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Stresses in Bolted Flange Coupling for Different Loading Case

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Abstract: *Bolted flange joints are critical components in piping and pressure vessel systems, where maintaining joint integrity and preventing leakage are primary concerns. While the strength of metallic joints has been well studied since the 1920s, leakage analysis remains a challenging issue due to the complex interactions between bolt load, internal pressure, flange stiffness, and gasket material properties. Gaskets play a crucial role in sealing performance, yet their nonlinear behavior and susceptibility to permanent deformation add complexity to joint analysis. Flange rotation and varying contact stresses further influence leakage, necessitating rigorous evaluation methods. This study presents a finite element (FE) model for analyzing gasket contact stresses under different loading conditions. The model accounts for variations in compression due to flange rotation and examines the sealing performance of different gasket materials. The findings provide insights into optimizing bolted flange joint design to enhance leakage prevention and improve structural reliability in high-pressure applications, including nuclear reactors and space vehicles.*

Keywords: *Bearing, Bearing cage, Stress, Deformation, Fillet radius, Radial load.*

1. 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, bolt load, 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. 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.

1.2 Bolted flange connection

It A bolted flange connection is a complex mechanical system whose components must be selected and assembled properly to provide reliable sealing over a wide range of operating conditions. All of the various components of the assembled bolted flange connection are important to the proper operation of the joint. The components consist of the piping, or vessels, the flange(s), the gasket(s) and bolts. In addition to the components themselves, the joint design and assembly are critical to the long-term operation of the joint. A=Fastener (A1=Bolt, A2=Washers, A3=Nut); B=Flange; C=Gasket A gasket is used to create and retain a A seal between two surfaces that are stationary – as opposed to a dynamic seal which is between two moving parts (ex: rotating or reciprocating). These static seals aim to provide a complete physical barrier to contain the fluid within the pipe or vessel and any potential leak paths a) between the surfaces of the flange or b) through gasket material itself.

1.3 Forces acting on bolted flange joint

The effects of both ambient and process temperature on the gasket material, the flanges and the bolts must be taken into account. These effects include bolt elongation, creep relaxation of the gasket material or thermal degradation. This can result in a reduction of the flange load. The higher the operating temperature, the more care needs to be taken with the gasket material selection. As the system is pressurized and heated, the joint deforms. Different coefficients of expansion between the bolts, the flanges and the pipe can result in forces which can affect the gasket. The relative stiffness of the bolted joint determines whether there is a net gain or loss in the bolt load. Generally, flexible joints lose bolt load. The media being sealed, usually a liquid or a gas with a gas being harder to seal than a liquid. The effect of temperature on many fluids causes them to become more aggressive.

2. Literature Review

Elkhlaidy et 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 thermostructural analysis. The critical thermodynamic parameters are identified through measured temperature data in operating conditions, and then these parameters are used in the thermostructural 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 thermostructural 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.

3. Finite Element Modelling

The finite element method (FEM) is a popular method for numerically solving differential equations arising in engineering and mathematical modeling. Finite Element Method (FEM) refers mostly to complex mathematical procedures used in your favorite solver. Think about it like a theory manual, lots of equations and mathematics. Finite Element Analysis (FEA) is usually used in the context of applying FEM to solve real engineering problems. Finite element analysis (FEA) is the use of calculations, models and simulations to predict and understand how an object might behave under various physical conditions. Engineers use FEA to find vulnerabilities in their design prototypes. FEA uses the finite element method (FEM), a numerical technique that cuts the structure of an object into several pieces, or elements, and then reconnects the elements at points called nodes. The FEM creates a set of algebraic equations which engineers, developers and other designers can use to perform finite element analysis. Frequently, the physical experiences of a product -- such as its structural or fluid behavior and thermal transport -- are described using partial differential equations (PDEs). Finite element analysis emerged as a way for computers to solve both linear and nonlinear PDEs. However, it is important to note that FEA only provides an approximate solution; it is a numerical approach to finding the real results of partial differential equations.

4. FEM modelling

In its most basic form, FEM is an approximation method that subdivides a complex problem space, or domain, into numerous small, simpler pieces (the finite elements) whose behavior can be described with comparatively simple equations. The basic concept in the physical interpretation of the FEM is the subdivision of the mathematical model into disjoint (non-overlapping) components of simple. Finite Element Modeling (FEM), also known as Finite Element Analysis (FEA), is a numerical method utilized to predict the performance of structural, thermal, fluid, electromagnetic and other physical systems. The method requires that the component being studied be broken into discrete elements, resulting in a finite element mesh.

