Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Research on the failure mechanism of non-metallic oil pipeline flange

To cite this article: Yu Weng *et al* 2024 *J. Phys.: Conf. Ser.* **2808** 012047

Journal of Physics: Conference Series **2808** (2024) 012047 doi:10.1088/1742-6596/2808/1/012047

Research on the failure mechanism of non-metallic oil pipeline flange

Yu Weng[1*], Dejun Li[1], Shuxuan Jiang[1], Shuang Yang[1], Gang Wu[1] and Zhian Deng[2]

[1]College of Petroleum Engineering, Xi'an Shiyou University, Xi'an, Shaanxi, 710065, China
[2]Quanzhou Vocational and Technical University, Quanzhou, Fujian, 362000, China

[*]Corresponding author's e-mail: wengyu009@hotmail.com

Abstract. Fiberglass flanges are gradually being applied in oil field mixed transportation pipelines due to their advantages such as corrosion resistance and easy forming. However, at the same time, the anisotropy and local discontinuity are present in glass fiber components. Starting from the discovery of cracking, leakage, and other issues in the fiberglass flange of a certain oilfield sewage export pipeline, a combination of experimental research and numerical analysis is used to study the on-site fiberglass flange joint. Considering the internal pressure, bending moment, bolt load, and other loads in actual operating conditions, mechanical performance tests are conducted on the flange substrate, and the mechanical properties and damage conditions are obtained. A finite element model including pipeline gasket flange is constructed, and the flange damage under preloading, operation, external bending moment, and other operating conditions is analyzed based on the nonlinear Hashin failure criterion and the Tserpes sudden stiffness degradation model. It is found that bolt holes are more prone to large-scale failure damage due to stress concentration. As the external bending moment increases, it will simultaneously reduce the gasket compressive stress and cause flange surface failure and damage. According to research, it is recommended that the pre-tightening force of bolts during pipeline operation should not exceed 400000 N, and the bending moment generated by factors such as wind load and soil load should not exceed 200 N·m.

1. Introduction

The research on leakage of bolted flanges at home and abroad mainly focuses on the leakage between steel flanges, with a focus on pipeline vibration under pressure and temperature, fatigue of steel structures, gasket creep, gasket material itself, and bolt torque [1]. Research on composite materials often focuses on the stress and thermal analysis of bolted connections or laminated plates. Therefore, the leakage mechanism of fiberglass pipe flanges is not yet mature, and there is relatively little experimental research, as well as a lack of validation of numerical models based on relevant experimental data. This article takes the 4-hole fiberglass bolt flange and steel flange joint in a low-pressure pipeline system as the research object [2]. Based on sealing failure and fiberglass flange strength failure, experimental research is conducted to obtain the physical parameters of the composite material. Through numerical research [3], the failure characteristics of fiberglass flanges in different working conditions such as pre-tightening, operation, and pipeline bending moment are studied, providing a reference for actual construction.

However, as a composite material and with weaker stiffness than steel structures, fiberglass pipe flanges are prone to damage when subjected to large service loads [4], resulting in damage and leakage failure at the connection components used in water injection and sewage collection production operations [5]. In addition, composite materials exhibit significant anisotropy, with interlaminar normal strength significantly lower than tangential strength, making the factors leading to the failure of composite structures uncertain [6]. Therefore, this study focuses on multiple cases of cracking and leakage of fiberglass flanges in sewage export pipelines in a certain oilfield and conducts an in-depth exploration of the failure phenomenon of fiberglass flanges [7].

2. Research method

2.1. Material testing methods

This study analyzes the flange connection of low-pressure fiberglass pipes with a diameter of D=50 mm. The size structure of fiberglass flanges is mostly made based on the size of steel structural flanges [8]. According to HG/T20592-2009 Steel Pipe Flange (PN Series) and the data provided by the manufacturer, the specific dimensions of the model are shown in Table 1.

