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Characterisation of reinforcement fabrics by fractal dimension

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CHARACTERISATION OF REINFORCEMENT FABRICS BY FRACTAL DIMENSION

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ABSTRACT

During lamination of fibre-reinforced polymer matrix composites, there is a potential risk that the operator may use fabric from the wrong roll. This could severely change the desired mechanical properties of the component. This paper presents a novel system that might be implemented within a quality system to ensure use of the correct fabric. Three carbon fibre reinforcement fabrics (300 gsm plain weave, 320 gsm single-tow twill and 375 gsm double-two twill) were characterised. Images were acquired using a high-resolution scanner**,** converted into binary, then analysed using ImageJ/Fraclac software. The slope of the Richardson Plot is the Fractal Dimension (FD). The three fabrics each had a distinct FD value, in the undeformed condition and when sheared up to 30° (the locking angle).

1. INTRODUCTION

1.1 Fractal dimension

A point in space has zero dimensions, a line has one dimension, an area has two dimensions, and a volume has three dimensions. A standard formula is $N = r^D$, where D is the exponent and r the magnification factor. In Euclidean geometry, D has to be an integer. Mandelbrot [1] introduced the concept of fractals and self-similarity (e.g. Sierpiński Triangle, or Koch Snowflake), which can be quantified as Fractal Dimension (FD). FD occurs when D is a real number, and can be determined by rearranging the equation for D. FD determination is automated within ImageJ software [2] with the FracLac plugin [3]. For patterns with, or without, self-similarity, either the Richardson Plot (length estimate *vs* length of scale is linear on a log-log plot) or the Box Counting Method (BCM) are applicable [4-7].

1.2 Image analysis of composite sections and surfaces using FD

A number of authors in Plymouth [8-10] have used optical microscopy with image analysis of cross-sections of composite plates to quantify the fibre distribution as FD. The mechanical properties and permeabilities correlated to FD. Mahmood [11] investigated Resin Rich Volumes (RRV) in fabric-reinforced composites and correlated data to FD. Labrosse et al [12] used FD to characterise surface finish on gel-coated composites.

1.3 The research question

It is an inherent characteristic of woven reinforcement fabrics that they have a repeating pattern. The principal weave styles used in composite materials and structures are plain weave, twill weave and satin weave. The weave style determines the mechanical and physical properties of the composite. The nature of the fabric is clearly evident from the colour: aramid (gold), carbon (black) and glass (clear). However, the discrimination of the fabric style requires greater skill. An inexperienced laminator, or an automated system without some form of mistake proofing, could take fabric from an incorrect roll with potential consequences for product performance. This use of FD to characterise images of reinforcement fabrics could be the basis of a novel, cost- and time-effective characterisation technique embedded in manufacturing quality systems.

2. EXPERIMENTAL METHODS

2.1 Materials

Three fabrics, woven with 6K tow carbon fibre, (Table 1) were studied. The fabrics were woven for an earlier project [10] by Carr Reinforcements Limited (Stockport, UK). The loom was reset for a continuous series of weave style using the same warp and weft fibres throughout.

Table 1: The carbon fibre fabrics examined in this study:

Fabric style	Areal weight (gm^{-2})	Warp tows/m	Weft tows/m
Plain weave	300 g/m^2	380	380
Single tow twill (STT)	320 g/m^2	380	420
Double-tow twill (DTT)	375 g/m^2	380	380

2.2 Image acquisition and analysis

After initial trials to establish reliable working methods, images of A4 sized samples of each of the fabrics were acquired on an Epson V700 (G32W007839) high-resolution scanner. Three master images were acquired for each fabric, then 1440 pixel high by 1080 pixel wide parent images were taken avoiding the edges of the master image. Each image was opened in ImageJ (Image > Type > 8 bit), manually thresholded (Image > Adjust > Threshold), converted to binary (Process > Binary > Make Binary) and analysed using the Fraclac add-in to determine FD (Analyze > Tools > Fractal Box Count). The FD value is shown on the graph in the software. Thresholding is subjective and was eliminated from the process after initial trails to obtain an objective data point. Typical images at the different analysis stages are shown in Figure 1 (no threshold).

