Elastic Interaction in Bolted Flange Joints during Hot Bolting and Disassembly

by

Ali TOFIGHI

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L’interaction élastique dans les assemblages à brides boulonnées lors du "hot bolting" et du desserrage

Ali TOFIGHI

RÉSUMÉ

Les assemblages à brides boulonnées sont des composants structurels essentiels utilisés dans un large éventail d'applications industrielles, notamment dans les installations pétrochimiques, les pipelines de pétrole et de gaz, ainsi que les centrales électriques. Malgré leur apparente simplicité, le comportement mécanique de ces assemblages sous des conditions de charge et de service complexes demeure une préoccupation majeure tant dans la phase de conception que dans l'entretien après la mise en service. Une procédure particulièrement délicate lorsque le système reste sous pression est le démontage ou le remplacement de boulons, communément appelé "hot bolting". Bien que souvent considéré comme une opération de routine, un desserrage mal exécuté peut entraîner des conséquences catastrophiques, telles que la perte de compression du joint, la séparation de la bride, la surtension des boulons, voire la défaillance du système.

Cette thèse présente une étude approfondie de l'interaction élastique des assemblages à brides boulonnées lors du processus de desserrage. L'accent est mis sur la compréhension de l'effet du retrait d’un ou plusieurs boulons sur la redistribution des contraintes dans les boulons restants, la déformation du joint d’étanchéité et la pression de contact exercée sur ce dernier. Une approche par modélisation par éléments finis (MEF) est adoptée pour simuler la réponse mécanique de brides à col soudé de classe 900 selon la norme ASME B16.5, équipées de joints spiralés métalloplastiques, sous précontrainte des boulons. Les simulations MEF, réalisées avec ANSYS, examinent des paramètres clés tels que l’évolution des contraintes dans les boulons, les déplacements verticaux et les contraintes de contact sur le joint pour différentes séquences de retrait des boulons.

Les résultats expérimentaux sont validés par des modèles analytiques et numériques afin de garantir la fiabilité des prédictions. En caractérisant le comportement d'interaction durant le desserrage des boulons, cette étude fournit des éléments critiques sur les seuils à partir desquels l'intégrité de l'assemblage et l'étanchéité peuvent être compromises. Elle explore également les conditions dans lesquelles les procédures de "hot bolting" peuvent être exécutées en toute sécurité, sans recourir à des dispositifs de serrage supplémentaires, à condition que la redistribution élastique des contraintes soit bien comprise et maintenue dans des marges de sécurité acceptables. Les conclusions de ce travail contribuent à l’amélioration des recommandations de conception, des protocoles de sécurité, et des stratégies de maintenance pour les assemblages à brides dans des environnements à haut risque.

Mots-clés : Assemblages à brides boulonnées, interaction élastique, "hot bolting", desserrage des boulons, contrainte de contact sur le joint, intégrité des brides, modélisation par éléments finis, ASME B16.5, sécurité de maintenance, fiabilité post-construction

Elastic interaction in bolted flange joints during hot bolting and diassembly

Ali TOFIGHI

ABSTRACT

Bolted flange joints are critical structural components used in a wide range of industrial applications, including petrochemical facilities, oil and gas pipelines, and power plants. Despite their apparent simplicity, the mechanical behavior of these joints under complex loading and service conditions remains a key concern in both design and post-construction maintenance. One particularly sensitive procedure while the system remains under operating pressure is the removal or replacement of bolts commonly known as hot bolting. Although often treated as a routine operation, improper handling during bolt untightening can lead to catastrophic outcomes, including loss of gasket compression, flange separation, bolt overstressing, or even system failure.

This thesis presents a comprehensive investigation into the elastic interaction of bolted flange joints during the untightening process. Emphasis is placed on understanding how the removal of individual bolts influences the stress redistribution in the remaining bolts, the deformation of the gasket, and the contact pressure exerted on the gasket. A finite element modeling (FEM) approach is adopted to simulate the mechanical response of ASME B16.5 Class 900 welding neck flanges equipped with spiral wound gaskets, under bolt preload conditions. The FEM simulations, conducted using ANSYS, examine key parameters such as bolt stress evolution, vertical displacement, and gasket contact stress during different bolt removal sequences.