According to HG/T20592-2009 Steel Pipe Flanges (PN Series), HG/T20613-2009 Fasteners for Steel Pipe Flanges (PN Series), and the "Practical Manual for Pressure Vessel Materials: Carbon Steel and Alloy Steel", the selected flange material is WCA, which is consistent with the pipe material. The alloy structural steel 35CrMo is selected for bolts and nuts, and the relevant material parameters are shown in Table 2. For the material parameters of the fiberglass pipe flange section, the mechanical test was conducted on a single-layer fiberglass reinforced epoxy resin board with a fiber content of 50% [9].

Table 1. Steel Flange Dimensions.

Nominal Diameter	Outside Diameter *D/mm*	Bolt Hole Center Circle Diameter *K/mm*	Bolt Hole Diameter *L/mm*
DN50	165	125	18
Nominal Diameter	Number of Bolt Holes *n/ individual*	Bolt *Th*	Flange Thickness *T/mm*
DN50	4	M16	18

Table 2. Material Performance Parameters.

Name	Elastic Modulus/ GPa	Poisson's Ratio	Yield Strength/ MPa
Flange and Connecting Pipe	212	0.288	205
Bolts and Nuts	214	0.286	735

2.2. Numerical analysis methods

This study uses ABAQUS software for numerical analysis, taking 1/2 of the circumference direction to establish a joint model, which includes bolts, nuts, fiberglass pipe flanges, steel flanges, and flange gaskets. The above geometric modeling is meshed. Hexahedral solid element C3D8R is used for the overall model, the GK3D8N element is used for the gasket to simulate contact performance, and the eight-node three-dimensional bonding element COH3D8 is used to simulate the cohesive bonding layer. Figure 1 shows the finite element model after meshing [10].

Journal of Physics: Conference Series **2808** (2024) 012047 doi:10.1088/1742-6596/2808/1/012047

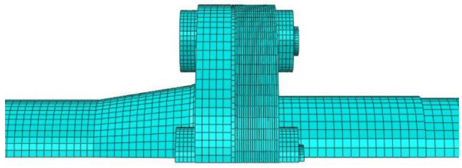


Figure 1. Finite element model.

In the process of flange joint analysis, the bolt load is set on a tangent plane in the middle of the bolt, and displacement constraints are added at the flange connection: displacement constraints are set on the upper connection of the fiberglass steel flange, complete fixed constraints are applied to the end face of the lower connection of the steel flange, and the end face of the upper connection of the fiberglass flange is free, as shown in Figure 2.

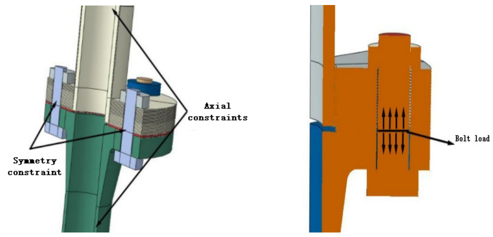


Figure 2. Boundary.

By setting a larger bolt load under pre-tightening conditions and continuously increasing the load, it is determined whether it will affect the integrity of the connection and cause strength damage to the fiberglass flange [11]. The calculation formula is taken from the national standard GB150-2011 fixed pressure vessel.

Five different bending moments of 200-1000 N·m are applied to the end face of the connecting pipe on the fiberglass flange as external conditions, and two different gaskets, chloroprene rubber flange gasket, and flexible graphite gasket, are studied under bolt loads of 20000-300 N and 30000-40000 N.

The Hashin [12] failure criterion can accurately determine various damage failure modes, and later scholars have revised and improved the original Hashin criterion. Therefore, this article chooses the three-dimensional Hashin failure criterion to predict the failure initiation of laminated plates.