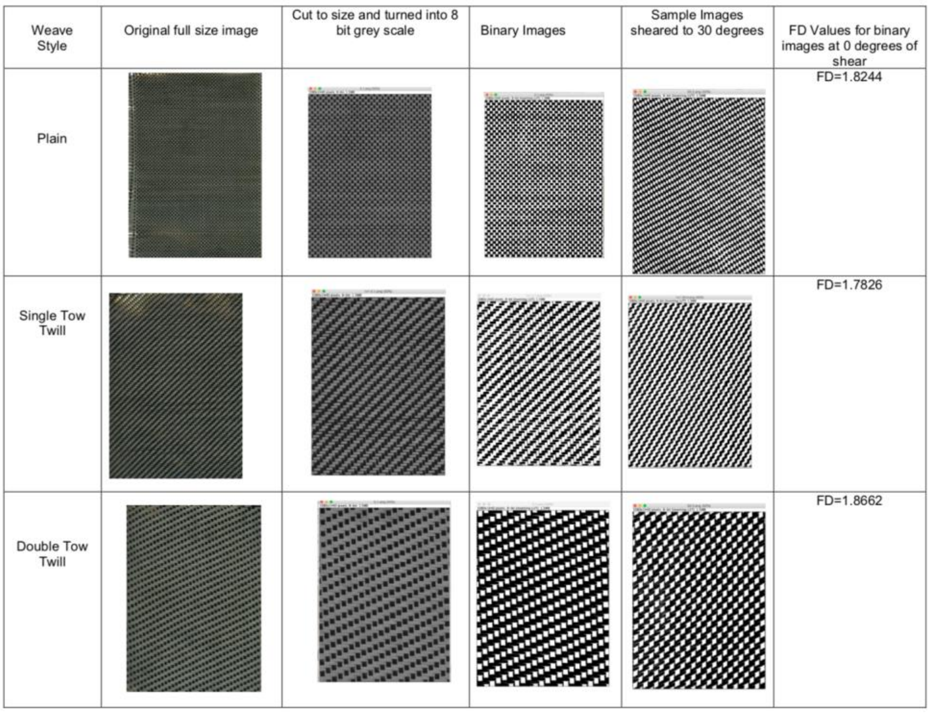

Figure 1: Processing from original scanned image to analysed cut-to-size image and FD.

3. RESULTS

3.1 Fractal dimension for three weave styles

To assess the reliability of the analysis, 12 quarter-size images were extracted from each parent image. The FD for each image, ranked in ascending order, is plotted in Figure 2, along with the data points for the respective parent images.