The experimental results are validated against analytical and FEM models to ensure the reliability of the numerical and analytical predictions and compared with experimental results. By characterizing the interaction behavior during bolt unloading, this study provides critical insights into the thresholds beyond which joint integrity and leak tightness may be compromised. Furthermore, it explores the conditions under which controlled hot bolting procedures can be safely executed without requiring additional clamping tools provided that elastic stress redistributions are well-understood and managed within acceptable safety margins. The findings of this work contribute to enhanced design recommendations, improved safety protocols, and more efficient maintenance strategies for bolted flange assemblies in high-risk operational settings.

Keywords: Bolted flange joints, elastic interaction, hot bolting, bolt untightening, gasket contact stress, flange integrity, finite element modeling, ASME B16.5, maintenance safety, post-construction reliability

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LIST OF ABREVIATIONS

AC	Alternating Current
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
FE	Finite Element
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
LVDT	Linear Variable Differential Transformer
MEF	Mechanical Engineering Faculty
NPS	Nominal Pipe Size
PCC	Post Construction Committee
PTFE	Polytetrafluoroethylene (Teflon)

LIST OF SYMBOLS

A_b nominal area of the bolt cross section (mm^2)

C_b elastic compliance of the bolt (mm/N)

$C_{i,j}$ amount of vertical compressive displacement of the gasket and flanges at the axis of bolt *i* due to a unit load in bolt *j* (mm/N)

E_b elastic modulus of bolt material (MPa)

E_f elastic modulus of flange material (MPa)

E_g elastic modulus of gasket material (MPa)

L_e effective bolt length (mm)

F_0 snug fit preload in each bolt (N)

F_b bolt tension (N)

F_i^m preload in bolt *i* after tightening all bolts in pass *m* (N)

F_i^{m-1} preload in bolt *i* after tightening all bolts in pass *m*-1 (N)

$F_{i,j}^m$ preload in bolt *i* after tightening bolt *j* in pass *m* (N)

$F_{i,j-1}^m$ preload in bolt *i* after tightening bolt *j*-1 in pass *m* (N)

F_j preload in bolt *j*, N

$F_{j,j-1}^{m-1}$ preload in bolt *j* after tightening bolt *j*-1 in pass *m*-1 (N)

i, j bolt number

n total number of bolts

m pass number

w_i displacement of flange at periodic bolt spacing (mm)

$[C]$ elastic compliance matrix

$\Delta F_{i,j}$ the corresponding bolt tension increment in bolt *i* after tightening bolt *j* (N)

ΔF_j bolt tension increment in bolt *j*, N

$\Delta\delta_{i,j}$ displacement increments of gasket and flanges at bolt *i* location after tightening bolt *j* (mm)

$\Delta\delta_{bi,j}$ displacement increments of bolt *j* (mm)

INTRODUCTION

Bolted flange joints are one of the most widely used mechanical connections in pressure vessels and piping systems. They serve a critical function in securely connecting pipes, valves, nozzles, and pressure vessels, forming a sealed pathway for the safe transport of fluids under pressure. The design of a bolted flange joint typically includes a pair of mating flanges, a set of bolts, and a gasket positioned between the flange faces to prevent leakage. While they are often perceived as simple and modular assemblies, their mechanical behavior is governed by complex interactions among the components, particularly under varying mechanical and thermal loads.

In industrial environments, especially in sectors such as oil and gas, power generation, petrochemicals, and process plants, bolted flange joints are frequently exposed to high-pressure and high-temperature conditions. Under such circumstances, the joint is subjected to significant mechanical and thermal stress that can affect gasket compression, bolt preload, and the structural integrity of the flange itself. Thermal expansion, pressure fluctuations, and cyclic loading can cause degradation of the sealing interface, loosening of bolts, and even joint leakage if not properly managed. As such, the design and maintenance of bolted flange joints in these environments must ensure both leakage tightness and structural integrity throughout the component's service life.

