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A Review on Finite Element Modeling and Analysis Of Gasket On Circular Bolted Flange Connection

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Abstract-Flanged joints with gaskets are very common in pressure vessel and piping systems, and are designed mainly for internal pressure. These joints are also used in special applications such as in nuclear reactors and space vehicles. The connection of a fuel duct to a rocket engine is a typical application of these joints in space vehicles. Prevention of fluid leakage is the prime requirement of flanged joints. Many design variables affect joint performance and it is difficult to predict the behaviour of joints in service. Therefore, in this study, a review has been done.

Keywords- Coupling, Ansys, FEM analysis, stress, deformation

I. INTRODUCTION

In the piping industry, there are several problems that continue to receive a considerable amount of research attention, particularly in the area of bolted-flanged joint design. Two problems that are critical in bolted flanged joint design are strength of the joint and leakage. The first problem has been studied since the 1920s for metallic joints with a general consensus on the available solution well established [1]. The second problem has been studied for almost an equally long period yet leakage analysis continues to be the subject of much study, as evident by the number of articles published in the past quarter century [2-4].

Here, an analysis is presented that can be used in design formulations for the detection of leaks for a specified pressure. There are many parameters that influence joint leakage (bolt load, internal pressure, gasket material, flange stiffness, flange geometry, contained medium, etc.); of these parameters, boltload, flange stiffness, internal pressure, and gasket material appear to be most critical.

Half of a typical raised face bolted flange is depicted in Fig. 1.1. This is one of the symmetries that can be exploited in modeling bolted flanged joints. There is another symmetry that can be used to reduce the size of the model, the wedge model shown in Fig. 1. Also, leakage can be analyzed using an axisymmetric model, taking into account proper boundary conditions, without loss of practical accuracy.Gaskets play an important role in the sealing performance of bolted flange joints, and their behaviour is complex due to nonlinear material properties combined with permanent deformation. The variation of contact stresses due to the rotation of the flange and the material properties of the gasket play important roles in achieving a leak proof joint.

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The complexities associated with the analysis of bolted flange joints with gaskets are due to the nonlinear. behaviour of the gasket material combined with permanent deformation. The material undergoes permanent deformation under excessive stresses. The degree of elasticity (stiffness) is a function of the compressive stresses, which act on the gasket during assembly and after it is put into service. It is commonly recognized that gasket stiffness has a predominant effect on the behaviour of the joint because of its relatively low stiffness.

Another inherent problem with bolted joints is flange rotation and contact stresses. These are caused by the bolt pre-load and increase when the joint is subjected to internal pressure. The ASME code has made an attempt to correct this problem by adding a rigidity constraint ‘J’ based on the fixed rotation.

This may not be adequate, as the rotation of the flange is not a unique value. Flange rotation causes variable compression across the gasket from the inner radius to the outer radius. Due to the variation in compression, the contact stresses also vary along the radius.In the present work, a finite element (FE) model for finding the contact stresses in a gasket has been developed.The sealing performance of different gasket models with varying loading and operating conditions has been studied. The distribution of contact stress on the gasket for different loading conditions has also been studied.

II. LITERATURE REVIEW

Elkhlaidyet al. (2023) developed a procedure suitable to determine the maximum bolt pre-stress required for the proper gasket seating in bolted flange connections. The proposed method is valid for all the flange types and assumes that the gasket leakage must be limited so as to not affect the flange joint integrity. A 3D finite element model is used in which elastic–plastic behaviour of the flange material, non-linear gasket material behaviour and non-linear flange–gasket contact are assumed. The final goal of the developed work is to update, using a more realistic perspective, the recommendations given by ASME PCC-1 Appendix-O for bolt pre-stress values when applied to standard dimensional ASME flanges. Additionally, in this work, the effect of the straight portion length of the flange hub at its welded connection with the connected pipe and the fillet radius at the hub-flange transition on the stresses and strains distribution are also addressed.

