$), R($i = 2$), etc. up to AH ($i = 10$) using countif and offset commands.

   The terms summed over $j$ are calculated in columns Q ($i = 1$), S($i = 2$), etc, up to AI ($i = 10$), and each column is summed in row 2, using an offset command to ensure that only required values are included. Note that the $1/n_i$ has been moved inside the $j$ summation for ease of implementation.

   The sum over $i$ and the initial multiplication are carried out in cell I 19.

2. The variance of $ADK$:

   $$\sigma_n^2 = \frac{an^3 + bn^2 + cn + d}{(n - 1)(n - 2)(n - 3)(k - 1)^2}$$

   Where:

   $$a = (4g - 6)(k - 1) + (10 - g)S$$

   $$b = (2g - 4)k^2 + 8Tk + (2g - 14T - 4)S - 8T + 4g - 6$$

   $$c = (6T + 2g - 2)k^2 + (4T - 4g + 6)k + (2T - 6)S + 4T$$

   $$d = (2T + 6)k^2 - 4Tk$$
3. The critical value, $ADC$:

$$ADC = 1 + \sigma_n \left( 1.96 + \frac{1.149}{\sqrt{k-1}} - \frac{0.391}{k-1} \right)$$  \hspace{1cm} (10)$$

The value of $ADC$ is calculated in cell I18.

4. The Anderson-Darling test statistic for normality of the pooled data:

$$AD = \sum_{i=1}^{n} \frac{1-2i}{n} \left( \ln(F_0[z_{(i)}]) + \ln(1 - F_0[z_{(n+1-i)}]) \right) - n$$  \hspace{1cm} (11)$$

Where the data have now been pooled to be \( \{x_i, i = 1, 2, ..., n\} \), and:

$$z_i = \frac{x_i - \bar{x}}{s}$$  \hspace{1cm} (12)$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$  \hspace{1cm} (13)$$

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$  \hspace{1cm} (14)$$

The value of equation (13) is calculated in cell AL1, and the value of equation (14) is calculated in cell AL2.
The normalised data is calculated in column AL using equation (12).

The $z_i$ used in equation (11) are sorted in increasing order. In order to avoid asking the user to sort data, a set of countif and offset commands have been used to identify the values of $i$, $Z(i)$, and $Z_{(n+1-i)}$ (given in columns AN, AL, and AM respectively) as required for equation (11). These calculations are in columns AT to EP. Many of these columns will not be used for typical sample sizes, but offset commands are used to avoid any not-a-number problems.

The logarithms of the cumulative distribution terms used in equation (11) are calculated in columns AO and AP, and the term in the summation in equation (11) is calculated in column AQ.

The value of AD is calculated in cell I22.

5. The observed significance level:

$$OSL = \frac{1}{1 + \exp(-0.48 + 0.78 \ln(AD^*) + 4.58AD^*)}$$

$$AD^* = \left(1 + \frac{4}{n} - \frac{25}{n^2}\right)AD$$

The value of $AD^*$ is calculated in cell I23, and the value of OSL is calculated in cell I24.

6. Cell defining whether each test is passed or failed.

The decision on whether the data all come from the same population is displayed in cell I20.

The decision on whether the pooled sample comes from a normal distribution is displayed in cell I25.

**Software testing:**

The calculation is tested in three ways.

1. The values of $AD$, $\sigma_n^2$, and $ADC$ calculated by the spreadsheet are compared directly to a Matlab implementation of the same equations. This test software does not have separate quality documentation since a) they are exactly equations (1) to (10), and b) the linear and indexed nature of the equations makes them extremely simple to implement in Matlab.

2. The test data are designed such that one test data set will pass both tests, one test data set will pass the $ADK$ test but not the $AD$ test, and one will pass neither.

3. The value of $AD$ for the pooled sample is compared to that calculated by the Matlab function *adtest*, which carries out the Anderson-Darling test for normality.

The test data is held in the file AndersonDarling_WithTest.xlsx, but is removed from the release version.

Further tests have also been carried out to check the software for more than 3 samples (by subdividing the largest sample) and these were passed, but are not considered as part of the acceptance criteria so are not documented here.

**Test 1:** Generate three samples of sizes 10, 15 and 20 from a normal distribution with mean 0 and standard deviation and 1. Both tests should be passed, and the value of $AD$ should be the same as that produced by Matlab’s adtest function to three significant figures.
**Result**: Pass. Data used are given in table 1. Value of $AD$, $ADK$ and $ADC$ were 0.1781, 0.594 and 1.673 respectively.

**Test 2**: Generate three samples of sizes 10, 15 and 20 from a uniform distribution on the interval $[0,1]$. Only the $k$-sample Anderson-Darling test should be passed, and the values of $AD$, $ADC$ and $ADK$ should be the same as that produced by Matlab’s adtest function and the self-coded Matlab calculations to three significant figures.

**Result**: Pass. Data used are given in table 1. Values of $AD$, $ADK$ and $ADC$ were 1.249, 0.759, and 1.673 respectively.