To maintain the performance of pressurized systems without interrupting operations, the industry often relies on a procedure known as hot bolting, the sequential removal and replacement of bolts while the system remains in service and under pressure. Hot bolting allows for maintenance and replacement of deteriorated bolts or gaskets without shutting down the facility, offering significant economic benefits by reducing operational downtime and increasing system availability. However, this procedure also carries inherent risks. Improper sequencing or insufficient understanding of load redistribution can result in excessive unloading of the remaining bolts, damage to the gasket, or even flange separation. These consequences pose a serious threat to plant safety and reliability.

A fundamental aspect of ensuring the safety and predictability of hot bolting procedures lies in understanding the elastic interactions that occur during the untightening of bolts. When a single bolt is loosened, the load it carried is redistributed among the remaining bolts and across the flange faces, altering the contact stress on the gasket and potentially deforming the flange. The behavior of the joint during this transition phase is highly nonlinear and depends on various parameters such as the initial bolt preload, the material and geometry of the gasket, the flange design, and the specific untightening sequence.

This thesis aims to investigate these elastic interaction phenomena in detail to support the development of predictive and safe hot bolting procedures. The study focuses on analyzing how the preload in individual bolts and the displacement of the flange change during each step of the untightening sequence. A range of parameters is explored, including:

1. Different gasket materials, which can affect compressibility and stress redistribution.
2. Various untightening patterns, which influence how the load paths evolve during bolt removal.
3. Different initial preload levels, which determine the joint's stiffness and elastic response.

To ensure the robustness of the study, the experimental results obtained from a custom-built test rig are compared with both analytical predictions and finite element method (FEM) simulations conducted in ANSYS. This multi-approach methodology allows for a comprehensive assessment of joint behavior and provides insights into the consistency and limitations of numerical and analytical models. The similarities and differences among the experimental, analytical, and FEM results are discussed to validate the findings and refine the modeling techniques.

Through this work, the thesis contributes to a more profound understanding of flange joint mechanics during bolt unloading, enabling safer application of hot bolting operations and informing future design and maintenance standards for critical pressurized systems.

CHAPITRE 1

LITERATURE REVIEW

1.1 Introduction

The present chapter provides a comprehensive summary of the literature review undertaken on the subject of bolted flange joints untightening during normal and operating conditions. This review aims to provide an in-depth understanding of the concepts and practices associated with this topic, as well as to examine the potential implications of previous research in the context of my work.

To begin, it will introduce the fundamental concepts and principles, including the importance of untightening bolted flange joints in industrial applications, the challenges associated with disassembling and maintaining these joints and introducing new technologies used for these disassembles such as utilizing velocity washers.

secondly, it will study the untightening of bolted flange joints in operation condition and explains concepts such as Hot bolting and half bolting.

Subsequently, the report will provide a detailed analysis of the articles reviewed, including their methodologies, key findings, and limitations. A critical evaluation of each article is provided while drawing attention to the strengths and weaknesses of the research and its potential implications for my work.

Finally, the report concludes with my interpretation of the reviewed literature and its potential impacts on the research to be undertaken. The gaps are identified in the literature and highlight areas for further research to advance knowledge in the field of bolted flange joints.

Figure 1.1 Bolted Flange Joint Assembly

1.1.1 Maintenance Service in Bolted Flange Joints

Bolted flange joints are commonly used in a wide range of industrial applications to connect pipes, valves, and other components. These joints are designed to create a tight seal and maintain their integrity over long periods of operation. However, over time, these flange joints can experience wear and tear due to environmental factors, vibration, and other operational stresses. To ensure the continued reliability of these joints, regular maintenance is required. Maintenance service for bolted flange joints typically involves a series of inspections and repairs aimed at identifying and addressing any issues that may impact the performance of the joint. The maintenance schedule may vary depending on the specific application, but it is generally recommended that inspections be carried out at least once per year.