He et al. (2023) proposed an approach to evaluate the pipeline's strength and sealing performance considering thermal effects in actual operating conditions by combining the experimental measurement and thermos-structural analysis. The critical thermodynamic parameters are identified through measured temperature data in operating conditions, and then these parameters are used in the thermos-structural analysis to obtain the actual temperature and stress fields. Then, the strength and tightness in complex temperature cases can be evaluated accurately. The pipe flange connection of a liquefied natural gas (LNG) fueling station is analyzed to verify the presented method's effectiveness. This method applies to evaluating the pipeline's strength and tightness and can predict the pipeline's performances under extreme temperatures using the tested data within the measurement range and the corresponding thermos-structural analysis. Furthermore, the work in this paper also provides a reference for the design and analysis of pipe flange connections working in complex temperature conditions.

Zacal et al. (2023) described characteristics of stress flow and deformations of two basic types of flange joints, which differ in the way of power flow. Subsequently, the methodology of EN 1591-1 standard is verified using the Final Element Method. The article also presents a description of the most common flange joints defects in technical practice and causes thereof. The ways to improve the methodology of flange joints design are discussed in the conclusion.

Nelson et al. (2023) studied the leakage of bolted flange joints in detail. The significance of variation in axial joint stiffness due to bolt load relaxation at elevated temperature is discussed. Attention is also given to sealing performance and prediction of leakage rate under different loading conditions. The load bearing capacity and failure criteria of flange joint, along with the effect of loading history are also discussed. Then, the focus is turned towards the numerical formulations of flange joint under dynamic loads, in addition to experimental techniques to extract its response. Further, the current challenges in this area along with future scope for improvement to achieve leak-proof and structurally sound flange joint are also discussed in this review article.

Xing and Wang (2023) presented modeling and dynamic analysis of bolted joint plates under general boundary conditions, where the flange geometry is considered. An artificial spring technique is utilized to simulate the general boundary conditions and connection of bolts. The energy functions of plates and flanges are obtained based on the Kirchhoff and Euler-Bernoulli beam theories, respectively. Then, by taking the Chebyshev polynomials as admissible functions, the Lagrangian approach is applied to obtain the equations of motion for the bolted joint plates. The discretized motion equation is obtained by employing the assumed mode method. The accuracy of the present method is verified by comparing the results with those from ANSYS. Finally, parametric studies are performed to analyze the effect of boundary spring stiffness, flange geometry parameters, the bolt number and its connecting stiffness, and the plate size on the vibration properties of bolted joint plates. The results indicate that there exist abundant frequency veering and mode shift phenomena in the bolted joint multi-plate structures.

Mehmanparast et al. (2020) undertakes a comprehensive review of the lessons learned about bolted connections from a range of industries such as nuclear, aerospace, and onshore wind for application in offshore wind industry. Subsequently, the collected information could be used to effectively address and investigate ways to improve bolted flange connections in the offshore wind industry. As monopiles constitute an overwhelming majority of foundation types used in the current offshore wind market, this work focusses on large diameter flanges in the primary load path of a wind turbine foundation, such as those typically found at the base of turbine towers, or at monopile to transition piece connections. Finally, a summary of issues associated with flanges as well as bolted connections is provided, and insights are recommended on the direction to be followed to address these concerns.

Cloostermans et al. (2023) investigated the potential of using fiber-optic sensors, more specifically fiber Bragg gratings, as strain sensors to estimate gasket stress in bolted flange connections with gaskets. To the best of our knowledge, it is the first time that said gaskets are instrumented with fiber Bragg gratings. For our experiments, we submit these gaskets to relevant mechanical loads, both in a laboratory setting and in a realistic industrial environment. We analyze the relation between the fiber Bragg grating response and the applied mechanical load to define transfer functions that allow estimating the gasket stress and hence the sealing performance of the flange connection.

Herath et al. (2023) investigated a performance-based design method through numerical analyses to improve the performance of the bolted stiffened end-plate connection. This method is primarily based on the strong column and weak beam concept. Here, primary and secondary yield mechanisms are organized in a hierarchy so that the connection failure occurs in a predefined way by identifying the yield mechanisms and failure modes of the connection. Through this, the targeted performance characteristics of the connection identified as ductility and energy dissipation capacity can be improved. Thus, this performance-based design method is a better approach than the conventional load resisting design method proposed by the code of practice.