**Test 3**: Truncate the samples used in test 2 so that the data contains replicates and repeat the test. Only the $k$-sample Anderson-Darling test should be passed, and the values of $AD$, $ADC$ and $ADK$ should be the same as that produced by Matlab’s adtest function and the self-coded Matlab calculations to three significant figures.

**Result**: Pass. Data used are given in table 1. Values of $AD$, $ADK$ and $ADC$ were 1.2616, 0.719, and 1.673 respectively.

**Test 4**: Create a sample of size 10 that is uniformly distributed on the interval $[0.3, 1.3]$; another of size 15 that is uniformly distributed on the interval $[0.6, 1.6]$; and one of size 20 that is uniformly distributed on the interval $[0.9, 1.9]$. Both tests should be failed, and the values of $AD$, $ADC$ and $ADK$ should be the same as that produced by Matlab’s adtest function and the self-coded Matlab calculations to three significant figures.

**Result**: Pass. Data used are given in table 1. Values of $AD$, $ADK$ and $ADC$ were 0.517, 4.019, and 1.673 respectively.
Table 1: Input values for each test.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Test 1 value</th>
<th>Tests 2 &amp; 3 value</th>
<th>Test 4 value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.99749</td>
<td>0.344199</td>
<td>0.667938</td>
</tr>
<tr>
<td>1</td>
<td>0.584885</td>
<td>0.227913</td>
<td>0.683587</td>
</tr>
<tr>
<td>1</td>
<td>1.394616</td>
<td>0.983344</td>
<td>0.35053</td>
</tr>
<tr>
<td>1</td>
<td>0.406205</td>
<td>0.884577</td>
<td>1.125261</td>
</tr>
<tr>
<td>1</td>
<td>1.15844</td>
<td>0.081704</td>
<td>1.128095</td>
</tr>
<tr>
<td>1</td>
<td>-1.57094</td>
<td>0.025952</td>
<td>0.596095</td>
</tr>
<tr>
<td>1</td>
<td>0.688322</td>
<td>0.95153</td>
<td>1.295529</td>
</tr>
<tr>
<td>1</td>
<td>-1.34215</td>
<td>0.626365</td>
<td>0.933522</td>
</tr>
<tr>
<td>1</td>
<td>1.562688</td>
<td>0.089556</td>
<td>1.17283</td>
</tr>
<tr>
<td>1</td>
<td>-0.06643</td>
<td>0.552144</td>
<td>0.328079</td>
</tr>
<tr>
<td>2</td>
<td>-0.64083</td>
<td>0.27315</td>
<td>1.529795</td>
</tr>
<tr>
<td>2</td>
<td>-0.70244</td>
<td>0.3861</td>
<td>0.664469</td>
</tr>
<tr>
<td>2</td>
<td>1.930602</td>
<td>0.955005</td>
<td>1.079013</td>
</tr>
<tr>
<td>2</td>
<td>1.665528</td>
<td>0.448767</td>
<td>1.208389</td>
</tr>
<tr>
<td>2</td>
<td>0.083537</td>
<td>0.061975</td>
<td>1.559836</td>
</tr>
<tr>
<td>2</td>
<td>0.84338</td>
<td>0.070925</td>
<td>1.16103</td>
</tr>
<tr>
<td>2</td>
<td>-2.12639</td>
<td>0.309934</td>
<td>1.383444</td>
</tr>
<tr>
<td>2</td>
<td>0.240374</td>
<td>0.252657</td>
<td>1.496177</td>
</tr>
<tr>
<td>2</td>
<td>-0.63142</td>
<td>0.796553</td>
<td>0.903378</td>
</tr>
<tr>
<td>2</td>
<td>-2.32635</td>
<td>0.067319</td>
<td>1.524677</td>
</tr>
<tr>
<td>2</td>
<td>0.747572</td>
<td>0.808818</td>
<td>1.162896</td>
</tr>
<tr>
<td>2</td>
<td>0.238494</td>
<td>0.130535</td>
<td>0.632331</td>
</tr>
<tr>
<td>2</td>
<td>-2.4117</td>
<td>0.191152</td>
<td>0.689063</td>
</tr>
<tr>
<td>2</td>
<td>0.318111</td>
<td>0.671129</td>
<td>0.793259</td>
</tr>
<tr>
<td>2</td>
<td>-0.66577</td>
<td>0.2291</td>
<td>0.764202</td>
</tr>
<tr>
<td>3</td>
<td>-0.03941</td>
<td>0.067987</td>
<td>1.047809</td>
</tr>
<tr>
<td>3</td>
<td>-2.46888</td>
<td>0.6854</td>
<td>0.944696</td>
</tr>
<tr>
<td>3</td>
<td>1.803094</td>
<td>0.147177</td>
<td>1.083565</td>
</tr>
<tr>
<td>3</td>
<td>-0.78304</td>
<td>0.555327</td>
<td>1.739988</td>
</tr>
<tr>
<td>3</td>
<td>1.26088</td>
<td>0.664467</td>
<td>1.682589</td>
</tr>
<tr>
<td>3</td>
<td>-1.34829</td>
<td>0.760569</td>
<td>1.771482</td>
</tr>
<tr>
<td>3</td>
<td>-0.59784</td>
<td>0.849665</td>
<td>0.972999</td>
</tr>
<tr>
<td>3</td>
<td>-0.38516</td>
<td>0.753371</td>
<td>1.562672</td>
</tr>
<tr>
<td>3</td>
<td>-0.10963</td>
<td>0.800647</td>
<td>1.200876</td>
</tr>
<tr>
<td>3</td>
<td>2.27959</td>
<td>0.720005</td>
<td>1.711761</td>
</tr>
<tr>
<td>3</td>
<td>-0.27597</td>
<td>0.810033</td>
<td>0.97519</td>
</tr>
<tr>
<td>3</td>
<td>2.07872</td>
<td>0.008884</td>
<td>1.761964</td>
</tr>
<tr>
<td>3</td>
<td>1.027182</td>
<td>0.093568</td>
<td>1.76413</td>
</tr>
<tr>
<td>3</td>
<td>-0.9002</td>
<td>0.412254</td>
<td>1.446509</td>
</tr>
<tr>
<td>3</td>
<td>0.344655</td>
<td>0.117104</td>
<td>1.391342</td>
</tr>
<tr>
<td>3</td>
<td>-0.73777</td>
<td>0.099122</td>
<td>1.163803</td>
</tr>
<tr>
<td>3</td>
<td>-0.27695</td>
<td>0.950055</td>
<td>1.73608</td>
</tr>
<tr>
<td>3</td>
<td>0.072346</td>
<td>0.4172</td>
<td>1.761492</td>
</tr>
<tr>
<td>3</td>
<td>-1.48627</td>
<td>0.383698</td>
<td>1.081312</td>
</tr>
<tr>
<td>3</td>
<td>0.302698</td>
<td>0.56627</td>
<td>1.518607</td>
</tr>
</tbody>
</table>
Interpretation and application of BS EN ISO 14126 Fibre-reinforced plastic composites – Determination of compressive properties in the in-plane direction