In addition to regular inspections and repairs, it is also recommended that bolted flange joints be periodically re-torqued to ensure that they remain properly tightened. This is particularly important for joints that are subject to thermal expansion and contraction, as these fluctuations can cause the bolts to loosen over time. Re-torquing involves tightening the bolts to a specified torque value using a calibrated torque wrench.

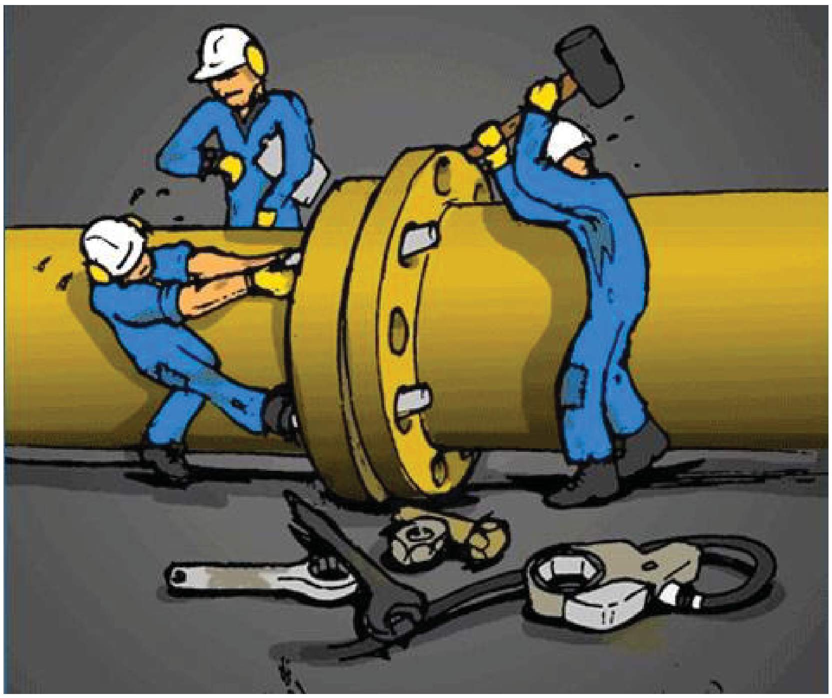

Figure 1.2 Maintenance service in bolted flange joints

1.1.2 Disassembling Bolted Flange Joints

Disassembling bolted flange joints is a critical process in the maintenance and inspection of piping systems, pressure vessels, and mechanical assemblies, particularly in industries such as oil and gas, aerospace, and power generation. These joints must often be separated to access internal components, replace gaskets, inspect for corrosion or wear, or perform repairs. However, disassembly poses significant challenges, especially when bolts have seized due to corrosion, thermal cycling, galling, or prolonged service under high pressure and temperature. Seized or over-tightened bolts can lead to bolt head breakage, thread stripping, or damage to flanges themselves, making reassembly difficult or unsafe. The disassembly process typically involves relieving residual stress, applying penetrating lubricants, controlled heating to expand components, or using specialized tools like hydraulic bolt tensioners or nut splitters. In cases of extreme seizure, destructive methods may be necessary. Successful disassembly requires careful planning, proper tools, and often a balance between preserving components and minimizing downtime or further damage.