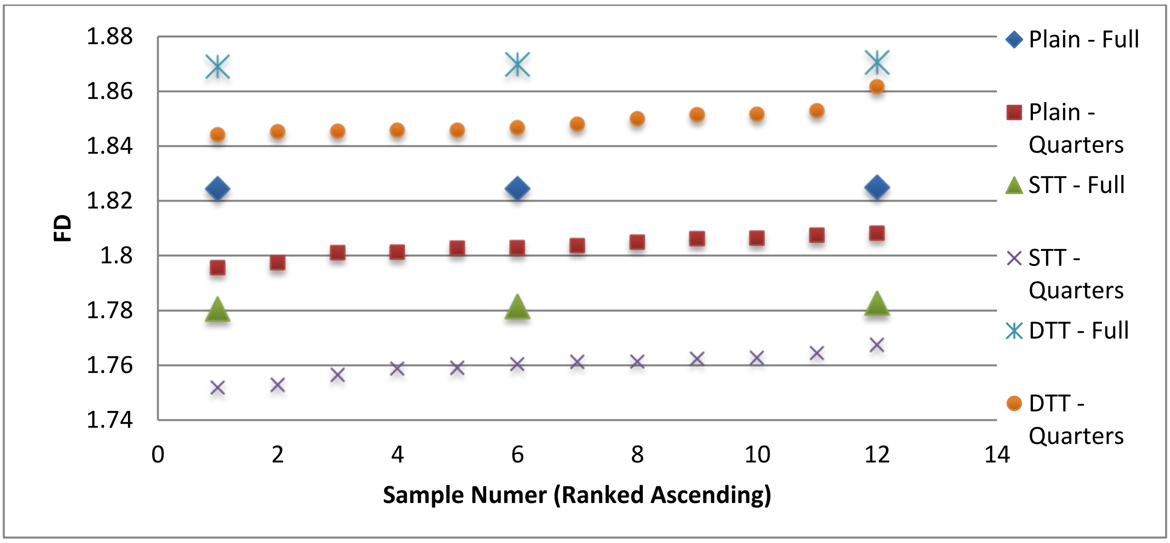

Figure 2: FD values of three fabrics for the different weaves

3.2 Fractal dimensions for sheared fabrics

Fabrics were sheared (simple shear) at 10° increments, up to the locking angle at 30°, before scanning. Figure 3 shows 48 data points (three fabrics, four parent images, four shearing angles). The data for each fabric lies in a distinct band and the highest coefficient of variation within a dataset is 0.18%.

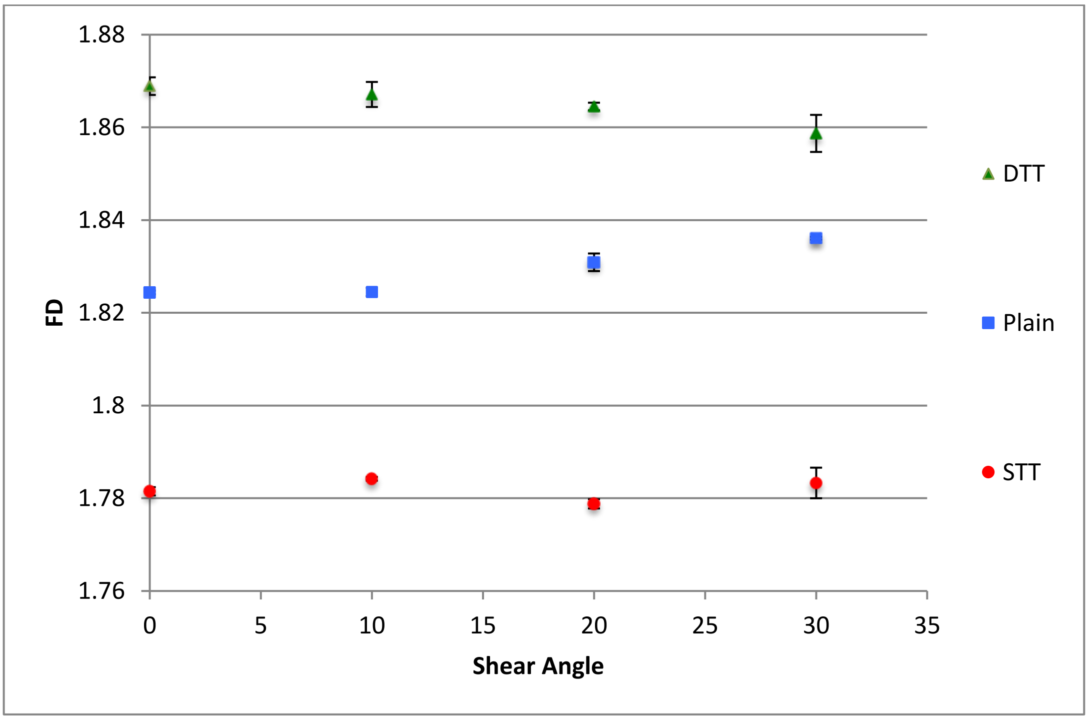

Figure 3: Variation of FD with shearing angle for three fabrics

3.3 Fractal dimension *vs* inside or outside the roll

To establish whether there was an effect of samples being taken from inside or outside the roll, six new samples were cut from the plain weave fabric and labelled according to edge/centre and front/back. The FD derived from a total of 192 images were analysed and plotted in Figure 4 on a compressed y-axis. Figure 5 presents summary data for the different sides of the roll.