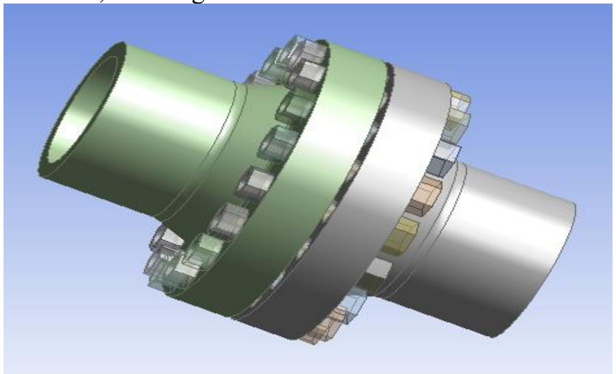

Fig. 4.1: FEM model of bolted flange coupling

4.1 Meshing

A mesh is made up of elements which contain nodes (coordinate locations in space that can vary by element type) that represent the shape of the geometry. An FEA solver cannot easily work with irregular shapes, but it is much happier with common shapes like cubes. Any continuous object has infinite degrees of freedom (DOF) which makes it impossible to solve using hand calculations. So, in FEM, we create a mesh which splits the domain into a discrete number of elements for which the solution can be calculated. A SOLID45 structural element is used to model the flange, bolt, gasket and pipe; three-dimensional 'surface-to-surface' CONTA174 contact elements, in combination with TARGE170 target elements are used between the flange face and gasket, bolt shank and flange hole, the top of the flange, and the bottom of the bolt in order to simulate contact distribution for both structural and thermal models. A 3-D interface element INTER195 is used as a special gasket element for meshing of the spiral wound gasket, which is compatible with SOLID45 structural elements.

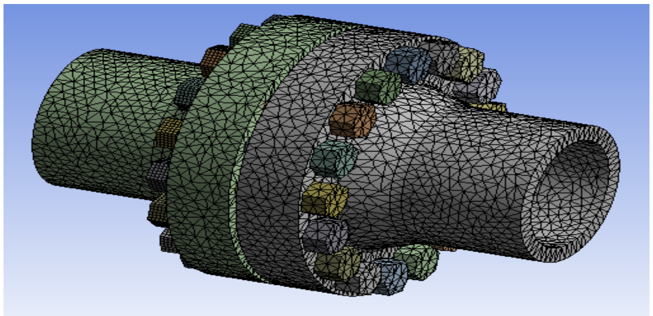

Fig. 4.2: Mesh model of bolted flange coupling

5. Boundary condition

The flow domain for the sound waves. The components of the simple expansion chamber muffler are the inlet, the expansion chamber, and the outlet. The length of the components are 30 mm, 150 mm, and 30 mm, respectively.

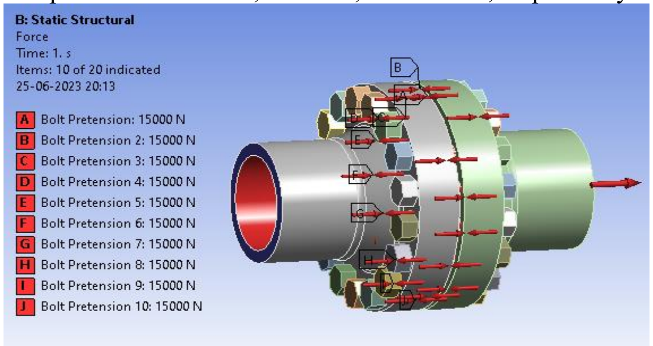

Fig. 5.1: Boundary condition applied on bolted flange coupling

Table 1: Boundary condition

Loading case	Loading type	Loading magnitude
Loading case 1	Bolt up force, design pressure	DP-15.3 MPa, PT-15KN
Loading case 2	Bolt up force, design pressure and axial force	DP-15.3 MPa, PT-15KN, AL-75KN
Loading case 3	Bolt up force, design pressure, axial force and torque	DP-15.3 MPa, PT-15KN, AL-75KN, Torque-505nm
Loading case 4	Bolt up force, design pressure, axial force, torque and bending load	DP-15.3 MPa, PT-15KN, AL-75KN, Torque-505nm, BL-9.75KN

Contact between the gasket and the flange face is modeled using ISL22A elements on the gasket and a sideline that is attached to the flange face. Also, since the gasket is not rigidly attached to the flange, it can be blown out by the internal pressure (this can happen in cases where softer gaskets are used and flange faces are very smooth). To model this, we use a standard Coulomb friction model. We assume a coefficient of static friction of 0.8, a very rough surface.

6. Result and Discussion

A simple expansion chamber Flange has been investigated in this study. The performance of the simple expansion chamber Flange has been evaluated in terms of transmission loss. The variation of transmission loss with frequency of sound wave imposed at the inlet of the Flange is shown in this section, stresses due to different loading conditions in bolted flange coupling are plotted.