1.1.2.1 Disassembling Process Using Velocity Washers

Velocity washers are advanced components engineered to facilitate the efficient disassembly of bolted flange joints, particularly in systems where bolts are prone to seizure due to factors such as corrosion, galling, or high preload conditions. These washers are specifically designed to minimize friction during both tightening and untightening processes, making them especially valuable in maintenance-intensive environments. The installation of a velocity washer is straightforward, serving as a direct replacement for a standard hardened washer. Positioned on the stud prior to nut engagement, its symmetric geometry ensures ease of installation without the need for specialized tools or alignment procedures. During assembly, the velocity washer performs identically to a conventional washer, accommodating standard torque application using typical bolting tools and techniques.The distinct advantage of the velocity washer becomes evident during disassembly. By rotating the nut approximately 12 degrees in the loosening direction, the internal mechanism of the washer activates a "pop" action, instantly releasing the bolt’s preload. This feature significantly reduces the torque required to remove the nut, allowing for manual or low-effort removal. As a result, the risks associated with galling, thread damage, or uncontrolled bolt release are substantially mitigated. Experimental evidence indicates that the use of velocity washers can accelerate the disassembly process by up to 30 times compared to conventional methods, thereby significantly reducing maintenance time and operational downtime. This efficiency, combined with the washer's compatibility with standard assembly procedures, underscores its utility in critical industrial applications.

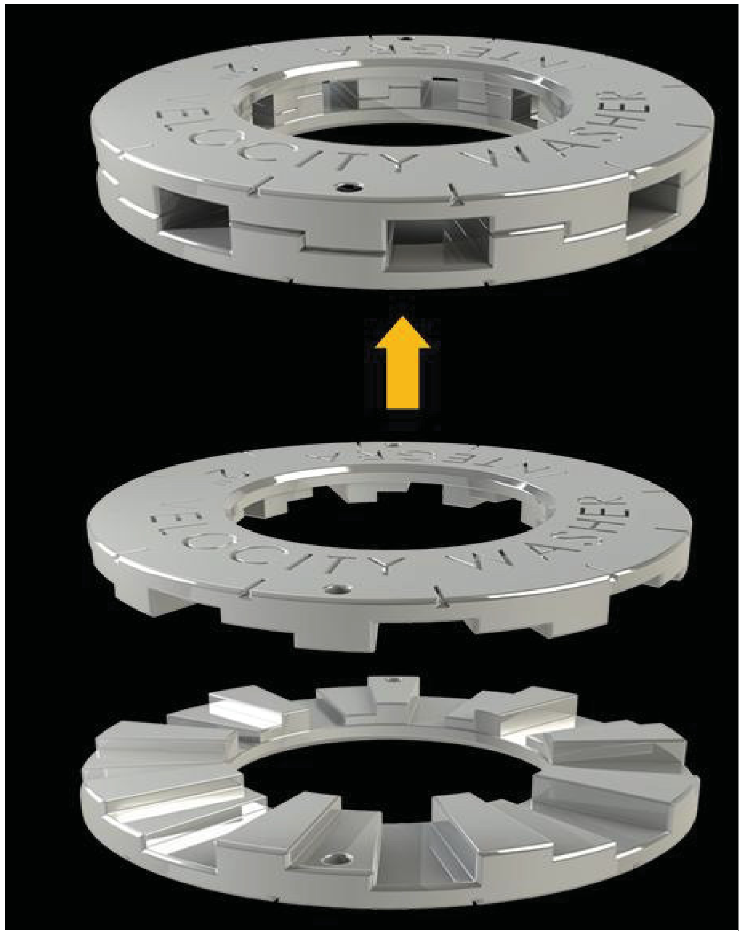

Figure 1.3 Velocity Washer by Flexitallic

1.1.3 Hot Bolting

Hot bolting is a crucial technique used in industrial operations where system shutdowns are either impractical or unfeasible. This method enables maintenance to be performed while the system remains operational, thereby minimizing downtime and reducing potential issues that may arise when the system is cooled and restarted. In order to execute hot bolting, specialized tools and equipment are required, including hydraulic wrenches and tensioners, to ensure the proper torque and tension of the bolts. Furthermore, this technique demands the expertise of trained personnel who possess a deep understanding of the specific requirements of hot bolting and are well-versed in mitigating potential hazards that may arise during the process.

1.1.2.1 Importance and Benefits of Hot Bolting

The importance of hot bolting lies in its ability to ensure the safe and efficient operation of critical industrial systems. In industrial settings, unplanned downtime can result in substantial losses in productivity, revenue, and reputation. By performing maintenance on bolted flange joints through hot bolting, industrial systems can continue to operate safely and efficiently without the need for costly shutdowns.

