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Aljuboury, Muhsin

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Bolted FRP flange joints for pipelines: A review of current practice and future challenges

Muhsin Aljuboury*, Md Jahir Rizvi, Stephen Grove, Richard Cullen

School of Engineering, Plymouth University, Plymouth, UK, PL4 8AA

*Corresponding author:

Email: muhsin.aljuboury@plymouth.ac.uk

muhsin.aljuboury@yahoo.com

Phone: +44 7778489984

Abstract

Metallic bolted flange and pipes have both been increasingly replaced by fibre reinforced polymer (FRP) materials in many applications which deal with extreme harsh environments such as oil, chemical, marine, etc. This is not only due to the FRP material's resistance to chemical reaction but also due to their inherent mechanical properties of high strength to weight ratio. However, very little research has been published regarding bolted flange joints made of FRP materials. Also, the availability of standards and relevant design codes are very limited for bolted FRP flange joints. Hence, the design guidelines, dimensional considerations and selection of fabrication methods for bolted FRP flange joints have yet to be optimized fully. For instance, the ASME Boiler and Pressure Vessel Code, section X and ASME PCC-1-2013 appendix O or other similar standards do not include specific rules for the design of bolted FRP flange joints. As a result, it is difficult to understand the consequences on the reliability of FRP flanges made with parametric variations and dimensional alterations. This has led the authors to carry out research to maximise the performance of bolted FRP flange joints through a series of experimenters and numerical simulations. The present article will focus on the available techniques to manufacture bolted FRP flange along with associated issues and possible challenges compared to metallic flanges.

Keywords: Bolted FRP flange joint, metallic flange joint, gasket, piping, adhesive bonding

Nomenclature:

<i>BFJ</i>	Bolted flange joint
<i>FEA</i>	Finite element analysis
<i>FFG</i>	Full faced gasket
<i>RTJ</i>	Ring Type Joints
<i>FRP</i>	Fibre reinforced plastics
<i>GRP</i>	Glass fibre reinforced polymers
<i>SWG</i>	Spiral wound gasket

1. Introduction

Bolted flange joints are increasingly used in pressure-containing equipment, such as pressure vessels and pipes, due to the convenience in forming reliable joints between two pieces of equipment. Most of these flanges are made of traditional (mostly metallic) materials. However, in many applications, such as offshore applications or chemical process industries, the corrosion resistance of these materials is low compared with non-metallic alternatives such as polymer composite materials. A study in the USA indicated that during the 1980's, the cost of corrosion was approximately \$8 billion/year, and that 60% of the US steel output went into replacement products [1]. A further study [2] in the USA has claimed that the annual direct cost of corrosion for drinking water and sewer systems was \$36 billion/year and for the gas-distribution network it was \$5 billion/year [2]. Hence, the high costs of installation and/or maintenance of the equipment and products made of conventional materials have led designers and engineers to find sustainable solutions to corrosion problems. One possibility solution is to use a material with good corrosion resistance, such as composite materials (fibre reinforced plastics), instead of metals.

Continuous fibre reinforced composites are attractive in pressure vessels, pipelines, marine, automotive, aerospace, sporting goods and infrastructure industries due to their unique combination of properties which includes high strength and modulus to weight ratios and high corrosion resistance [3, 4]. For instance, the weight of a 12 inch diameter pressurized fuel line for carrying liquid hydrogen in a space shuttle has been reduced by 20% when it has been manufactured from composite materials [5]. In addition, fibre reinforced plastics (FRP) has a long life expectancy, less environmental concerns and low installation and maintenance costs [6]. Another important advantage of FRP is that the designers have the ability to vary the material properties for a specific application. For example, high resin content provides maximum corrosion resistance; high glass content provides maximum strength. Therefore, the designers can combine these two elements to produce a satisfactorily reliable design. Similarly, they can also vary the mechanical properties by changing the directions of the fibres to sustain multiaxial sheet move efficiently.

In spite of the good performance of FRP materials in pressure vessels and piping systems over the last four decades, only a few publications [6, 7] can be found regarding bolted FRP flange joints. In addition, standardization and the relevant design codes are inadequate. Currently, all design methods are modified from their equivalent metallic design methods, neglecting the different behaviour of composite flanges [7].

2. Literature review

The bolted flange joint (BFJ) includes flange, hub, pipe, gasket and bolts. Based on the geometry, flanges can be categorized into many types which will be described below. Some flanges can be manufactured from non-metallic materials such as FRP composites; these are the full faced gasket and raised face flanges. On the other hand, the O-ring gasket, ring gasket, tongue and groove and male and female flanges cannot be manufactured using composite materials due to geometric complexity near the contact faces.

2.1 Overview of metallic bolted flange joints

Based on the contact faces, bolted flanges are categorized into several types. The main purpose of these categorizations is to seat the sealing gaskets to meet the requirements of the design conditions, such as internal pressure and design temperature specified by ASME B16.5 [8] and B16.47 [9]. Among others, most common flanges are the full face gasket, ring

gasket, O-ring gasket, raised face, male-female and tongue-groove flanges. All these flanges, will be discussed later.

Full faced gasket flanges (FFG), are also known as full faced gasket (FFG) flanges as the entire contact faces are covered by a gasket (Fig. 2.1.a). Therefore, the gasket will sit on the same plane as the bolting circle. The FFG flange provides a good resistance against the bending moment produced by the bolt-up force. However, this type of flange with full face gasket requires a high bolting force to maintain the seal. This is due to the large area of contact which needs more pressure to deform the gasket into the irregularities within the contact areas of the mating flange faces. Thus, the FFG flange is preferred for low-pressure applications with a soft gasket. In addition, it is most common to use FRP materials or brittle materials such as cast iron to produce this type of flange. These materials provide resistance to bending moments produced by the flange rotation [4].

Ring Type Joints (RTJ), as shown in Fig. 2.1.b, have two identical grooves cut into flanges faces. A soft metal (self-energizing) octagonal or oval gaskets is placed between these identical grooves. By applying compressive stress through bolt force, the “soft” metal gasket deforms into the grooves of the flanges, which are made of materials harder than the gasket, and creates a very tight and efficient seal. In addition, the metal-to-metal contact takes place outside of the bolt circle so that the rotation and the bending moment of the flange are very limited. However, high fabrication accuracy is required for maintaining the dimensions of the gasket grooves in order to achieve the required tightness. Ring type joints are used for high pressure and/or high-temperature applications such as power plant, petroleum, petrochemical and refineries [10]. Therefore, this type of flange is rarely manufactured with FRP materials [11].

Flat ring gasket flanges have physical geometry similar to the FFG flange, but both the gasket shape and the applications are different. This type of flange uses a flat ring gasket that sits at the inside area of the bolt circle. Therefore, no contact occurs between the flanges outside the bolt circle and this leads to rotation of the flange when the connection is tightened. This rotation also produces high bending stresses at the hub-flange intersections. These bending (axial) stresses with hubless flanges (Fig. 2.1.c1) are higher than those with the hubbed flanges (Fig. 2.1.c2) [7]. This difference is due to the additional materials that resist rotation in the hubbed flange. However, these flanges are simple in shape and easy to manufacture. Both metallic and the non-metallic gaskets are used with this type of flange. The main use of the ring gasket flange can be found in low and medium pressure applications.

Fig. 2.1: Bolted flange (a) Full face gasket flange, (b) Ring type joint and (c) Flat ring gasket flange.

Raised face flanges (Fig. 2.2.a) have the area inside the bolt circle higher than the bolting surface area. This is to reduce the contact area between the flange and the gasket and to achieve high pressures on a small gasket area. Consequently, the pressure containment capability of the joint increases but a high flange rotation, which is considered one of the disadvantages of this flange, is produced in the hub region due to the moment of the bolt force, and hence no flange contact outside the bolt circle is established [11]. Nevertheless, many types of gaskets are used with this type of flange such as flat ring, spiral wound and double-jacketed. Raised face flanges are very popular for applications that have medium and low-pressure service.