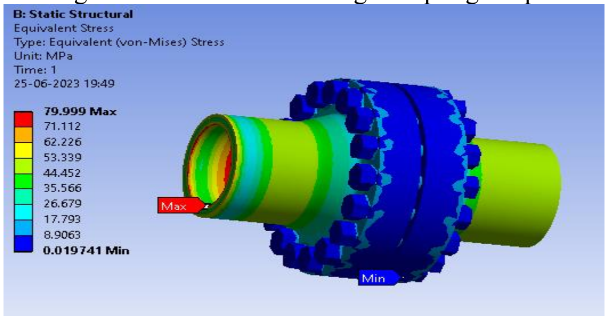

Fig. 6.1: Stresses in bolted flange coupling for loading case 1

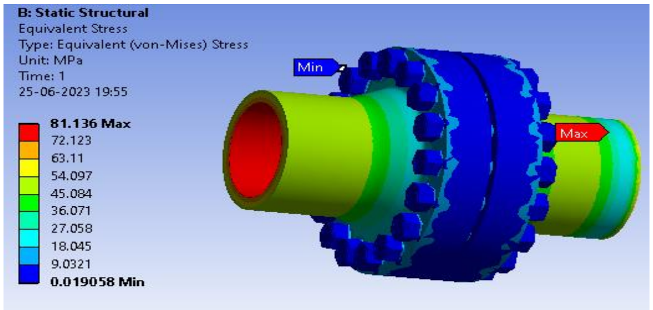

Fig. 6.2: Stresses in bolted flange coupling for loading case 2

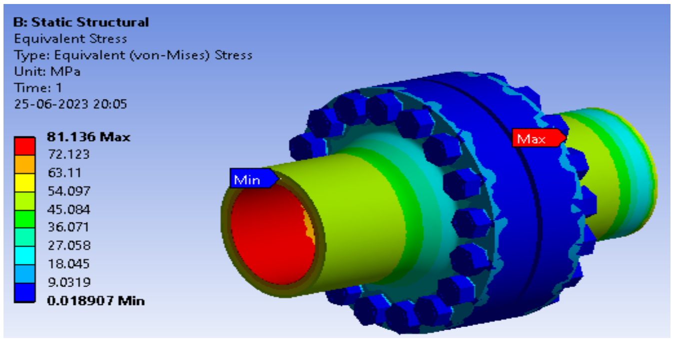

Fig. 6.3: Stresses in bolted flange coupling for loading case 3

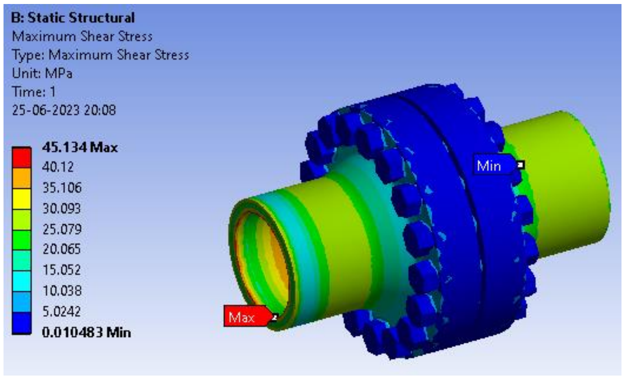

Fig. 6.4: Stresses in bolted flange coupling for loading case 4

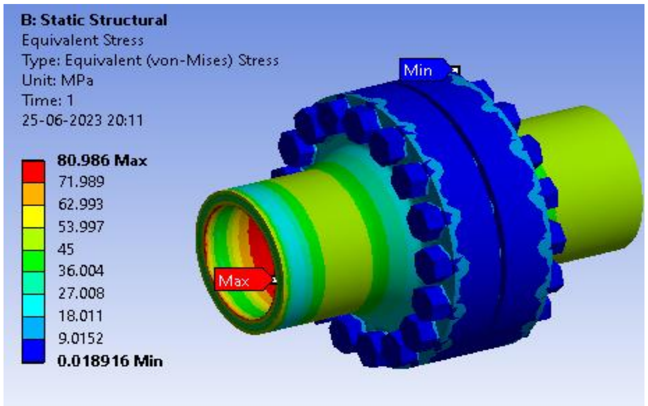

Fig. 6.5: Stresses in bolted flange coupling for loading case 5

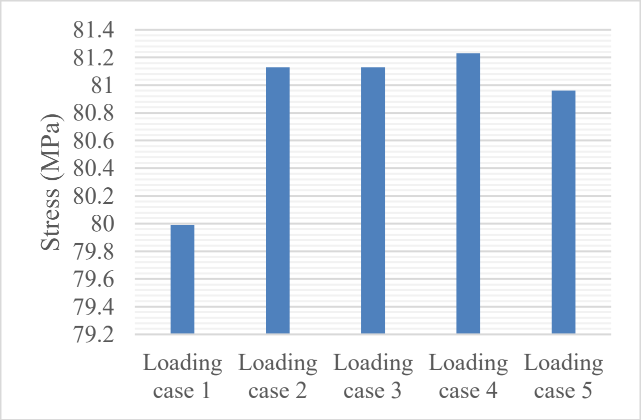

Fig. 6.6: Stresses in bolted flange coupling for different loading case

6.2 Stresses in gasket

In this section, stresses due to different loading conditions gasket are plotted.