Based on the application scenarios of different reduction schemes, this article ultimately selects the material parameter degradation method proposed by the Tserpes model to reduce the stiffness of the damaged area [13], corresponding to different failure damage modes of the three-dimensional Hashin progressive damage criterion. After comprehensive consideration, a combination of the three-dimensional Hashin asymptotic failure criterion and the Tserpes sudden stiffness degradation model is selected for the analysis of fiberglass flanges. A UMAT progressive damage subroutine is written by using the FORTRAN language, taking into account the cohesion model, laying a solid foundation for the development of finite element simulation.

3. Research and analysis

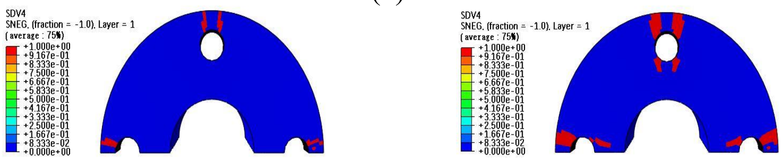
3.1 The effect of bolt load on the strength of flange joints under pretensioning conditions

Based on the three-dimensional Hashin failure damage criterion, when SDV≥1, it can be considered that complete strength failure damage occurs. By applying bolt loads of 40000 N, 50000 N, 60000 N, 70000 N, and 80000 N to the bolts, the strength damage cloud maps of fiberglass flanges under different bolt loads are obtained, as shown in Figure 3 to Figure 6. It can be seen that as the bolt load increases, the most common strength failure damage modes in the radial strength-dominated fiberglass pipe flange connection are matrix tensile failure and matrix compression failure.

Journal of Physics: Conference Series **2808** (2024) 012047 doi:10.1088/1742-6596/2808/1/012047

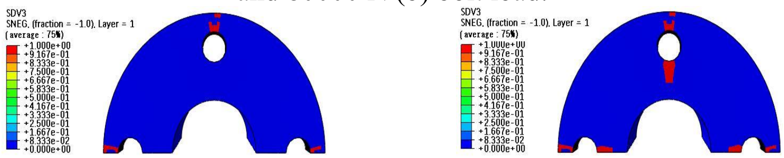
(a) (b)

Figure 3. Tensile failure diagram of chloroprene rubber fiberglass flange matrix at 50000 N (a) and 80000 N (b) bolt load.



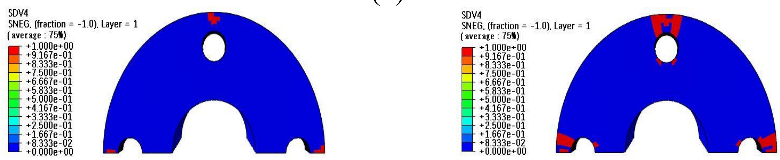
(a) (b)

Figure 4. Compression failure diagram of chloroprene rubber fiberglass flange matrix at 60000 N (a) and 80000 N (b) bolt load.



(a) (b)

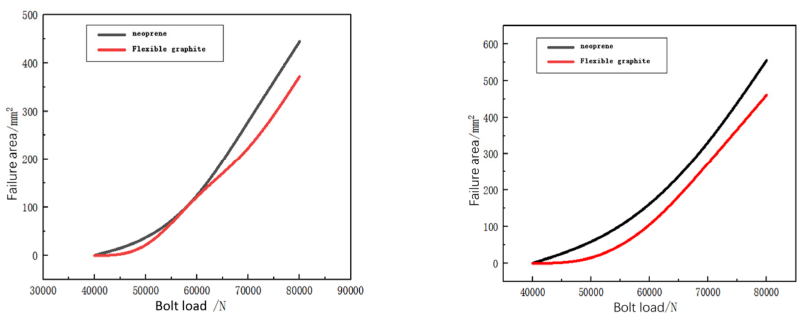
Figure 5. Tensile failure diagram of flexible graphite fiberglass flange matrix at 60000 N (a) and 80000 N (b) bolt load.



(a) (b)

Figure 6. Compression failure diagram of flexible graphite fiberglass flange matrix at 60000 N (a) and 80000 N (b) bolt load.