Tongue and groove flanges have matched faces. One of the flange faces has a rib (tongue) machined on its face, while the mating flange face has a groove (Fig. 2.2.b). The gasket is placed onto the groove and it cannot be pushed to the outside due to the hydrostatic force produced by the internal pressure [11]. The main difference between this flange and the O-ring gasket flange is that it has a raised ring on one flange face and a groove on the other face of the mating flange, whereas the O-ring gasket flange has two identical grooves on each matching flange face [11]. Advantages include self-alignment, evenly distributed compressive forces on the gasket, less erosive or corrosive contacts of the gasket with the fluid in the pipe and better sealing performance. However, the replacement of the gasket is very difficult for some applications and this leads to damage to the flange especially for high-

temperature applications. Also, this type of flange incurs high manufacturing costs [10]. The main applications are pump covers, valve bonnets, toxic fluids and explosives.

Fig. 2.2: Metallic flanges: (a) Raised face flange (b), Tongue and groove flange and (c) Male and Female flange.

Male and female flanges have two matched faces. One of the mating flanges (male) has a ring area that is extruded from its contact face. The other mating flange (female) has a groove machined into its face. The gasket is squeezed into a narrow place and is prevented from moving by the outer surfaces of the female flange (Fig. 2.3.c). This flange differs from the tongue and groove and the raised face flanges because both the inside diameter of the extruded area of the extruded ring and the matched depression extend into the flange base. This retains the gasket on its outer diameter and makes it distinct from both the tongue and groove flange and the raised face flange [11]. The flange is easy to assemble and can be used in any position. Its sealing is very good and better than the raised face flange. Thus it is used for higher service pressures than the raised face flange but lower than those used with the tongue and groove flange. This type of flange is also used with heat exchanger shell to channel and cover flanges.

2.2 Overview of composite bolted flange joints

Bolted flange joints made of fibre reinforced plastic (FRP) are widely used in many industries such as chemical, power plants, petrochemical and offshore oil and gas industries. This is because the systems in these industries usually include pumps, valves and other fittings that require periodic removal for maintenance. The FRP bolted flanges were developed in response to significant corrosion problems with either metallic and non-metallic pipes [12]. In addition, the use of composite flanges to connect composite pipe helps to avoid the mismatches during thermal expansion of metal connecting pieces and composite pipes [13].

In this study, full face gasket (FFG) flange has been chosen for study. As the gasket covers all its face, the FFG flange has a good ability to reduce or minimize the applied bending moment. It has therefore become attractive to designers, especially for use with brittle materials such as cast iron, glass, porcelain and other ceramic materials [14]

2.2.1 Materials system

2.2.1.1 Matrix Materials

The main purpose of the matrix in a composite material is to support the fibres and to transfer the load between them. In the through-thickness direction of composites (at right angles to the plane of the reinforcement), mechanical properties are very much matrix dominated, and designers must pay particular attention to transverse interlaminar shear stresses. These matrix-dependent properties are also affected by the operating temperatures. Moreover, the matrix protects the fibres from the environment such as water absorption, chemical or acidic attack as well as mechanical abrasion. Generally, matrix materials can be polymer, metals or ceramic. Due to the low costs and the ease of manufacturing, thermosetting polymer matrices (such as polyester, epoxy and vinylester) are commonly used in composites structures [15].

Polyester resins are widely used in applications such as tanks, pipes, liners, automobiles and aircraft, that require good resistance against water, chemical attack and the effects of weather [6, 15-18]. Polyester resins are; low in cost, fast in cure, have relatively high shrinkage [16] and good mould-releasing capability after curing. In addition, they have high insulation, high UV resistance and moderate strength. Moreover, polyester resins are very versatile. At room temperature, the liquid polymer is stable for months or even years. In spite of its great stability characteristics, it can be triggered to cure within few minutes by adding a peroxide catalyst [15, 19, 20].

Epoxy resins provide the higher mechanical performance, good resistance against corrosion and chemical attack and lower water absorption compared to other commonly-available resins [6, 15, 16]. They are used with various fibres reinforcement for many composite structures such as aircraft, missiles, boats and automotive. In addition, epoxy resins are used as adhesives, caulking compounds, casting compounds, sealants, vanishes and paints. Epoxies are cured quickly and easily at temperatures between 5°C and 150°C (depending on the curing agent) without releasing any volatiles. This results in low shrinkage (1.2% - 4% by volume), and hence helps to achieve accurate dimensions of fabricated structures. However, epoxy resins are more expensive and care is required with regard to mould release. [17, 19].

Vinyl ester resins are widely used in chemical-resistant FRP equipment such as pipe, ducts, scrubbers, flue stocks and storage tanks, which represent their largest commercial usage of vinylester [17]. This type of resin has excellent resistance to acid, base, solvents, hypochlorites and peroxides and can be used in a neat form (e.g. no diluent). Moreover,

vinylester resins are superior to the polyester resins due to low viscosity and fast curing as well as are superior to the epoxy resins due to better chemical resistance and tensile strength. Vinylester resins have less volumetric shrinkage upon curing compared to polyester resins but the shrinkage is greater than epoxy resins. The cost of vinylester resin lies between the costs of epoxy and polyester resins. However, vinylester resins exhibit only moderate adhesive strength because of high volumetric shrinkage values [6, 15, 16].

2.2.1.2 Fibres reinforcement

Glass Fibres are widely used as reinforcements for general composites due to better hardness, corrosion resistance and inertness properties. Furthermore, they are flexible, lightweight and cheaper than most other relatively high modulus fibres. Glass fibres are divided into five types. E - Glass fibres are preferred where high tensile strength, good corrosion or chemical resistance and low costs are required. S and R glass fibres are used where enhanced mechanical properties are required but the cost is three to four times higher than that of E-glass fibres. C-glass fibres are used for corrosion resistance in an acid environment. D-glass fibres are used for dielectric properties in electrical applications [15, 21].

Carbon fibres are lightweight, stiff and strong. These fibres are usually available either as "high-modulus" or "high strength", and are dominant in aerospace applications, where high performance and weight saving are economically justified. In addition, carbon fibres have good fatigue strength, moderate thermal conductivity and have a very low coefficient of linear thermal expansions (CTE). In contrast, carbon fibres have low impact resistance, low strain-to-failure and moderate electrical conductivity, which may cause electric shock or short-circuiting in unprotected electrical machinery [15, 19].

Aramid fibres are man-made organic polymer and are known for their ability to absorb impact energy. They have low density and high strength [15, 16, 19]. Aramid fibres have very low thermal conductivity and very high vibration damping. There are several disadvantages of aramid fibres, including low compression strength and temperature dependent mechanical properties (approximately 75-80% of tensile strength is lost at 177°C). Aramid fibres are very sensitive to ultraviolet radiation and a significant percentage of tensile strength is lost during prolonged direct exposure to sunlight.

2.2.2 Manufacturing techniques of GRP flange

There are various fabrication processes to combine fibre reinforcements and resins for producing composite components or structures. The American Society of Mechanical Engineers (ASME) [22] has recommended four methods for producing GRP flanges: contact moulding, filament-winding, resin transfer moulding and vacuum infusion process.

Contact moulding or hand lay-up is a simple, low cost process and suitable for large structures. This is an open moulding process and only one male or female mould is used. The layers of fibres (in the form of mat, woven roving and cloth) impregnated with resin are placed inside the mould and compacted using a roller to eliminate air bubbles and to facilitate uniform resin distribution. This process is repeated many times until the required thickness is reached. Usually, curing of hand lay-up is done at ambient temperature but heating could be applied to accelerate the process. It is a slow process (up to 500 units per year per mould) [6, 15, 21, 23].

Filament winding is primarily used for hollow products such as pipes, pillars, storage tank and containers. This is done by impregnating continuous fibre reinforcement with resin, then winding onto a rotating mandrel using a delivery eye. The delivery eye moves back and forth along the axis of the mandrel, so the angle of the fibre orientation and the thickness of the composite laminate are both dependent on the mandrel's rotational speed and the linear speed of the delivery eye. Various physical strengths can be obtained by varying the winding angle of the fibre. Most commercial companies prefer to use this process to fabricate GRP flange due to its high production rate (up to 500 kg of composites per day) [15, 16, 23].

Resin transfer moulding (RTM) injects pre-catalysed resin (at relatively low pressure) into a matched mould cavity containing fibre reinforcement. The dimensions of the product are directly controlled by the tool cavity thus a moulding of consistent shape and weight can be obtained. The advantages of this technique are: (1) the fibre volume fraction can be controlled very well; (2) usually very consistent mechanical properties; (3) a wide variety of resin systems and fibre reinforcements can be applied; and (4) very complex components can be produced. However, matched moulds with high dimensional accuracy as well as higher capital costs of equipment and moulds are required [24-26].