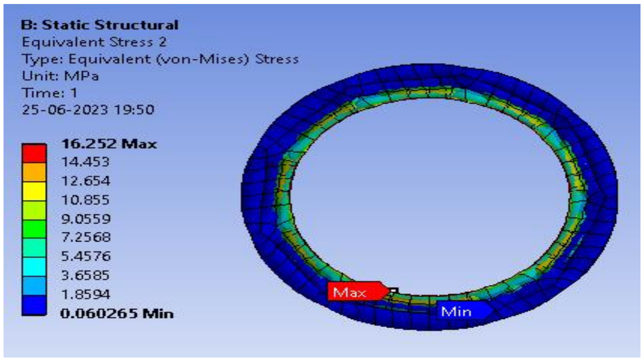

Fig. 6.7: Stresses in gasket for loading case 1

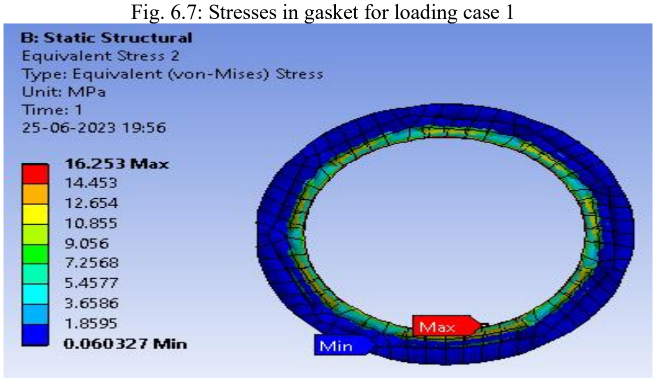

Fig. 6.8: Stresses in gasket for loading case 2

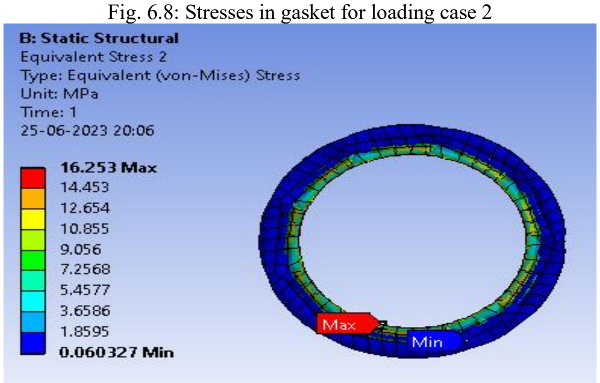

Fig. 6.9: Stresses in gasket for loading case 3

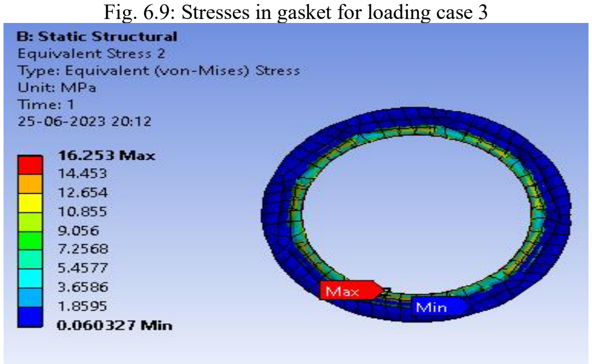

Fig. 6.10: Stresses in gasket for loading case 4

7. Conclusion

The bolted flange coupling is a reliable and widely used mechanical joint for connecting two shafts under various loading conditions. Its performance depends greatly on the design parameters—such as bolt strength, flange material, bolt pre-tension, and alignment accuracy—which collectively ensure safe torque transmission and prevent failures.

Under different loading cases—such as tensile, compressive, bending, and torsional loads—the coupling's structural integrity and efficiency can be evaluated by analyzing stress distribution and deformation at the bolt and flange interfaces. Proper selection of bolt size, tightening torque, and flange thickness is critical to maintain uniform load sharing and prevent loosening or fatigue.

In conclusion, a well-designed bolted flange coupling provides high strength, easy maintenance, and excellent reliability across different loading conditions. Understanding the mechanical behavior under each case helps optimize the coupling design for maximum performance, safety, and service life in mechanical power transmission systems.

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