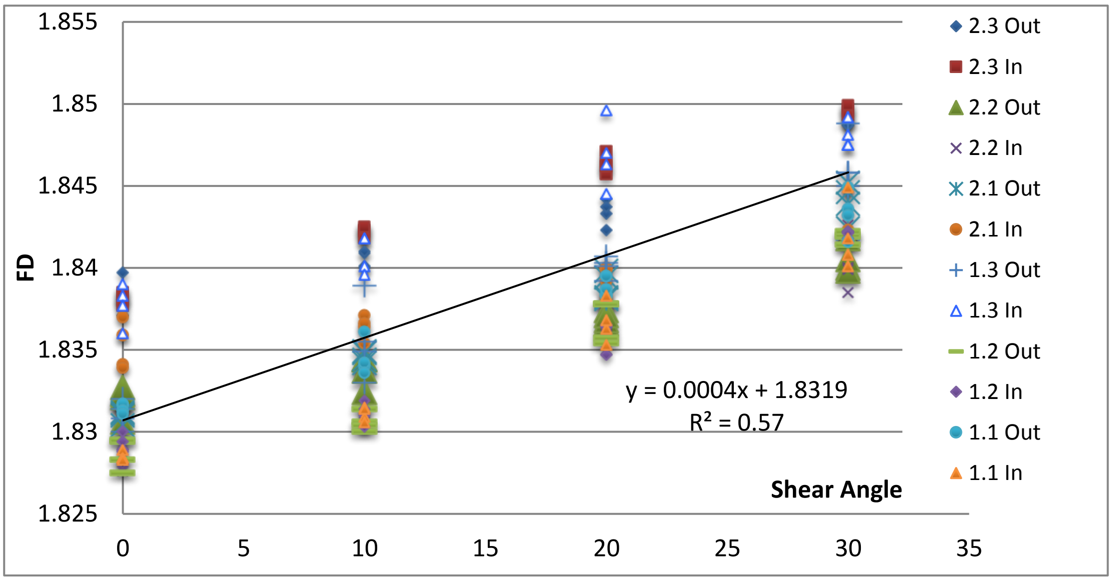

Figure 4: FD variation with position, side of roll, and shearing angle for plain weave fabric.

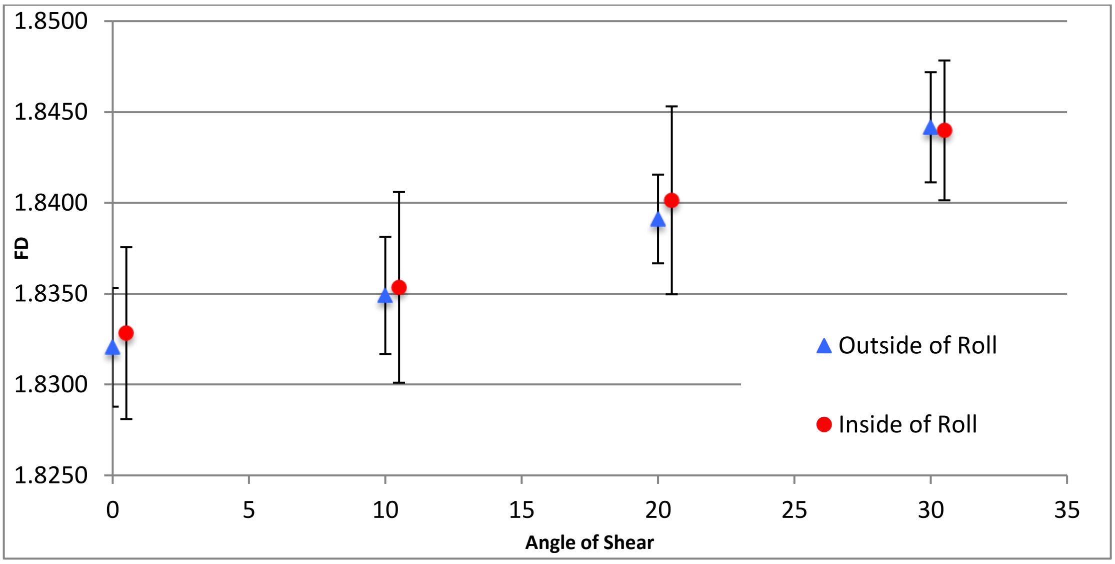

Figure 5: Mean ± one standard deviation for 24 images in each condition (192 data points analysed: coefficients of variation < 0.3%).