Vacuum infusion process (VIP) produces higher quality in contact moulding by sealing a polymeric bag to the periphery of the mould process (Fig. 2.3). A vacuum is drawn under the bag, thus applying up to 1 bar of consolidation pressure, which removes trapped air and increases the fibre content of the composite. This method is also suitable for production of large, high quality, lower cost composite parts. [23, 24, 27]. It is widely accepted that the advantages of the vacuum infusion method supersedes the disadvantages. This Method is one of the good methods that can be used to manufacture the bolted flange joint made of composite materials.

Fig. 2.3: Vacuum infusion process [28].

2.2.3 Use of braided fabric

Two-dimensional braids are available in two types: (1) biaxial and (2) triaxial. Biaxial braid is the most commonly used and is produced using two sets of yarn carriers that rotate around the braiding axis. One of these two sets rotates in clockwise direction whereas the other set moves to the opposite direction creating a single layer of braided fabric [29]. Triaxial braid is involves a third yarn carrier which adds longitudinal yarns to the biaxial interlacing yarns (Fig. 2.4) [30].

Biaxial yarn angles can be varied from 25° to 75° [16] so the braid can be dropped over the top of mandrels that vary in cross-sectional shapes and/or dimensions along their length

without needing to cut the yarn (Fig. 2.5). The attachment points or holes can be preformed into the fabric to reduce the steps in component finishing and to improve the mechanical performance of the components. This is because biaxial braid helps to avoid cutting the fibre reinforcements at the attachment site [30]. In contrast, triaxial braid cannot be used with a mandrel which has varying cross-sectional areas as the axial/warp yarn locks the diameter of the braid and prevents the internal expansion and contraction.

Fig. 2.4: Mandrel over-braiding [30].

Fig. 2.5: Circular braiding around a complex shape [31].

A previous study [32] has indicated that the most common types of failures in commercially available GRP flanges manufactured by hand lay-up or filament winding processes occur at the flange-hub intersections, due to the discontinuity of fibres in this region (Fig. 2.6).

Fig. 2. 6: Flange failure at the hub neck [32].

2.3 Performance of metallic bolted flange joints

The flat face flange has been widely used in the early years of the process industries. At that time, cast iron was commonly used to manufacture the flange. Without having any existing standards, full face (FF) flanges were manufactured and widely used because the gasket covers a large area of its face and this reduces the undue stress on the flange. The FF flanges were usually used to connect pipe-to-pipe, pipe to pump or any other equipment such as pressure vessels at various levels of the pressure and temperature.

When the use of flanges started to grow, wrought-iron rolled plate replaced cast iron. The new method used a rolled angle section which was then riveted to the vessel's shell. When the welding technique was introduced to join pipes, tanks and pressure vessels at high pressure levels, manufacturers preferred to use forged-steel materials to produce FF flanges.

To date, many theories, methods, and standards such as ASME, JIS, BS, CODA and DIN have been developed to make the design of the flange viable and reliable. The following sections will discuss in detail the factors which affect the performance of metallic flange joints.

2.3.1 Effects of nominal flange diameter

The variation of the nominal diameter of bolted flange connection has an effect on the flange performance and is considered as a key to optimise the design. Omiya et al. [33] has studied stress analysis of flange joint using Elasto-Plastic (EP) FEA and ASME method. They have found that the hub stress with larger diameter is smaller than that with a smaller diameter. However, they have found opposite trends when the ASME design method has been used. Also, a variation in the axial bolt force (load factor) was observed as positive with the smaller nominal diameter and as negative with the larger nominal diameter. According to the EP-FEA analysis based on the JIS B 2490 standards, leakage of gas was predicted. It has been seen that the sealing performance of smaller nominal diameter with a non-asbestos gasket was better than that of larger nominal diameter with an asbestos gasket. Naser [34] has studied the influence of the nominal diameter of the bolted flange. The study has shown that all the stresses in tangential flange, hoop and longitudinal hub have decreased with the increase in the nominal flange diameter.

2.3.2 Effects of flange thickness

The most important factors that have significant effects on the performance of the flange and its optimum design are the flange geometry and the dimensions. The variation of flange thickness has been studied by many researchers. Nash et al [35] has developed a finite

element model of a full face metal-to-metal tapered-hub flange. They found that the flange thickness had a large effect on the radial flange stress, but had no significant effect on either the longitudinal or the tangential hub stresses. In addition, they have compared the results with ASME and PD5500 codes and found that the flange radial stress of these codes was conservative (i.e. safe, since they predict high stress) whereas the flange tangential stress was not conservative (i.e. unsafe) when compared to the FEA results. Naser [34] performed analytical, FE modelling and experimental investigations for the bolted flange connection and it has been observed that the thickness has a positive effect on the flange stress (hoop and radial), which is decreased with the decrease in the flange thickness. The study also proposed a new design method for bolted flanges.

2.3.3 Effects of hub thickness

Stress concentration at the hub/flange intersection due to flange bending is one of the important problems that probably lead to failure of the flanges. A number of studies have focused on this problem and tried to solve it by varying the hub thickness. Naser [34] studied the relationship between hub thickness and flange stress (hoop and radial). It has been claimed that the flange hoop stress is increased but the flange radial stress is decreased with the increase in the hub thickness.

2.3.4 Effects of hub length

Hub length plays an important role for maximizing the bolted flange design because of its influence on the stresses of the joint system, especially, for the hub stress and for the strength of the pipe-flange adhesive bonded connection. Nash et al [35] stated that the hub longitudinal stress is reduced significantly as the hub length is increased but the flange radial stress is almost independent of the hub length. It has also been observed that the flange tangential stress is reduced slightly as the hub length is increased.

2.3.5 Effects of flange rotation

Applying bolt load and internal pressure together tend to bend the flange and cause rotation. This generates a deformation of the gasket accompanied by uneven compression which has a significant effect on the sealing performance. Shoji and Nagata [36] conducted a comparison study of raised face bolted flange joint with nonlinear gasket using a 2D axisymmetric and 3D FE (finite element) models. The results of the numerical simulations indicate that the flange rotation is larger in pressurized condition for both 2D and 3D models. Furthermore, they have noted that the modelling of bolt holes in 3-D has no significant effect on the results.

The influence of variation in taper angle (different flange's surface profiles), flange thickness and bolt preload were studied by Abid and Nash [37] using two-dimensional axisymmetric model. They found that the highest values of longitudinal, radial and tangential stresses are at the hub/flange intersection, at bolt circle diameter and at inside diameter, respectively. The maximum longitudinal stress was recorded for the positive taper angle. The highest value of radial stress was observed for the negative taper angle. In addition, the tangential stress is increased with an increase in the flange thickness for positive angles, but it is decreased for negative and no taper angles. It has been observed that the longitudinal stress is decreased with an increase in the flange thickness up to 20 mm and then becomes constant above 20 mm in all three flange profiles. In contrast, the flange rotation is reduced as flange thickness is increased. Other researchers [38, 39] have observed that the flange rotation is decreased by increasing the temperature of the joint system.

2.3.6 Effects of thermal loading

In high temperature applications, the effects of thermal loading (internal fluid operating temperature) should be taken into account in the analysis of the structural integrity and sealing ability for the bolted flange joint. Unfortunately, the current codes and standards for flange joints do not account for the influence of temperature [38, 40]. Abid [38] and Abid and Ullah [39] developed a 3D nonlinear FE model to investigate bolted flange joint strength and sealing capacity under combined internal pressure and different steady-state thermal loadings. The results indicated that both the sealing and the strength are greatly influenced by the thermal load. The radial variation of the temperature distribution through the flange and the gasket is greater in the hub because the flange ring works as a cooling fin. Apart from bolt axial stress, the stresses of the flange, bolt and gasket are decreased by applying the internal pressure and all the stresses decrease further with additional thermal loads. However, the internal pressure does not affect the axial bolt stress when the thermal load is decreased. Guruchannabasavaiah et. al [41] carried out a non-linear finite element analysis to study the effect of internal fluid temperature and bolt load on the gasket sealing between a flange and blind flange in a pressure vessel. The results showed that the vertical deformation in the blind flange increased with both the bolt load and thermal load and the maximum stress intensity was affected significantly as bolt load increased. In addition, the contact stress between the gasket and the flange interfaces was greatly increased by increasing the bolt load but reduced rapidly as thermal load is applied. Therefore, a gap occurs at the lower values of the applied bolt force.

