ABSTRACT

The objective of this work is an experimental and numerical investigation for a bolted composite flange connection for composite pipes, which are used in the oil and gas applications, and obtain a joint with high strength and high corrosion resistance. For the experimental part, we have designed and manufactured the required mould, which ensures the quality of the composite materials and controls its surface grade. Based on the ASME Boiler and Pressure Vessel Code, Section X, this GFRP flange has been fabricated using biaxial glass fibre braid and polyester resin in a vacuum infusion process. Numerically, an investigation is carried out using 3D finite element analysis (FEA) of a bolted GFRP flange joint including flange, pipe, gasket and bolts. This model has taken into account the orthotropy of the GFRP material and the non-linear behaviour of the rubber gasket material for both the loading and non-loading conditions. Furthermore, the leakage propagation between the flange and the gasket has also been simulated in this investigation by using the pressure-penetration criteria PPNC in ANSYS. Finally, the flange has been tested under the internal pressure and the agreement between the experimental and numerical results is excellent.

Keywords: GFRP Bolted Flange Joint; Piping Connection; Leakage Investigation

INTRODUCTION

Metallic bolted flange joints are the most popular means for connecting piping systems, pumps and pressure vessels that contain fluid and gas under high pressure and need periodic removal for maintenance [1]. This type of joint has been extensively investigated and written about for many decades and have probably been studied more than almost all other pressure vessel or pipeline components [2]. The most significant contribution that has been done over the years about the flange design and its calculations was by Waters et al. [3] and is known as Taylor Forge method [4]. Based on this work many of the standard and codes have been established such as ASME [5] for the metallic flange and ASME Boiler and Pressure Vessel Code, Section X [6]. Recently, bolted metallic flange joints and pipes have been increasingly replaced by fibre reinforced polymer (FRP) materials in many applications which deal with extreme harsh environments such as oil, chemical, marine environment, etc. This is due to the unique combination of the fibre reinforced plastic materials properties, which includes high strength and modulus-to-weight ratios and high corrosion resistance [7, 8]. 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 [9]. In this paper, an investigation has been conducted on the bolted flange joint made of GFRP materials. This flange has been designed and
manufactured based on the ASME Boiler and Pressure Vessel Code, Section X [6] and using glass fibre braid and polyester as raw materials and manufactured by the vacuum infusion process (VIP). In addition, a 3D FEA model has been established to simulate the bolted flange joint (consisting of flange, pipe, adhesive, bolts and gasket). This model has taken into account the orthotropy of the composite materials and the non-linear behaviour of the rubber gasket and the leakage development. Finally, the flange joint has been tested under various ranges of the bolt load and internal pressure.

EXPERIMENTAL METHOD

Fig. 1. shows a schematic diagram of the fabrication process of the bolted GFRP flange that has been designed and manufactured according to ASME [6] and using vacuum infusion process (VIP). To achieve the required dimensions of the flange, a mould has been designed and manufactured with two main parts known as mandrel and plate as well as an O-ring gasket and four bolts to seal the contact between them. (Fig. 2). The quality of the mould not only determines the inherent quality of the composite material but also controls the surface quality of the composite laminate. Therefore, its surface has been polished carefully.

For the raw materials of the flange, a glass fibre braid reinforcement has been chosen in this study to give continuity over the entire flange body and so minimize the risk of failure that usually occurs at the flange-hub intersections due to the discontinuity of fibres in this region. In addition, this will reduce the bending moment, thereby reducing the flange rotation that encourages leakage propagation. Polyester is selected as the matrix material because of its low cost and good shrinkage that facilitates the flange removal from the mould after curing. Finally, the flange has been machined to remove the extra edges that are outside the required dimensions, and drilled to create the holes of the bolts as shown in Fig. 3.

ASSEMBLY AND TESTING OF THE BOLTED FLANGE JOINT (BFJ)

In order to test pressure vessel that include the manufactured BFJ, a filament-wound pipe has been used to bond it with the flange. The two parts are bonded together by using a taper-taper bonding joint, which is the strongest among the other bonding joint types, and PSX.60 epoxy as an adhesive material. Double acrylic blind flange is used to close the flange after putting a rubber gasket between them. For the other end of the pipe, a heavy-duty GFRP flange with steel blind flange have been used to close it and connect the fittings as shown in Fig. 4. These fittings are the inlet and outlet of the fluid, the inlet of the pressure pump and the other hole is to connect the pressure gauge. Many strain gauges have been utilized to measure the strains on different places of the flange body while the BFJ is
under the testing at the bolt-up stage and the operating stage. In addition, two strain gauges are embedded inside two bolts to measure the axial strains of the bolts and investigate the relationship between the bolt load and the pressure. In order to apply the same load for all bolts, a digital torque wrench adapter has been used to transfer the same torque to the bolts that have strain gauges to the other. Finally, this pressure vessel has been tested under various bolt loads and internal fluid pressures.

**FINITE ELEMENT ANALYSIS (FEA)**

The BFJ has been simulated using a 3D finite element analysis with ANSYS version 18. The simulation includes flange, pipe, adhesive bonding, gasket and bolt with dimensions and shapes compliant with the ASME Boiler and Pressure Vessel Code, Section X [6]. As shown in Fig. 5, a 1/6th portion of the circumference of the Bolted flange joint has been modelled. This is due to the rotational symmetry about the axial axis of the BFJ and reduces the total simulation time and computer resources.