By comparing the strength damage cloud maps of fiberglass flanges under different types of gaskets, it is found that under the same bolt load, the deformation degree of chloroprene rubber is greater. The trend of the tensile and compressive failure area of fiberglass flanges under different bolt loads using chloroprene rubber and flexible graphite gaskets under pre-tightening conditions is shown in Figure 7. For fiberglass flanges with predominantly latitudinal strength, when loaded to a maximum of 80000 N, subtle matrix tensile failure occurs only on the surface layer of the flange under bolt load.



(a) (b)

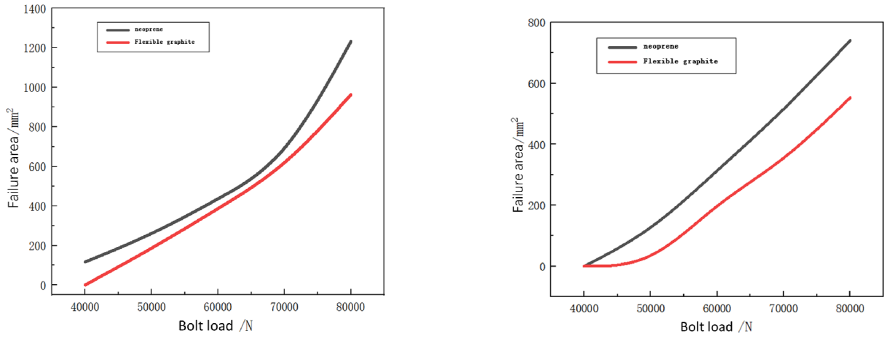
Figure 7. Failure and damage trend of fiberglass flange under pre-tightening condition.

3.2. Failure analysis of flange joints under operating conditions

After being subjected to the axial force caused by internal pressure in the pipeline, matrix tensile and compressive failure damage is more likely to occur on fiberglass flanges with predominantly meridional strength compared to pre-tightening conditions. In the flange gasket connection system using chloroprene rubber, matrix tensile failure occurs under a bolt load of 40000 N, while matrix compressive failure occurs under a bolt load of 50000 N. In the flange connection system where flexible graphite is used as a flange gasket, the tensile failure of the matrix occurs under a bolt load of 50000 N, while the compressive failure of the matrix remains unchanged compared to the pre-tightening condition, but the failure range has increased.

The trends of the tensile and compressive failure area of fiberglass flanges under different bolt loads using chloroprene rubber and flexible graphite gaskets under operating conditions are shown in Figure 8.

For fiberglass flanges with predominantly latitudinal strength, the axial force generated by internal pressure in the pipeline has a relatively small impact on the fiberglass flange joint under operating conditions. Only in flange joints where chloroprene rubber is used as a flange gasket, does matrix tensile failure occur on the bolt load bearing surface, which still only occurs at the maximum bolt load of 80000 N, but the failure range has increased. For the bolted flange connection system using flexible graphite as a fastening gasket, the structural safety is still maintained and there has been no failure.



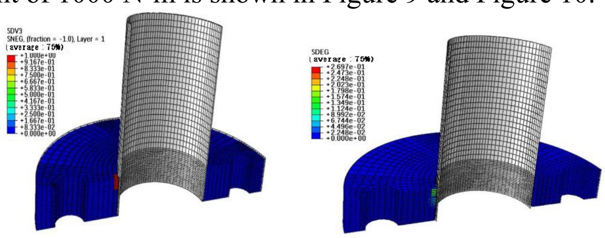
(a) (b)

Figure 8. Trend of failure and loss of fiberglass flanges under operating conditions.