2.3.7 Effects of material stiffness

Sawa et al [42] have studied the influence of the material stiffness of the hub, flange and gasket (E_1 , E_2 and E_3 , respectively) as well as gasket thickness. A 3D theory of elasticity was used to analyse the distribution of the contact stress which dictates the sealing performance. The results revealed that the distribution of the contact stress tends to be uniform as the ratio of E_1/E_3 and the thickness both are increased. Also, the gasket seating width and the moment arm were both increased by increasing both the ratio of E_1/E_3 and the thickness of the gasket, whereas it has been considered constant in JIS and ASME standards. On the other hand, the hub stress is increased as the internal pressure and the thickness of the gasket both are increased and the stress for aluminium gasket was larger than that of the mild steel gasket.

2.3.8 Effects of bolt preload

To avoid bolt failure during the operating condition, it is necessary to understand the relationship between the axial bolt force and the internal pressure. The bolt load has been calculated during bolt up or the operating conditions in many standards or codes such as EN1591-1 [43], ASME PCC-1-2013 Appendix O [44] and the ASME Boiler and Pressure Vessel Code, section X [22]. Nash et al. [35] found that the hub longitudinal stress was largely affected by the bolt preload, but the flange radial stress was slightly influenced and the maximum flange tangential bending stress was almost independent of the bolt loads. On the other hand, increasing the pre-stress bolts has a positive effect on the longitudinal displacement to prevent the leakage. Omiya et al. [33] proposed a new method of calculating the preload bolt by taking into account the allowable leak rate and the scattered bolt preloads. In addition, previous studies [41,42] have clarified that the internal pressure has insignificant influence on the pre-bolt load, in contrast, the maximum allowable internal pressure largely depends on the axial bolt force [42, 45]. Furthermore, other researchers [37, 38] have commented that the bolt load is affected by the temperature of the internal fluid due to

different thermal expansion values of the bolt flange and gasket [38, 39]. Zahavi [46] has conducted nonlinear FEA analysis for bolted flange connections by taking into account the changes in the geometry and the friction between flange-gasket faces subjected to the loads to increase the accuracy of the results obtained for bolt force and to accurately predict the leakage point. Moreover, Rotscher diagram has been used and the results have been compared with the experimental results from other published papers. In the study, it was noted that the incremental bolt force was almost independent on the internal pressure and a good agreement could be found between of the compared results.

2.3.9 Effects of bolt spacing

Do et al [47] have investigated the impact of bolt spacing on the circumferential distribution of gasket contact stress in bolted flange joints. This study [48] has applied an analytical approach which was developed based on the theory of circular beam on elastic foundation as well as a finite element based numerical method together with an analytical models developed by Koves. Two bolted heat exchanger (HE) flange joints with various bolt thicknesses and bolt numbers were studied. One of the flanges was 24 inch HE flange and the other was 52 inch HE flange. Also, they have studied the influence of the gasket modulus. The results have indicated that the bolt spacing has a great effect on the circumferential gasket contact stress. It has also been found that both the flange thickness and the stiffness of the gasket have a significant influence on the stress distribution.

2.3.10 2D Axisymmetric and 3D FE modelling of the flange

In order to save time and data volume, many studies have carried out the comparisons between 2D axisymmetric and 3D FE analyses. Hwang and Stallings [49] have performed a comparison study between 2D axisymmetric finite element model and a 3D solid finite element model for the bolted flange connections. This study has applied axisymmetric and non-axisymmetric loadings for both 2D and 3D models and non-axisymmetric bolt pretensions for 3D model only. Both the bending and the shear forces were unevenly distributed and both the torque and the axial forces were evenly applied on the top boundary surfaces of the pipe section. The results have indicated that the 2D axisymmetric model provides accurate results with axisymmetric loading. When non-axisymmetric bolt pretension is applied, the differences in results between the 2D and the 3D models were found between -1 and +1 % in the pipe sections and between -3 and +21% in the joint sections. Approximately 35% variation in results between 2D and 3D models was observed in the pipe sections for the non-axisymmetric loading representing the operating conditions.

2.3.11 Considerations for the FRP flanges

Most of the above parameters are still valid for the FRP bolted flange but the natural behaviour of the composite materials should be taken into account by the designers. These parameter are the orthotropy of the FRP material, which can be used to reinforce the composite in the direction that is subjected to high loads, the orthotropic thermal conductivity, the range of the working temperature and others, which some of them will be mentioned in next section.

2.4 Performance of composite flange joints

A review of literature reveals that only a few studies have focused on composite flange joints. Tao et al. [13] investigated the development of connection between carbon fibre poles and advanced composite material flanges rather than the traditional flanges manufactured by aviation aluminium alloy in stratosphere truss structure. A Toray T700S – 12K carbon fibre in three-dimensional full five directional braiding technology and tri-functioned epoxy resin TDE - 85# were used to manufacture the flange through RTM (resin transfer moulding) process. FEA has been applied for the numerical analysis. The results reveal that the joint of carbon fibre poles with the carbon-fibre composite flange performed better than the aviation aluminium alloy flange under the same operating conditions.

Sanjay et al. [50] have conducted analytical stress analyses of a non-gasket composite flange and a metallic flange. They have also conducted finite element analysis for carbon-epoxy composite flange to calculate the radial and the axial stresses. Both flanges were subjected to internal pressure of 15.32 MPa. The results show that the composite flange has better performance compared to the metallic flange, and the fibre orientations should be [0/45] and [0/60] to ensure the best performances.

Whitfield et al. [51] carried out both numerical and experimental studies for creep and unsymmetrical shrinkage during the post-cure of GFRP pipe flange manufactured by hand lay-up method. Chopped strand mat fibre and Derakane Momentum 411-350 vinylester resin and a steel mould have been used for manufacturing the flange. The steel mould represented the inside dimensions of the flange. A number of strain gauges were embedded during lamination between the layers and on the outer surfaces. From the investigations, they have noted that the correlations between spring back results are poor but for strain, results are good. The authors listed two possible reasons, firstly, due to the thermal stress related creep in the resin at the elevated temperature during post-cure and secondly, various cure profiles have been applied at various stages of lamination process. Sun [6] has studied the FRP bolted flange connections. Analytical approach using classical and shear deformable laminated plate and shell theory as well as finite element analysis have been carried out for identical flanges. An experimental investigation has been carried out for non-identical flanges (e.g. blind flange). E glass woven roving and mat, and Vinylester resin were used to manufacture the flanges along with two types of gaskets (rubber and asbestos). A good agreement has been found between the analytical and the numerical results.

Estrada and Parsons [7, 52] have investigated the strength and the leakage of a modified glass fibre reinforced plastic (GFRP) stub flange joint by using three-dimensional analysis and axisymmetric finite element models. It has been found that over three-quarters of the contact between the gasket and the flange are lost, however, the pressure in the remaining contact portion is greater than the internal pressure. Most of the contact between the hub and the stub has been lost due to the stub rotation whereas the pressure remains almost uniform in the circumferential direction except at the ends where the contact pressure is higher on the sides of the bolts.

Kurz and Roos [53] performed analytical, experimental and numerical investigations on the design of floating type bolted flange connections (better known as Loose Flange) made of GRP materials capable of working at temperatures up to 80°C in chemical industries. Various types of gaskets made of rubber (EPDM) and polytetrafluoroethylene (PTFE) were used to check the performances of the gaskets with GRP bolted flange at that elevated temperature. It has been found that both the PTFE-gasket and PTEF-gasket with diffusion barrier perform better than EPDM-gaskets with sufficient tightness to achieve the leak rate criterion of the TA Luft and are capable of tolerating the creep relaxation. In terms of the design analysis of

other parts of the components, the bolt-force has been decreased with heating up to 80 °C but bending occurred at the top surface of loose flange between bolts in the circumferential direction. It has also been noted that the loose flange rotates due to the moment. The results of analytical, experimental and FEA simulations all have shown good agreements with each other.