Mir-Haidari and Behdinan (2022) proposed a novel and robust analytical formulation for implementation in FE analysis that accurately captures and represents the nonlinear dynamic characteristics of bolted flange connections. The proposed nonlinear analytical lump model has demonstrated significant accuracy and precision in capturing the nonlinear dynamic characteristics of bolted flange connections with spigots under various loading conditions. The proposed model clearly represents and characterizes the nonlinear phenomena of peak amplitude damping and frequency shift. It is also computationally efficient, making the model feasible for implementation when performing nonlinear analyses of large structural assemblies such as full aeroengine models. Moreover, the proposed analytical lump model is universal, permitting its implementation in various structures with different material properties and geometries.

The validity and accuracy of the proposed model has been verified using nonlinear experimental test data for an aeroengine casing assembly.
Miao et al. (2021) presented a field experiment to study the interaction effect on the clamp bolt tightening. In the experiment, three types of clamp and three tightening sequences were included. Then, finite element models considering the actual nonlinear transverse compressed behaviour of main cables were devised to simulate the bolt tightening procedures, thus providing an effective numerical tool to understand the nonlinear interaction effect on clamp bolts tightening. The experimental results provide validations for subsequent numerical studies, showing that the devised finite element modeling method can effectively predict nonlinear deformation of the main cable and the residual tension force of the clamp bolts. Moreover, the tightening efficiency of different tightening sequences are discussed based on the experimental and the numerical results. Conclusions can be drawn that for the clamps with much longer length and much more rows of bolts, the degree of the nonlinear interaction effect tends to be higher. The side-to-centre bolt tightening sequence is more effective than the centre-to-side sequence.

Li et al. (2021) The complex micro-slip phenomenon of the contact interface will lead to the nonlinear stiffness of the connection structure, as well as the structural damping and energy dissipation. As the most important connection structure of the combination rotor, the mechanical properties of bolted flange joint interface are needed in the dynamic analysis of the combined rotor. Therefore, it is urgent to model and test the friction contact interface in the nonlinear dynamic analysis of rotor. In this paper, two sets of mechanical characteristics test system were built to test the dynamic parameters of tangential and bending directions of the bolted flange joint interface.

Then, the mechanical behavior and the change regularities of dynamics parameters were studied under different external excitation, bolt distribution andtightening torque. The results show that once the bolt preload is above the rated torque, stiffness softening behavior is not significant; and then the tangential stiffness of the jointinterface tends to be stable, with the variation range of 8.08~8.96 e8N/m; the equivalent bending stiffness coefficient is about 3.38~3.83 e6N·m/rad. With the decrease of bolt preload, the external excitation and the number of bolts have a significant effect on the stiffnessreduction of the joint. Finally, the change interval of the dynamics parameters of the interface obtained by the experiment provide basis for the uncertainty dynamic analysis and optimization of the rotor.

Patel et al. (2020)Bolted flange joints are widely used in engineering structure. The evolution of leakage is studied using detailed contact finite element analysis. The distribution of stress at the gasket is analyzed using a contact condition based on slide-line elements using ABAQUS, a commercial finite element code. Slide-line elements also take into account pressure penetration as contact that is lost between flange and gasket. Results are presented for a particular flange, a raised face flange sealed by a mild steel gasket. Although a lot of pipe flange connections are exposed to elevated temperature during long-term plant operation, a sealing performance of the pipe flange connections at elevated temperature is not well understood because of the experimental difficulty and the analytical problems due to the lack of the materials properties of gaskets at elevated temperature. The authors have been evaluating the effect of the material properties of spiral wound gaskets (SWG) and the sealing performance of the pipe flange connections at elevated temperature.