3.3. Numerical analysis of flange joint failure under external bending moment

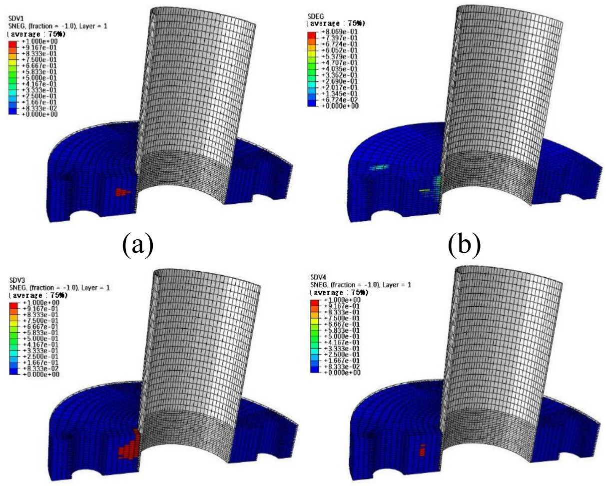
As the external bending moment applied to the pipeline joint continues to increase, it may have an impact on the strength of the fiberglass flange. By applying a bending moment to the end face of the connecting pipe on the fiberglass flange and increasing it, the following failure cloud maps of the fiberglass flange structure can be obtained based on the three-dimensional Hashin criterion and stiffness degradation (SEDG). The following are examples of the failure damage cloud maps of the chloroprene rubber fiberglass flange joint.

The failure damage cloud diagram of the chloroprene rubber gasket fiberglass flange joint under a maximum bending moment of 1000 N·m is shown in Figure 9 and Figure 10.



(a) (b)

Figure 9. Matrix tensile (a) and Delamination (b) failure damage diagram of fiberglass flange under bolt load of 20000 N.

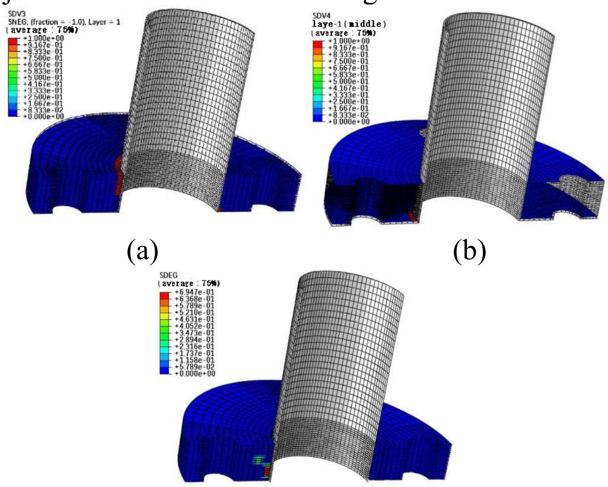


(a) (b)

(c) (d)

Figure 10. Fiber tensile (a), Delamination (b), Matrix tensile (c) and Matrix compression (d) failure damage diagram of fiberglass flange under 30000 N bolt load.

For the study of strength failure caused by external bending moments in fiberglass reinforced plastic (FRP) mainly with latitudinal strength, the failure damage cloud map of the chloroprene rubber FRP flange joint is also taken as an example. For example, the failure damage cloud map of the chloroprene rubber gasket FRP flange joint under a maximum bending moment of 1000 N·m is shown in Figure 11.



(a) (b)

(c)

Figure 11. Matrix tensile (a), Matrix compression (b) and Delamination (c) failure damage diagram of fiberglass flange under bolt load of 20000 N.

4. Conclusion

Taking the fiberglass flange connection of a certain oilfield sewage export pipeline as the research object, considering material anisotropy and using the determination of mechanical performance parameters of fiberglass epoxy resin board as the numerical simulation analysis basis, the failure problem of fiberglass flange and steel flange connection under longitudinal and latitudinal strength, bolt load, internal pressure, and external bending moment is discussed. The strength failure damage of fiberglass flange is numerically studied and judged. The conclusions of this study are as follows:

(1) Among the load conditions involved, the strength of the flange itself and the external bending moment are the two main factors leading to the failure of the flange joint. Although bolt load, pipeline

Journal of Physics: Conference Series **2808** (2024) 012047 doi:10.1088/1742-6596/2808/1/012047

internal pressure, and gasket type have a certain impact on the failure of the joint system, their impact is relatively weak.