Konstantin and Sándor [54] have studied the optimisation of GRP- Loose flange joints. Two models including PTFE gaskets have been used to simulate the optimisation of material properties and geometric shapes. An evolutionary algorithm has been used for the optimisation. They have observed that a number of parameters such as thickness of seal, thickness of flat washer, height of collar and number of materials in lower layer have no influence on the characteristics of the flange connection. In contrast, other parameters such as type of screw, width of flat washer, materials of upper layer and the thickness of the loose flange have a large effects on the performance of the flange connection.

Fangueiro [55] has performed experimental investigations on the development of fibrous preforms of FRP T-pipe connections. 3D weft-knitted fleecy fabrics with different structures such as fleece yarn linear, average ground yarn and average fleece yarn have been tested to optimize the mechanical properties. Glass fibre and polyester resin were used with RTM to manufacture the T-tube connection. The results obtained from the tests indicate that the sample PA Glass 544 Tex exhibit the best performance to manufacture the T-connection with 43% fibre mass fraction and this is close to the desired value of 40%.

2.5 History of standards development

Over the last few decades, many theories and methods have been proposed about the design of a flange based on an elastic analysis of the interaction of flange bending and gasket compression mechanisms. The first method is called Taylor-Forge method. This method has been developed during 1920s and 1930s by D. B. Westrom and E.O. Waters [56] and published as an Engineering Department Bulletin by Taylor-Forge in 1951 [57]. Later, it was included in a booklet, Modern Flange Design, by the same company.

This method is based on using two separate ring gaskets instead of a full face gasket, one lies outside and the other is in the inside of the bolt circle [14]. Based on Taylor-Forge method, a number of design codes and standards have been published such as ASME, CODAP, DIN, JIS and BS [58] [56]. In 1961, Schwaigerer published the second method using the basic design rules of the full face gasket flange connection [59]. A third method has been published by Blach et al. in 1986 [60]. These two methods were based on uneven gasket compression to resist the applied bending of the flange under the operating condition. For composite flange, section X has been added in 1968 to the ASME Boiler and Pressure Vessel Code with the following title “Fibre-Reinforced Plastic Pressure Vessels” [6].

2.6 Compressed gaskets

When placed between two objects (e.g. flanges) gasket create a static seal, preventing leakage under various operating conditions such as high pressure and/or temperatures. Once axial load is applied through bolts, gaskets deform and fill the microscopic spaces and surface irregularities between the mating flange faces. Gaskets also compensate for any dimensional changes in the flange geometry caused by pressure or temperature variations during operation [10]. Depending on the nature of the applications, gaskets are required to have a number of characteristics such as good recovery, limited relaxation, good compressibility, face adaptability, high strength and chemical and temperature resistance. Based on the materials

used, gaskets can be as: non-metallic, semi-metallic and metallic [61, 62] which are discussed in details in the following sections.

2.6.1 Metallic gaskets

Metallic gaskets are manufactured from one or a combination of more than one metal with various geometries and sizes. These gaskets are often used for high pressure and/or high temperature applications thus require bolt loads higher than those applied for semi-metallic and non-metallic gaskets to ensure high quality sealing. Ring joint, lens joint and corrugated metal gaskets (Fig. 2.7) are considered as the dominant types in the current market.

Ring gasket joints are usually fabricated as oval or octagonal cross sections (Fig. 2.7.a) depending upon the geometry of the flange grooves [11, 63]. Various metals and alloys are used to make the ring gaskets. The materials should be softer than the materials used for the flange's grooves so that the gasket plastically deforms (rather than the groove) and flows into groove's irregularities. This deformation occurs due to high axial bolt load which is applied upon a small bearing area of the ring gasket. Ring gaskets are mainly used in the petroleum industries for high pressure and temperature applications that require high integrity sealing and with valves and pipework assemblies [11, 62].

Lens ring gaskets have spherical sealing faces especially designed to suit mating flange recesses (Fig. 2.7.b). These gaskets provide high integrity and are used for high pressure/temperature applications [62]. As for all the metallic gaskets the materials must be softer than the flange materials. Therefore, the deformation will occur on the gaskets rather than on the flanges when compressive load is applied. Both the compressive load and some of the hydrostatic pressure force increase the contact pressure between the flange and the gasket to insure the sealing

Corrugated metal gaskets are divided mainly into two categories, which are corrugated gasket without layers or corrugated solid metal and corrugated gaskets with soft layers. The corrugated gaskets without layers can be made like flat, tongue, groove and sectional ones. They are preferred in the applications that require mechanical strength, good thermal conductivity as well high corrosion resistance and hi pressure [11]. The corrugated gaskets with soft layers are usually covered with soft layers on both sides. However, based on the sealed medium, additional layers can be used with uneven or distorted sealing surface. These layers are made of graphite, ceramic or PTFE materials. These type of gaskets are suitable with low pressure and higher temperature applications with acids, oils and chemical mediums. Fig. 2.7.c illustrates the corrugated gaskets with soft layers.

Finally, most of the metallic gaskets are not common gasket with the FRP bolted flanged joints, which require a soft gaskets such as rubber gaskets.

Fig. 2.7: Metallic gaskets (a) Ring joint gasket (b) Lens ring gasket (c) Corrugated gasket.

Żyliński [45] performed a numerical analysis of bolted flange connection using an aluminium gasket. FEA has been developed to model the bolted joint with special elements, hexahedral 21-node and 28-node isoparametric, for the contact zone. Due to the cyclic symmetry of the joint, a $1/16^{\text{th}}$ portion of the bolt joint has been modelled. The effect of internal pressure in the gap between the gasket and the arising flange was taken into account during the progression of joint opening. Experimental results were used for comparison. The results reveal that the contact pressure is increased along the gasket radius direction but it is decreased as the internal pressure is increased. Apparently, there is no clear difference between the results for 21-node and 28-node elements. In addition, the working load (internal pressure) has insignificant influence on the pre-bolt load, but the pre-bolt load has a decisive effect on the maximum permissible internal pressure. On the other hand, the maximum permissible internal pressure was independent of the gasket thickness. Furthermore, the maximum von-Mises stress is observed at contact surfaces between the bolt head and the flange.

2.6.2 Semi-metallic gaskets

Semi-metallic gaskets consist of both metallic and non-metallic materials. The metallic portion provides the strength to the gaskets while the non-metallic part is intended to offer resiliency, conformability and sealability. These types of gaskets are used for various operating conditions and can generally be used at higher pressures and temperatures than the non-metallic gaskets [61]. Mainly, semi-metallic gaskets are used with most types of the flange such as raised face, tongue and groove and male and female flange.

The spiral wound gasket (SWG) is one of the important semi-metallic types. This gasket is a composite structure of metal strip, sealing strip of fillers and outer/inner steel rings as shown in Fig. 2.8.a. The mechanical properties of the SWG are dominated by the metal spiral strips

which are usually stainless steel. Therefore, the SWG has a good resilience and recovery due to V-shape of the metallic spiral strip. Also, it meets the most accurate conditions for both loads; temperature and pressure in the flange joint and has a good resistance in corrosive and toxic mediums. However, complete parallel flange faces are required to install it [62, 64, 65]. Krishna et al [58] had carried out a comparison of the gasket's influence on the sealing performance of a bolted flange. A three-dimensional FE model of bolted flange connections with gaskets has been developed and analysed using ANSYS. Spiral wound gaskets with various filled such as; asbestos (AF), graphite (GF) and PTFE (TF) filled have been used with their nonlinearity characteristics obtained from experiments. The results show that the distribution of the contact stress is non-uniform in the radial direction across the gasket width and depends on both the gasket type and the flexibility of the flange. These factors are not accounted by the ASME code, so the leakage may occur even at the flange rotation of less than 3° that is specified by ASME. The highest and the lowest axial bolt force have been observed with TF and GF gaskets respectively when the internal pressure is increased. This is due to low and high stiffness of TF and GF gaskets respectively. It is also apparent from the results that the TF spiral wound gasket has the least variations in the contact stress distributions whereas the GF spiral wound gasket has an opposite trend.

Omiya et al. [33] have studied the influence of non-linear characteristics of non-asbestos and asbestos spiral wound gaskets (SWG) on the sealing performance. Contact stress distribution has been calculated and the leak rate has been examined. It has been found that the radial variations of gasket stress distributions with a smaller nominal diameter of the flange joint (around 3 inch) are smaller than those with a larger nominal diameter (around 20 inch). In addition, the sealing performance with smaller nominal diameter and non-asbestos gasket is better than those with larger nominal diameters and asbestos gaskets.