1.1.2.2 Risks and Challenges of Hot Bolting

If hot bolting is done without a thorough engineering assessment, flange analysis, or justification, there's a systemic risk of violating safe operating limits. Many accidents in process industries have occurred when hot bolting was used casually or without proper procedures.

While hot bolting can be safely executed under strict controls, it is an inherently high-risk maintenance activity. It should only be performed with detailed flange calculations, clear justification, skilled personnel, and emergency mitigation plans in place. Alternative methods like controlled depressurization, or technologies such as live bolt tensioning systems, are often safer options when feasible.

1.1.4 Half Bolting

Half bolting is a maintenance technique where only half the bolts in a flange joint are worked on at a time to preserve sealing integrity during operation. Removing half the bolts shifts load onto the remaining ones, which must be capable of carrying this increased stress temporarily. Not all flanges or gasket types can tolerate this load redistribution and careful engineering analysis like FEA is required. half bolting requires precise planning, risk assessment, and engineering validation to ensure system safety, but can significantly reduce downtime in critical systems.

1.2 Analytical and Numerical Studies

Numerical approaches in research refer to the use of mathematical models and algorithms to analyze data and make predictions. These approaches are widely used in many fields, including science, engineering, economics, and social sciences. Numerical approaches can provide more accurate and precise results compared to other methods. They can be used to analyze large and complex data sets that would be difficult or impossible to analyze by hand. Numerical approaches are often faster than manual methods, allowing researchers to obtain results more quickly. They can be used to simulate complex systems or processes, which can help researchers understand how they work and how they might be improved. They also can help researchers identify patterns and relationships in data that might not be immediately obvious.

The accuracy of numerical approaches depends on many factors, including the quality of the data used, the complexity of the model, and the accuracy of the algorithms used. Generally, the more complex the model, the more accurate the results will be, but also the longer it will take to run. It is important for researchers to carefully validate their models and algorithms to ensure that they produce accurate results.

Finite Element Analysis (FEA) is a numerical approach used to simulate the behavior of structures and materials under different conditions. It is widely used in engineering and design to predict how a structure or material will respond to external forces or loads.

Numerical approaches have revolutionized the field of research by providing a powerful and versatile tool for analyzing data and making predictions. While there are some limitations to these approaches, their benefits far outweigh their drawbacks, and they will likely continue to play a vital role in research for years to come.

1.2.1 Finite Element Analysis

The basic principle behind Finite Element Analysis is to divide a complex structure or material into smaller, simpler elements, which can be analyzed individually. These elements are connected at points called nodes, and their behavior is described by a set of mathematical equations. By solving these equations for each element, the overall behavior of the structure or material can be predicted.

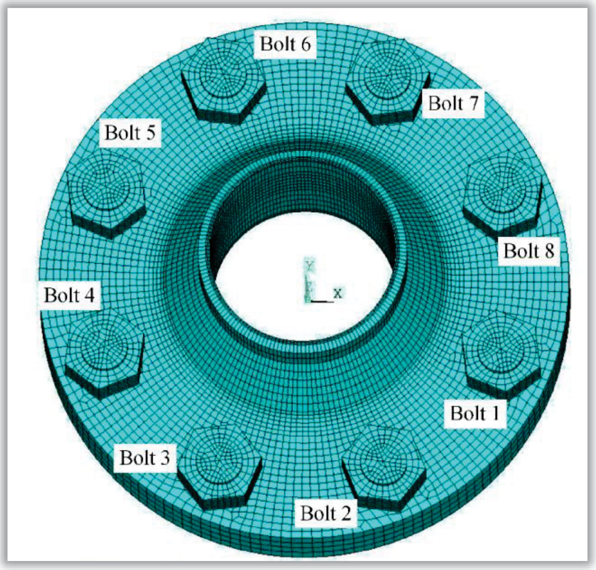

Figure 1.4 FE modeling of bolted flange joints

The process of FEA involves several steps:

Geometry and Mesh Generation: The structure or material being analyzed is modeled using specialized software. The model is then divided into small elements, and each element is assigned material properties, such as density, elasticity, and thermal conductivity.