(2) With the increase of bolt load, stress concentration occurs at the bolt hole and matrix failure damage occurs. The degree of tensile and compressive failure damage to the substrate on the flange surface is inversely proportional to the strength in the weft direction. Therefore, it is advisable to choose a substrate with higher latitudinal strength when using it to withstand greater bolt loads.

(3) The failure and damage mode exhibited under the bending moment and bolt load is mainly caused by the inward tensile failure of the matrix generated from the flange neck, that is, the longitudinal strain generated under the external bending moment has serious damage to the adhesive performance between the flange and the pipe wall. Therefore, in design, the focus should be on strengthening the flange neck and improving the strength of the adhesive curing agent.

This work was financially supported by the Natural Science Basic Research Program of Shaanxi (Program No. 2021JM-402), and the Research Fund of Key Laboratory of High-Performance Manufacturing for Aero Engine (Northwestern Polytechnical University), Ministry of Industry and Information Technology (Grant No. HPM-2022-03).

References

[1] Liu L, Wang X, Wu Z, et al. Effect of fiber architecture on tension–tension fatigue behavior of bolted basalt composite joints [J]. Engineering Structures, 2023.
[2] Duc T Q, Nhut P, Matsumoto Y. Strengthening of Multi-bolted Connections in Pultruded GFRP by Glass Fiber Sheets: An Experimental Study [J]. Applied Composite Materials, 2023, 30:833 - 856.
[3] Zhang B, Jin X, Yu T, et al. Sealing characteristics of aramid fiber reinforced rubber gasket with scratch depth and width defects [J]. Polymer Composites, 2023.
[4] Behera S, Mohapatra D R, Mondal S. Free Vibration Analysis of FRP Sandwich Composite Plate and Quantification of Uncertainties in its Vibration Response [J]. International Journal of Structural Stability and Dynamics, 2023, 23(03).
[5] Rino Nelson N, Siva Prasad N, Sekhar A S. Stress distribution and performance of threaded bolts in gasket flange joints [J]. Materials Science & Engineering Technology, 2021(9):52.
[6] Wu C L, Kan J C, Wang Q H, et al. FEM analysis of the modular prefabricated steel-concrete composite beam-column internal joint under reciprocating action [J]. Steel & Composite Structures: An International Journal, 2021(1):41.
[7] Signetti S, Bosia F, Ryu S, et al. A combined experimental/numerical study on the scaling of impact strength and toughness in composite laminates for ballistic applications [J]. 2021.
[8] Reed M. Baker Hughes Offers Composite Flexible Pipe for Onshore Pipelines [J]. Pipeline & Gas Journal, 2021(3):248.
[9] Zhou Y X, Chen B, Li J Y. Application and Evaluation of Non-Metallic Pipeline in Lamadian Oilfield [J]. Advanced Materials Research, 2013, 694-697:521-525.
[10] Huan-Zhi C, Shao-Jun L, Jun-Chao Z, et al. Research on the Problem of Sealing Heat Exchanger Pipe Flange and Pipe Plate [J]. Guangzhou Chemical Industry, 2014.
[11] Zhou W, Wang H. Study on sealing performance of bolted flange structure after creep based on ABAQUS [J]. IOP Conference Series Earth and Environmental Science, 2021, 687(1):012150.
[12] Hashin Z. Fatigue Failure Criteria for Unidirectional Fiber Composites [J]. Journal of Applied Mechanics, 1981.
[13] Nguyen-Hoang M, Becker W. Efficient Stress and Failure Analysis of Bolted Joints for Composite Laminates [C]// Deutscher Luft-und Raumfahrtkongress 2021.