The metal jacketed gasket consists of a metallic shell that surrounds either metallic or non-metallic compressed filler (Fig. 2.8.b) The metal jacket provides blow out resistance and resists the pressure, temperature and corrosion, whereas the filler provides the gasket resilience and compressibility. Generally, this type of gasket is used with heat exchangers, pumps and valves. However, it requires flatness of flange with smooth surface finishes and high bolt loads.

Another type of semi-metallic gasket is named as Kammprofile (grooved) gasket. This gasket consists of a metal ring (outer) made of steel, Kammprofile ring with concentric grooves made of steel, sealing and sealing layers made of either graphite or PTFE or even metals (e.g. aluminium and silver) as shown in Fig. 2.8.c. Kammprofile gaskets are used for high pressure and temperature applications such as power plant, nuclear industries, heat exchanger and pipelines. However, it is very expensive and could be damaging to the flange faces if it is used without soft covering layers and/or subjected to a high bolt load. The Kammprofile gaskets have the same concept of the metal reinforced gasket which consists of core material and two soft layers covering the faces.

Fig. 2.8: Semi-metallic gaskets: (a) Spiral wound gasket, (b) Metal jacketed gasket and (c) Kammprofile gaskets.

2.6.3 Non-metallic gaskets

Non-metallic gaskets are usually fabricated as composite sheets and then punched according to the required geometry. Often, these gaskets are used in low to medium pressure applications. However, these gaskets could be used for extreme chemical environment and temperature if chosen correctly. Non-metallic gaskets are suitable for the use with flat face flange and raised face flange. The advantages of these gaskets are: good chemical resistance, low bolted load is required, they can be deformed easily and fill the irregularities of flange faces to keep the seal and do not require the flange surfaces to be perfectly finished. However, the blowout resistance for these gaskets is low. Depending on the types of materials used, non-metallic gaskets are classified into the following types: PTFE, rubber, graphite and fibre reinforced gaskets.

PTFE gaskets have good chemical resistance. These types of gaskets are easy to adapt perfectly to the flanges and have good ability to maintain the sealing. Furthermore, these gaskets have excellent isolation properties. However, there are a few drawbacks, for example, poor mechanical properties, creep and limited temperature resistance. Moreover, PTFE gaskets are not suitable to use with fluorine gas and Melton alkali metals.

One of the most common non-metallic gaskets is rubber, such as EPDM, Neoprene, Nitrile, Viton and Silicone. EPDM and Neoprene gaskets are widely used throughout the water industry due to excellent resistance to water, steam, heat, weathering, chemical, mechanical

and wear. Nitrile gaskets are mainly used in the oil industries and have high resistance to aliphatic hydrocarbon oil.

Viton gaskets have excellent resistance to chemical attack by oxidation and are widely used in the chemical industries. Also, these gaskets have good resistance to oil at low temperature and hot air. These gaskets are not influenced by sunlight and ozone. However, the resistance is weaker against steam, aliphatic and aromatic hydrocarbons.

Graphite gaskets are usually reinforced with a stainless steel insert. These gaskets have good corrosion resistance is excellent against a wide variety of acids, alkalis, salt solution, organic components and heat transfer fluids even at high temperatures. Furthermore, graphite gaskets are used in oxidizing conditions at temperatures from -200°C to $+500^{\circ}\text{C}$. However, these gaskets are affected by sulphuric and phosphoric acids, and it is recommended to avoid using this type of gasket in such cases.

Fibre reinforced gaskets are usually manufactured as sheets and then cut or punched depending on the required shape and size. These sheets consist of three components, fibres, fillers and binders. The quality and the properties of the gaskets are dependent on the properties of these components as well as production processes. The fibres aramid, carbon, cellulose, glass and mineral fibres are often used as reinforcement fibres and NBR (Nitrile Butadiene Rubber) is most commonly used as a binder. Generally, fibre reinforced gaskets are cheap and easy to cut or punch to obtain the required size but the temperature resistance is low because of the rubber binder.

Shoji and Nagata [36] presented FE analysis of a raised flange with nonlinear gasket using a 2-D axisymmetric and 3-D solid element FE models. Based on the load condition, the analysis has been carried out in two steps- pre-load and pressurized. Due to the nonlinearity of the gasket, they have used two values of modulus of elasticity (compression and decompression) depending on the states of the gasket whether in compression or decompression. Results of the numerical simulations indicate that the gasket stress increased from the inner radius toward the outer radius of the gasket for both the 2-D and the 3-D models, and the stresses are higher in pre-load condition than in pressurized condition.

2.7 The characteristics of composite pipes commonly used with flanges

Filament winding technology is the most favourable process for the manufacture of FRP pipe because of its high rate of productivity. Therefore, the use of these pipes has been increased in various applications alongside the further development of this technology [66, 67]. Xia [66] developed an analytical procedure to assess the influence of stacking sequence for the multi-layers filament wound structures using three-dimensional (3D) anisotropic elasticity theory. Three specific carbon fibre/epoxy angle-ply pipe designs, A [+55/-55/+55/-55], B [+55/-55/+30/-30] and C [+55/-30/+30/-55], were analysed. All these pipes were tested under internal pressure and the stress, strain and displacement distributions calculated. The pipe of type A has almost constant hoop and axial stresses through the thickness and its hoop to axial stress ratio is 2. However, types B and C show discontinuous variations of the hoop and axial stresses at the interface laminas and their hoop to axial stress ratio is no longer constant. In terms of shear stress, all three types show discontinuities, but the smallest range was with type A. Moreover, all three types exhibit continuous variations of hoop strain and the smallest values are observed with type A. Furthermore, only types B and C show discontinuous radial strain and the variation is higher with ± 55 lay-up angle than that of ± 30 lay-up angle. The radial displacement is not affected significantly by the stacking sequence whereas the hoop rotation depends largely on the stacking sequence, especially for type C.

Merting et al. [68] carried out an experimental investigation for tubular filament-wound structures which were made using a state of the art production method. Three winding angles ± 30 , ± 45 and ± 60 were utilized for winding eight tows of Owens-Corning E-glass fibre. The specimens were tested under internal pressure and axial force. The results indicate that the multi-angle wound pipe exhibits overall better performance in resisting damage compared to the ± 60 angle-ply lay-up.

Meijer and Ellyin [69] conducted a study of the strength of $[\pm 60^\circ]_3$ glass fibre reinforced epoxy tubes to produce a baseline failure envelope when they subjected to multiaxial stress. These pipes are manufactured by filament winding and tested under 14 different ratios of hoop to axial stress. These stresses are the consequences of applying internal pressure together with tensile and compressive axial loads. According to the results, they observed five distinct modes of axial tensile structure failure such as weepage, local leakage, burst and axial compressive failures. They also developed the maximum strain failure criterion that was fitted to the failure strain data but was observed to be unsatisfactory for two regions of the data. Moreover, it is found that when the local leakage failure occurred under an axial compressive stress, the maximum strain failure criterion over-predicted the strength at the stress ratios.

Onder et al. [70] studied the influence of winding angle and temperature on the burst pressure of the filament wound composite pressure vessel. They utilized FEM, experimental approaches and an elastic solution procedure developed based on Lekhnitskii's theory to verify the optimum winding angle. In addition, the Tsai-Wu failure criterion, maximum stress and strain theories were used to predict the burst pressure of tubes, which were tested under the closed-ended condition. The glass fibre reinforced (GRP) pipes were manufactured with four layers, which were oriented symmetrically and anti-symmetrically at $[+45^\circ/-45^\circ]_s$, $[+55^\circ/-55^\circ]_s$, $[+60^\circ/-60^\circ]_s$, $[+75^\circ/-75^\circ]_s$ and $[+85^\circ/-85^\circ]_s$. They concluded that the optimum winding angle of the composite pressure vessel under internal pressure loading should be 55° . Hygrothermal loading has insignificant influence on the burst pressure, whereas it is affected significantly by temperature, especially at high temperatures. Arikan [71] conducted a failure analysis of filament wound composite pipes with an inclined surface crack under static internal pressure. The pipes were made from glass/ epoxy with antisymmetric layers at $(\pm 55^\circ)_3$ winding angles with different angles of the cracks. According to the results, the burst pressure increases with the increase in the crack angles. The delamination area also increases with an increase in both the burst strengths and the crack's angles.