3.4 Fractal dimension for randomly sampled images

Images were extracted from the parent/master image using a random number generator to select the top/left coordinate. Table 2 and Figure 6 present the data for STT and DTT fabrics at four shearing angles.

Table 2: Mean ± standard deviation (coefficient of variation %) for random fabric images

Shear angle	**0°**	**10°**	**20°**	**30°**
DTT fabric	1.8655±0.0007 (0.04)	1.8649±0.0013 (0.07)	1.8654±0.0027 (0.14)	1.8630±0.0026 (0.14)
STT fabric	1.7819±0.0011 (0.06)	1.7850±0.0010 (0.06)	1.7799±0.0018 (0.10)	1.7837±0.0020 (0.12)

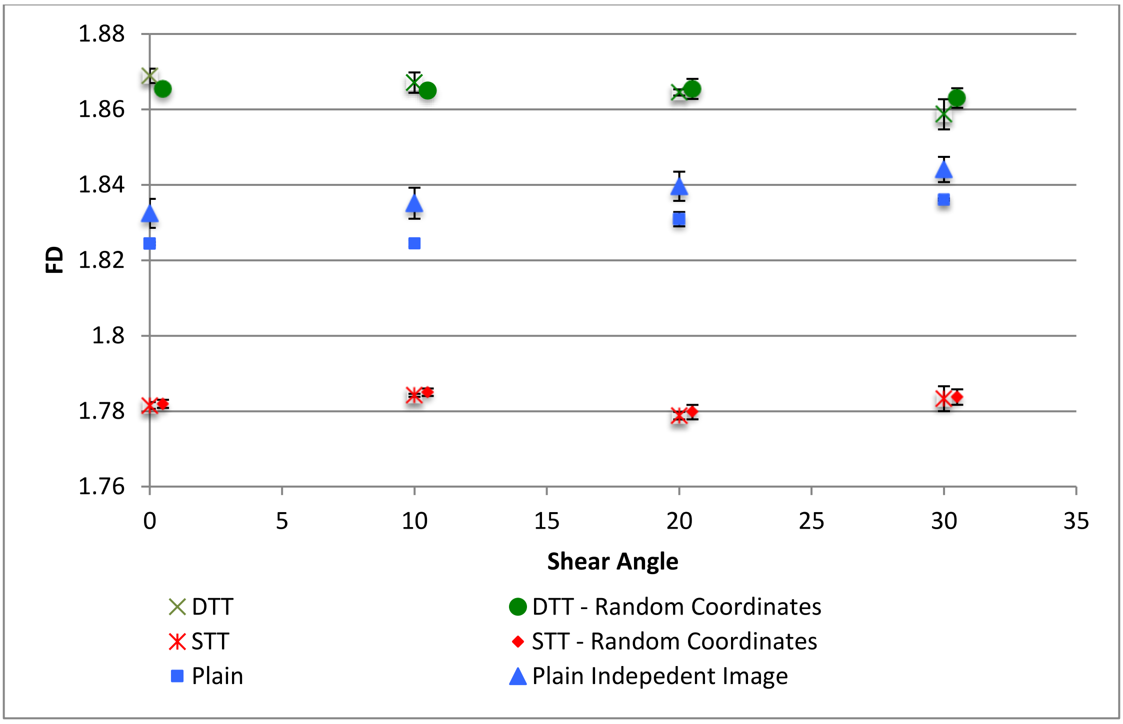

Figure 6: Mean FD ± one standard deviation for all sheared fabric images (random image data points offset by 0.5° for enhanced visibility)

To establish the effect of image processing, a series of analyses were run using the median FD image reflected (left-right), inverted (top-bottom) and both reflected and inverted. Processing the image increased the FD very slightly. Processing and returning to the original image returned the FD to the original value. Figure 7 presents the data from these processed images.