**MATERIALS PROPERTIES**

As mentioned earlier, this model has taken into account the orthotropy of the composite materials. Therefore, the orthotropic mechanical properties of the flange, divided into two parts (flange and hub), and the pipe have been calculated by using composite Autodesk software [10]. In all composite parts, the braid angles of the braid fiberglass sleeves are measured experimentally and are considered as fixed at ±65°, ±44.5° and ±55° for the flange, hub and the pipe, respectively. Similarly, the fibre volume fractions (Vf) are obtained for all parts using a burn off method, and they are found to be 60.7% for the flange, 61.1% for the hub and 51% for the pipe. In addition, the crimp angle of the fabric of the flange is also measured but its effect on the elastic properties is small and has been ignored. The fastener parts (bolt, washer and nut) are made of stainless steel (304) and their properties are assumed isotropic and linear with E= 193 GPa, v=0.3.

A Viton rubber gasket has been used in this investigation. It is simulated as non-linear material because of its non-linearity response during either loading or unloading. Therefore, a load compressive mechanical test has been conducted to find the mechanical characteristics of the gasket based on ASME D575-91 [11]. These data are shown in Fig. 6. In addition, transverse shear stiffnesses TSSxy= TSSxz= G/h=1062.88 MN/m3 have been used in FEA. The shear modulus (G) has been measured according to BS ISO 1827 [12] and h is the thickness of the gasket (3 mm). In addition, the coefficient of the friction between the flange and the rubber gasket is measured experimentally as 1.1.
BOUNDARY CONDITIONS

Some of the boundary conditions have been applied on the selected portion in this FEA model due to the symmetry around the axial axis and the axial symmetry on the mid thickness of the rubber gasket. As shown in Fig. 7, the circumferential displacements in the normal direction on the surface of the circular symmetry are fixed, i.e. $U_\theta=0$. Also, the displacements of elements located at the bottom surface of the gasket are fixed, i.e. $U_z=0$. The remaining boundary conditions have been divided into two stages. For the bolt up stage, an axial force has been applied on the lower face of the bolt to deform the rubber gasket and seal the contact between the flange and the gasket (Fig. 7a). During the operating condition, internal pressure and hydrostatic end force are induced on the joint system as well as the fluid pressure penetration (FPP) between the flange and the gasket (Fig. 7b). The hydrostatic end force is calculated based on the inner diameter of a pipe. The fluid pressure penetration (FPP) between the flange and the gasket is modelled by using a pressure-penetration criterion using the contact element real constant PPCN [13]. This feature of fluid pressure penetration capability has been added from version 12.0 of ANSYS [14].

![Fig. 6: Characteristics of the rubber gasket obtained experimentally](image)

![Fig. 7: 3D model flange joint with mesh and boundary conditions (a) Bolt up stage (b) Operating stage](image)
RESULTS AND DISCUSSION

This section presents the numerical and experimental results of the bolted flange joint (BFJ) subjected to the variable clamping force (Bolt up conditions) up to 9.69 kN, which is the design bolt force that has been calculated based on the ASME code [6] when the flange is subjected to internal pressure 3.4 bar. Also, it is exposed to increasing internal fluid pressure (operating conditions) up to the leakage point.

TOTAL DEFORMATION

Fig. 8 shows the distribution of the total deformation of the bolted flange joint under the bolt load 9.69 kN and during the operating conditions under internal pressure 8 bar as well as the bolt force that has been initially applied. It is apparent from this Fig. 8 in both stages that the maximum deformation has occurred at the bolts and the hole around the bolts. This is due to the axial force of the bolts, which is required to keep the flanges together and seal the contact between the gasket and the flanges. As shown in Fig. 8-a, the total deformation increased when the internal pressure is applied, which causes additional bending of flange.

LEAKAGE PROPAGATION

This study also included an experimental and numerical investigation about the leakage of the fluid. During the experimental test, the internal pressure has been increased and the leakage has taken place at pressure 9.2 bar whereas the FEA results showed that the leakage has occurred at pressure 8 bar. As expected, this small difference is due to the spring back of the GFRP flange after curing. This spring back results from the shrinkage of the resin and cannot be taken into account in the FEA analysis.

AXIAL STRAIN

The variation of the flange hub axial strain with internal pressure is illustrated in Fig. 9 for both cases (experimental and numerical). The strain has been measured at the top surface of the hub and at high 100 mm from the lower surface of the flange. The ordinate is the axial strain produced on the hub of the flange and the abscissa is the internal pressure. The results have shown that this area is subjected to compression strain. As illustrated in the Fig. 9, there is linear behaviour between the internal pressure and the compression strain and the agreement between the experimental and numerical results is excellent.

HOOP STRAIN

Fig. 10 presents the relationship between the flange hub hoop strain and the internal pressure. The ordinate is the hoop strain produced on the hub of the flange at the same location of the axial strain and the abscissa is the internal pressure. It is seen that a tension strain is produced in this point and increases with internal pressure. This occurs as a result of the internal pressure, which has been applied on all of the internal faces.
CONCLUSION

The manufacturing of the bolted GFRP flange joint has been done in two steps, which are manufacturing of the mould and flange fabrication. The manufactured mould has exhibited a good performance during the manufacturing process. The fabricated flange has demonstrated good strength and reliability. As shown in the results, the values of the strains are very low during the testing, which means that the flange is quite stiff and strong as a result of the good selection of the processing method and materials. In addition, the FEA analysis has shown a good agreement with the experimental results. Therefore, it can be used as an efficient means to study the bolted flange joint compared to other methods, which are relatively time-consuming and expensive.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the financial supports provided by the Higher Committee for Education Development in Iraq (HCED).

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