Based on the above findings and the others, the optimum winding angle of filament wound composite pipes subjected to internal pressure is $\pm 55^\circ$ which leads to produce equal circumferential and axial stresses [7].

2.8 Co-bonding of composite flange with composite pipe

The use of adhesive bonding methods with very large and complex composite structures [72] made of similar or dissimilar materials is continuously increasing. The parts of such complex structures are usually manufactured separately and bonded using adhesives to reduce labour and fabricating costs [73, 74]. Both the adhesive properties and the joining methods significantly affect the performance and the behaviour of adhesively bonded composite structures [75]. In many applications, traditional mechanical joints with fasteners have been replaced by adhesively bonded joints because of its advantages; these include fast and cheap joining technique, uniform stress distribution over large area without holes (holes cause stress concentration) and high dynamic strength [76-79].

For the FRP flange-pipe joint, industry prefers the convenience of adhesive bonding. The bonding technique is generally divided into three categories: Taper-taper, straight-taper and straight-straight joint [80]. There are a few other types which can also be used, however, these are the most common (Fig. 2.9).

Fig. 2.9: Three different types of adhesive bonded joint between flange and pipe [80].

1. **Taper-taper joint:** the inner diameter of fitting or flange bell or socket is tapered and the outer diameter of the end of the pipe is also tapered (shaved). Then, they are matched and joined by a thin glue line and no integral pipe stop is required. Due to the largest contact area between the matching components, taper-taper joint is considered the strongest option. However, this type of joint requires more manufacturing time compared to the others.
2. **Straight-tapered joint:** the flange bell, fitting, or socket is tapered internally and the end of the pipe is shaved with uniform outer diameter (i.e. straight pipe end). A thin glue line is not often achieved and this results in lower joint strength. However, the required installation time is less than the taper-taper joint.
3. **Straight-straight joint:** the end of the pipe is prepared with straight shave or standing, and the flange bell or fitting or socket has no tapered surfaces. The main advantages of this type of joint are shortest fit up time requiring fewer tools. However, this type of adhesive joining technique offers medium strength and it requires an integral pipe stop.

Nemes [81] examined the adhesive bonded joints for pipes made from different materials (hybrid materials) like titanium, aluminium and carbon/epoxy. They discovered that the maximum values of orthoradial stress ($\sigma_{\theta\theta}$) exist on the free edges of adhesive and the shear stress has two peaks that are located at equal distances from the free ends. Moreover, the shear stress (τ_{rz}) decreases with the length of overlap which has an optimum dimension of 80 mm. Furthermore, increasing the thickness of the adhesive has a positive effect on the orthoradial stress but reduces shear stress values.

Yang [12] studied the design of adhesive joint for composite pipes which is subjected to tensile loads. It has been found that the maximum peel and shear stresses occur at the free

edges of adhesive length but both stresses are nearly zero in elsewhere. The optimal lengths of the joints are 65 mm and 90 mm for 54°wound pipe and 20°coupling respectively.

Cheng, Wu [82] presented a study about adhesive bonding for smart composite pipes by using piezoelectric layers within composite layers of coupler under tensile loading. The piezoelectric layers work as a sensor for the deformation produced by the applied mechanical load and provide signals which are used to calculate the peel and the shear stresses. According to the results, maximum peel and shear stresses are located at the edges of adhesive layer. The optimal design conditions could be achieved by choosing suitable piezoelectric materials.

Oh [83] investigated the tubular adhesive joint for the steel-composite adherents piping under thermal expansion and mechanical torsion. A finite element was utilized to calculate the thermal residual stresses generated by the cooling of the joint from 80 °C to 20 °C. It has been discovered that the torque transmission capability increases with the increase of stacking angles up to ± 25 degrees and then decreases. Thermal stress has a significant effect on the adhesive joints. Oh [84] in a separate article discussed the torque capacity of tubular adhesive joints with different composite adherent. It has been illustrated that the steel-carbon/epoxy joint is much affected by the thermal stress compared with the steel-glass/epoxy joint, so at a stacking angle $\phi = 45^\circ$ the failure might occur due to thermal stress only even without any external loads. The strength of steel-carbon/epoxy is lower at high values of ϕ . However, the strength of steel-glass/epoxy joint increases with ϕ . However, the effect of residual stress reduces when ϕ is increased.

Kumar [85] has presented a study of tubular adhesive bonds with functionally modules graded bond line (FMGB) and mono-modules line (MMB) under tensile loads. Based on the findings, it can be said that the peel and shear stress peaks of FMGB are much smaller than those in state of mono-modules adhesive joint under the same load conditions. Spaggiari and Dragoni [86] have carried out analytical an investigation on the tubular lap bonded joint under torsion to regularize the torsional stresses by using functionally graded modulus adhesive (FGA). The aim of that is to change theoretically the elastic properties of the adhesive as a function of the reinforcement inside the bond line. This will allow to minimize the stresses considerations which are usually high at the edges.

EDO [80] performed comparative studies of butt and strap joints with adhesively bonded joints (taper-taper joint, straight-taper joint and straight- straight joint). All the joints were experimentally tested under various loads such as tensile, bending, allowable wind loads and thermal load. The results have shown that the butt and the strap joints are stronger than all other types of adhesively bonded joints when subjected to environmental loads. Results from bending and tensile tests have shown that taper-taper joint has a superior strength over other types of adhesively bonded joints. However, taper- taper joint is slightly weaker under thermal and wind loads.

2.9 Flange joint Fasteners

In most flange and gasket joints, fasteners apply the compressive pressure on the gasket through flanges. The main function of these fasteners is to clamp the connection sufficiently for maintaining the seal and preventing the slip of the gaskets. Therefore, the fasteners must be made of strong materials to keep the tension that is induced on the initial preload as well as the additional loads that are induced during the operating condition due to the internal pressure, temperature and corrosion. To achieve a successful installation, all components of the flange assembly should be taken into account by the designers. However, one of the most neglected components in the joining process is the fasteners and this negligence results in frequent joint leakage. Hence, the principal fastener components such as bolts or studs, nut

and washers should be chosen carefully depending on the application requirements. On the other hand, the bolt load should be applied correctly as one of the major weaknesses in the FRP flange industry at the moment is that most FRP manufacturers publish torque values but with no bolt load or lubricant on which they are based. This creates confusion/ignorance at installation resulting in cracking of flanges at one end or leakage of gaskets at the other.

The bolt is a threaded fastener with a nut at each end. Since the performance of the seal is dependent upon the level of the tension in the fasteners, ASME recommends applying a preload of 40% to 70% of a bolt's yield stress. Therefore, the materials should be chosen with a good safety factor based on the application conditions. The standards also recommend that the number of fasteners should be chosen in such a way that the distribution of pressure across the gasket remains as uniform as possible. Due to the flange bowing, the compression stress of the gasket is greater near the fasteners's holes.

Nuts are always associated with fasteners of flanged joints in which finished hex nuts and heavy hex nuts are most commonly used. Heavy hex nuts are slightly thicker and larger than finished hex nuts and used with high temperature and high pressure applications which require high axial forces. This load is generated by tightening nuts along the threads of the fasteners, so the threads play a major role in clamping operation. To avoid stripping these threads, it is necessary to choose fasteners and nuts with sufficient size, materials strength and length of engagement. The other problem between fastener components that should be avoided is galling, which is a cold welding (partial or full) and occurs between the mating faces that are under high loads due to the molecular bonds between them. To avoid this problem, it is recommended to use correct lubricant, coarse thread surfaces rather than fine and appropriate fastener components materials that are resistant to galling.

Washers are very important in bolted flange joints. They are recommended with FRP joints to distribute the applied loads of the bolts around the bolt holes. Consequently, a more even gasket load will be achieved, reducing potential leak paths of contained media. In addition, the use of washers is to protect the nut seating area and improve translation of torque inputs into bolt preload during the tightening process by reducing the friction between the turning nut and joint components resulting more accurate torque readings when using a torque wrench. Moreover, washers prevent embedding the nuts against the flange faces or inside the fasteners holes, thus the damage at joint surfaces.