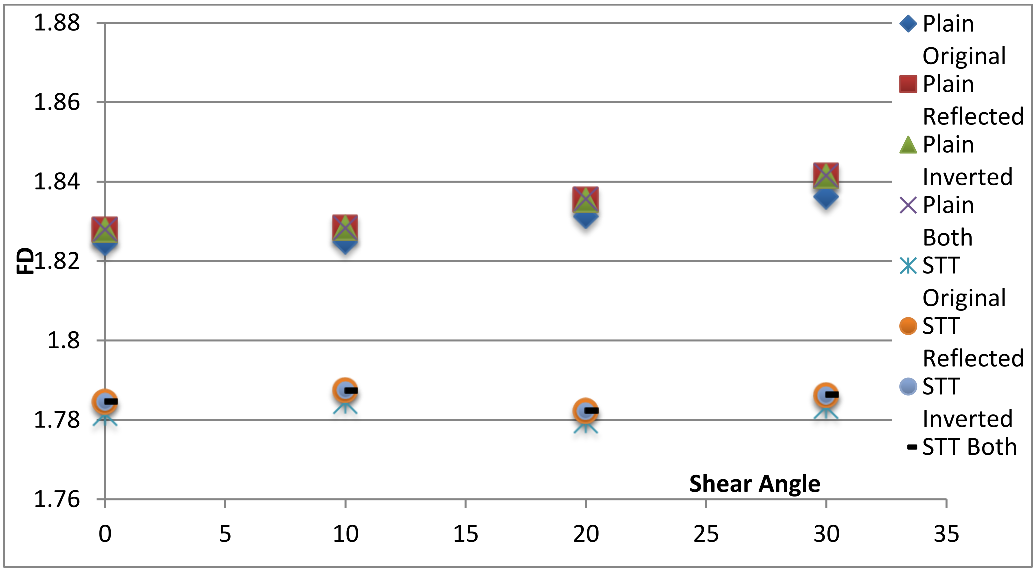

Figure 7: Fractal dimensions for processed (reflected/inverted/both) images.

4. DISCUSSION

4.1 Limitations of the study

The study reported here only considered woven biaxial carbon fibre fabric reinforcement. Further work ids needed to eastblish FD values for unidirectional and/or stitched fabrics and for aramid or glass fabrics.

When images of the fabrics were scanned, the positioning of the warp and weft fibres was undertaken by eye and global and/or local misalignment may have occurred. The shearing of the fibres was undertaken with care, but the process may have resulted in some fibres not remaining parallel to their companions. These potential errors probably reflect the situation in a real manufacturing facility.

Notionally identical scanners were used on different days. As the highest coefficient of variation is just 0.25%, the technique would appear to be insensitive to the specific equipment used.

4.2 Future work

In order to implement the system into a manufacturing situation it would be appropriate to establish the imaging system resolution necessary to achieve the reliability obtained in the experiments reported here. The use of digital SLR cameras or even mobile phone cameras may be practical subject to validation of the capability. It would also be sensible to establish the sensitivity of the system to lighting variations within the workplace.

It would be interesting to consider how the in-plane image FD and the laminate cross-section FD vary and to determine factors affecting that correlation (e.g. fibre volume fraction in the laminate.

5. CONCLUSIONS

This study used a high-resolution scanner to obtain digital images of three carbon fibre reinforcement fabrics (300 gsm plain weave, 320 gsm single-tow twill and 375 gsm double-two twill). Those images were processed and analysed using Image software with the FracLac add-in to obtain a fractal Dimension (FD) for the image. Each of the three fabrics had a distinct FD with very low coefficient of variation regardless of sample position or shearing angle. The techniques described in the paper may form the basis for a novel system that might be implemented within a composite manufacturing quality system to ensure use of the correct fabric.

6. ACKNOWLEDGEMENTS

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