Task:
You are going to study and then apply an international standard for evaluating the compressive strength and modulus of a Fibre Reinforced Plastic (FRP) composite material. The standard you will use is BS EN ISO 14126 Fibre-reinforced plastic composites – Determination of compressive properties in the in-plane direction.

Procedure:
Before you DO anything, you should:
- Wear appropriate Personal Protective Equipment (PPE) as provided by the laboratory instructor
- Familiarize yourself with the Health & Safety instructions of the laboratory provided in a separate sheet

You will be provided with specimens prepared ready for testing. You should identify whether the specimens are in scope and can be tested following the principles of this standard. You should also identify whether the equipment is appropriate, and if the fixture follows the standard’s requirements and is set-up correctly. The laboratory instructors will perform the test; however, you will have to ensure they are following the procedure within the standard correctly. At the end of this exercise you will calculate the compressive strength and modulus of the material and make a judgment on whether this is acceptable based on the requirements of the standard.

- Read through the copy of BS EN ISO 14126 and familiarize yourself with the procedures it contains
  - Identify whether this is a harmonized standard
  - Identify which committee prepared the standard
  - Identify which standard this one supersedes
  - Identify which documents are consulted and what key issues this standard addresses
- You have been provided with a set of unidirectional carbon fibre reinforced epoxy specimens
• Is the material in scope?
• Make a list of all the checks and measurements you need to perform on the specimens prior to testing
• Have the specimens been machined correctly?
• Is the geometry of the specimen in line with the standard’s requirements?

- Consider the various strain measurement techniques and suggest an appropriate one for the specimen and material that satisfies the requirements of the standard
- For the test equipment and fixture
  - Identify if the load cell is appropriate for the measurement to be performed
  - Check whether the indicated load cell is within the tolerances indicated by the standard
  - Suggest and perform checks to conclude whether the fixture has been set-up correctly
  - Suggest a spot check approach for the speed of the test
- What are the factors that determine whether the test you have undertaken is valid?
  - Check that the test is valid
  - Calculate and report the compressive strength and modulus for the specimen

**Reflection:**

By the end of this laboratory exercise you will have:
- An appreciation of the structure of an international standard
- Experience in using an international standard to test a composite material
- An understanding on judging the results of a test according to an international standard
Interpretation and application of BS EN ISO 14126 Fibre-reinforced plastic composites — Determination of compressive properties in the in-plane direction

Resourcing:

You will need:

- Appropriate PPE that will be provided by the laboratory instructor
- A copy to the Health & Safety procedures relevant to the exercise you will be performing
- A copy of ISO 14126
- A set of five untested compression specimens of glass woven fabric reinforced epoxy composite, of which one should be strain gauged and ready for testing
- Two of the untested specimens should be deliberately cut to be outside of the required tolerances

Trainer’s Notes:

Try to maximize the learners’ autonomy and decision-making in this practical. However, teamwork and sharing of ideas can be improved by allowing them to work in small groups.

As you will be in a laboratory you will need to check the learners follow the Health & Safety procedures at all times.

It is important that the learners identify which specimens are out of tolerance and should not be tested.

It is equally important that the learners perform all appropriate check to the equipment and the fixture, and elaborate on the factors that determine whether the test they have undertaken is valid.