2.10 Issues with drilling of composite materials

As the field of composite applications expands, the need for various types of machining such as drilling, milling, turning and cutting have increased. For example, it has been reported that over 100,000 holes [87] are made for a small single engine aircraft so in a large transporter aircraft, millions of holes are made. Consequently, drilling account for as much as 40% for all machining processes [88]. It has been found that the FRP flange with drilled bolt holes performs better in terms of strength than those with moulded holes [89]. However, drilling is a complex process and requires better understanding of drilling composites because of the inhomogeneous and anisotropic properties [90]. Typical damage in composites after drilling include peel-up and push out delaminations [91-93] as shown in Fig. 2.10, intralaminar cracking, fibre/matrix debonding and thermal damage by the heat produced during drilling. The most serious defect is delamination as it leads to decrease the load carrying capacity of composite laminates [94]. Delamination generally occurs between adjacent laminas. Therefore, the properties of resin and the fibre as well as its configuration play important roles in its occurrence.

Fig. 2. 10: Delamination (a) peel-up delamination (b) Push-out delamination [93].

It is worth mentioning that peel-up delamination occurs due to the cutting force when the drill starts to abrade the laminate. This is because an upward peeling force is created with the forward movement of the drill. This force tends to separate the upper laminas from the uncut portion held by the downward thrust force. The value of this force depends on the friction between drill and composite and drill tool geometry [94, 95]. On the other, the push-out delamination is caused by the compression, which is applied on the workpiece by the drilling tool. This force pushes and breaks the interlaminar bond between adjacent laminas in the regions around the hole. At some point, the push-out delamination will occur when the uncut portion becomes smaller and its resistance of the deformation is decreased and the thrust force exceeds the bond strength between the composite layers. Thereby, the adjacent layers at the bottom surface of the laminate are deboned before completing the drilling process. In order to avoid delamination, it is recommended to reduce the thrust force by changing the geometry of the drill tools [94, 95].

Tagliaferri et al. [96] conducted an experimental investigation about drilling of composite panels, which were made of six layers of glass fabric VR 181/ epoxy prepreg with autoclave curing. High speed steel (HSS) tool of 8 mm in diameter has been used with cutting fluid but without backing. The experimental results show that the damage extent is significantly affected by the cutting parameters. Increasing the cutting speed shows less damage extent whereas higher feed speed leads to poorer cut quality. They also observed that the damage extent does not influence the tensile strength of GFRP laminate that contains the holes. They have recommended that the optimal cutting speed/feed speed ratio can be obtained for maximum bearing strength by lowering the drilling speeds.

Khashaba [97] has carried out a study for randomly oriented GFRP laminates to evaluate the influence of the varying fibre volume fraction (V_f) and drill size on the notched tensile strength and pin bearing strength. The results indicate that the fibre volume fraction plays a significant role on the notched tensile strength, pin bearing strength and stress intensity factor. Due to the important effect of the ratio of randomly oriented GFRP laminate to drill diameter, it is recommended that this ratio must be greater than 5 for the development of full bearing strength.

In a separate work, Khashaba [92] carried out an experimental study to determine the influence of the drilling variables and material variables on the thrust force, torque and delamination of GFRP (thermoset) composites. The drilling variables considered are cutting speed and feed rate whereas material variable involved fibre shape, filler and matrix type

such as cross-winding/polyester, continuous-winding with filler/polyester, chopped/polyester, woven/polyester and woven/epoxy composites. In this study, a more accurate but inexpensive technique for measuring the delamination size within 10^{-3} mm has been demonstrated. The results have revealed that the sand filler in the continuous-winding composite raises the values of cutting forces and push-out delamination and increases further with increasing cutting speeds. In contrast, the push-out delamination decreases with an increase in cutting speeds for drilling cross-winding, woven and chopped composites. This happens due to a decrease in the thrust force. It is worth noting that the woven fabric composites have higher push-out delamination than that made of chopped fibres. For the same fibre shape (woven), the matrix has significant influence on the delamination and the torque. Both the peel-up and the push-out delamination as well as the torque of woven/polyester composite are higher than that for woven/epoxy composites. The thrust forces in drilling continuous-winding composite are more than three orders of magnitude higher than those in the cross-winding composites. During drilling both the chopped and the continuous-winding composites; delamination, chipping and spalling damage mechanisms were observed, however, the delamination was observed at different edge position angles with drilling woven composites.

Davim et al. [98] have studied the effect of cutting parameters (cutting speed and feed rate) and drill geometry on the thrust force, damage, surface roughness and cutting pressure. Two different types of 5 mm diameter drills (helical flute “Stub Length” and brad & spur) as illustrated in Fig. 2.11 have been used to drill a disc made of GFRP material using a hand lay-up process. They have also utilized analysis of variance (ANOVA) and Taguchi technique for identifying the impacts of drilling conditions. Based on their experimental findings, they have concluded that both the specific cutting pressure and the thrust force have been significantly affected by the cutting parameters. Damage increases with cutting speed and the feed rate. On the other hand, the cutting speed has the highest influence on the surface roughness. It has also been observed that better cutting performance could be achieved with the brad & spur tool than the Helical flute “Stub Length”.

Fig. 2. 11: (a) Helical flute “Stub Length” K10 drill; (b) “Brad & Spur” K10 drill [98].

Abrao et al. [99] carried out comprehensive investigations to identify the influence of drill geometries on the drilling performances of GFRP composites. A number of drills (EDP27199, A1141, A1163 and A1167A as can be seen in Fig. 2.12) have been used and the effect of the cutting parameters has been investigated. Results from this work indicate that the lowest and the highest thrust forces could be obtained from EDP27199 and A1167A drills respectively. The thrust force increases as the feed is increased and this happens due to the elevation in the shear area. The effect of cutting speed on the thrust force can be considered as negligible. The least damage on the laminate has been observed with tool drill EDP27199 which provides lowest thrust force. The second smallest delamination area has been found with drill tool A1167A with the highest thrust force. The damaged area increases considerably with feed rate and moderately with cutting speed.

Fig. 2. 12: Drills used in the experimental work: (a) EDP27199, (b) A1141, (c) A1163 and (d) A1167A [99].

Tsao [88] investigated the drilling of carbon fibre reinforced plastic (CFRP) laminates using three types of step-core drills (step-core twist drill, step-core saw drill and step-core candle stick drill) as shown in Fig. 2.13. The study examined the effects of drilling parameters such as diameter ratio, feed rate and spindle speed on the thrust force. By analysing the variation of these types of drills and their drilling parameters, it has been concluded that the step-core saw drill offers the highest drilling thrust force compared to the other step-core drills and the thrust force is influenced significantly by the selected cutting parameters. The thrust force has inverse relations with both the diameter ratio and the spindle speed but has a proportional relation with the feed rate. It has been concluded that a combination of low feed rate (e.g. 8 mm/min), high spindle speed (e.g. 1200) rpm and the high diameter ratio (e.g. 0.74 mm/mm) could be the best experimental condition of drilling CFRP with various step-core drills.

(a) Step core twist drill

(b) step core saw drill

(c) step core candlestick drill

Fig. 2. 13: Photograph for various step-core drills [88].

Conclusion

Metallic bolted flange joints (BFJ) are heavy and susceptible to corrosion in the presence of water and other liquids. Fibre reinforced polymers (FRP) are an alternative material, but relatively little published work on their design and manufacture has been found. In addition, agreed standards and relevant design codes for bolted FRP flange joints appear to be inadequate. Currently-used design procedures are modified forms of metallic design methods,

which neglect the unique characteristics of composite laminates. The manufacturing process, together with the reinforcement and laminate specification, are not defined adequately, although they affect the strength of the flange. This has resulted in the failure of some of the current BFJ designs which are available in the market. Furthermore, the mismatch between the mechanical properties of metallic flange and composite pipe can result in weak points in the structure of pipelines – differential thermal expansion can be avoided by using a composite flange, and this is especially important in high temperature applications.

Other areas that need more investigation include the composite pipe-flange adhesive bond, which is subjected to an unsymmetrical load around the axis of the pipe, due to the bolt loads as well as the internal pressure. Optimizing the composite drilling parameters could produce bolt holes with less damage. The rubber sealing gasket plays an important role in the joint performance, and an understanding of its nonlinear behaviour and its influence on leakage propagation is required so that material selection can be optimised.

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