Zhang et al. (2020) study the effect of different bolts tightening sequences on the stress of bolts work-piece, the finite element simulation and stress test experiments are adopted. Three types of bolt work-piece: two, five, and frame type bolts work-pieces are studied under different tightening sequences. The stress values and distribution are obtained under different tightening sequences by simulation. It is observed that the stress distribution tendency of bolts work-piece has little change under different tightening sequences. It also notices that the tightening sequences have no effect on two bolts work-piece due to the symmetry of work-piece. In five bolts work-piece, the variation range of stress under tightening from ends to middle is smaller than that under sequence tightening, which indicates that better stress uniformity is obtained under tightening from ends to middle in five bolts work-piece. Similarly, in frame bolts work-piece, the variation range of stress under symmetrical tightening is smaller than that under sequence tightening, which indicates that better stress uniformity is obtained under symmetrical tightening in frame type bolts work-piece. Furthermore, the experimental results are in good agreement with the simulation results. Moreover, the stress variation mechanism is revealed by analyzing residual preload variation under sequence tightening.

Jaszak andAdamek(2019)presented the method of design and strength analysis of the flange-gasketed-bolted joint. In the first part, analytical calculations were carried out. Their purpose was to determine the assembly torque of nuts to achieve the desired tightness. The flanged joint designated as DN100 PN40 with two different gaskets was taken into consideration. The analytical calculations were performed in accordance with the algorithm included in PN EN 1591-1.

Zhang and Xiao (2019) in the present work, finite element models were used for analyzing the stress distribution of metal-to-metal contact pipe flange connection under different internal pressures, temperatures, and external bending moments to evaluate the sealing and strength performance. A metal-to-metal contact pipe flange connection device was also experimented. It was found that the results of the axial bolt force and flange hub stress obtained from the experiments were in fairly good agreement with the finite element simulations. The leakage test of metal-to-metal contact type gasket was conducted to highlight its leakage characteristics under different temperatures.

The methods to determine the maximum allowable bending moment of a metal-to-metal contact flange joint according the strength criterion and the sealing criterion were analyzed. The results showed that the maximum allowance bending moment was determined by the strength criterion rather than by the sealing criterion with different thermal loadings when the initial bolt-up stress was high enough to achieve metal-to-metal contact.

Zhu et al. (2019) In previous work, an analytical model based on the theory of circular beams on linear elastic foundation was proposed to predict the bolt tension change due to elastic interaction. Based on this model, this paper presents a novel methodology for the optimization of the tightening sequence. The target preload and the load to be applied to each bolt in each pass can be calculated to achieve uniform final preload and avoid bolt tension reaching yield under a number of specified tightening passes. The validity of the approach is supported by experimental tests conducted on a NPS 4 class 900 welding neck flange joint and by finite element analysis on this bolted joint using the criss-cross tightening and sequential patterns. This study provides guidelines for bolted flange joints assembly and enhances its safety and reliability by minimizing bolt tension scatter due to elastic interaction.

III. CONCLUSION

1. Accuracy and Reliability: FEA is a powerful numerical technique for simulating the behavior of complex mechanical systems, including couplings. When properly executed with accurate material properties and boundary conditions, FEA provides reliable results that can help engineers understand how couplings perform under various loads and conditions.
2. Design Optimization: FEA can be a valuable tool in the design and optimization of couplings. Engineers can use FEA to iteratively refine the geometry and material selection of couplings to achieve desired performance characteristics, such as minimizing stress concentrations or maximizing torque transmission.
3. Stress Analysis: FEA is particularly useful for assessing the stress distribution within a coupling. This is crucial for ensuring that the coupling can withstand the expected loads without experiencing excessive deformation or failure.
4. Fatigue Analysis: Couplings often undergo cyclic loading conditions. FEA can be employed to analyze fatigue life and predict the number of cycles a coupling can endure before failure, aiding in the selection of appropriate materials and design modifications.
5. Environmental Factors: FEA can also incorporate environmental factors, such as temperature variations, corrosion, or other environmental stressors, to assess the long-term durability and reliability of couplings in different operating conditions.

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