Boundary Conditions and Loads: The boundary conditions, such as fixed or free edges, and external loads, such as forces or pressures, are defined.

Solving the Equations: The mathematical equations for each element are solved using numerical methods, such as the finite element method. The results are combined to predict the overall behavior of the structure or material.

Post-Processing: The results are analyzed to determine the stress, strain, displacement, and other properties of the structure or material.

In conclusion, Finite Element Analysis is a powerful tool for simulating the behavior of structures and materials and is widely used in engineering and design. By breaking down complex systems into smaller elements and analyzing them individually, FEA can predict how a structure or material will behave under different conditions, helping to improve designs and reduce costs.

1.2.2 Research on Elastic Interaction, Tightening, and Untightening Behavior

Elastic interaction in bolted flange joints refers to the phenomenon where the tightening or loosening of one bolt in the joint can cause a change in the load distribution among all the bolts in the joint. This is due to the elastic deformation of the flanges and gaskets under load, which causes the stiffness of the joint to change. Elastic interaction can result in non-uniform bolt loads and gasket compression, which can affect the joint's overall performance and longevity. Understanding and properly accounting for elastic interaction is crucial in achieving a uniform preload in all bolts and ensuring the joint's reliability and safety.

An article conducted by Linbo Zhu, Abdel-Hakim Bouzid, and Jun Hong on the topic of elastic interaction in bolted flange joints. The primary objective of this research was to establish a uniform preload at the bolts in every pass by calculating and incorporating the stress generated by other bolts in previous passes through the utilization of Finite Element Analysis (FEA) models. The approach employed in this study involved defining a target for the final load based on prior research, and then utilizing the PCC-1 method to calculate precise preload numbers for each pass. Specifically, in this novel approach, the tension of other bolts is applied to determine the tension on the targeted bolt via three equations. The results are obtained via FEA models, and these values are subsequently applied to the next pass.

The results of this study reveal that the proposed method is more accurate than the PCC-1 method in three passes, but less accurate than the PCC-1 method in four passes, which is a reasonable observation. This approach has widespread applications and can save considerable time when retightening flanges, while also offering superior accuracy when compared to previous methods.

The findings of this study are highly significant for research in the area of elastic interaction of bolted flange joints during untightening. Notably, the equations utilized to calculate the elastic interaction coefficient matrix and the flange displacement factors are of particular interest. Furthermore, this study underscores the importance of considering errors introduced by the software during the unloading phase, as well as the impacts of flange ring rotation on gasket displacement.

The data, FEA modeling, tables, and figures presented in this study are highly valuable for future research in this field. Overall, this report provides critical insights into the behavior of bolted flange joints and presents novel methods for achieving uniform preload at bolts. As such, this paper can serve as a valuable reference for researchers, academics, and professionals involved in this area of study.

1.2.3 Distribution of gasket contact stress in bolted flange joints

Bolted flange joints may need maintenance while in operation. During such maintenance work, bolts may need to be either tightened further or removed and replaced. While this approach avoids costly shutdowns, it also carries a risk as changes in bolt load can lead to an unbalanced load on the gasket. This can cause a drop in local gasket contact stress to a critical level, resulting in significant leaks that can endanger the safety of workers.

The article titled "Effect of Bolt Spacing on the Circumferential Distribution of the Gasket Contact Stress in Bolted Flange Joints" by Tan Dan Do, Abdel-Hakim Bouzid, and Thien-My Dao addresses an important issue related to the contact stress level unbalance around the flange when the bolts are subjected to initial tightening in bolted flange joints. The authors aimed to investigate the circumferential distribution of gasket contact stress variations and compared

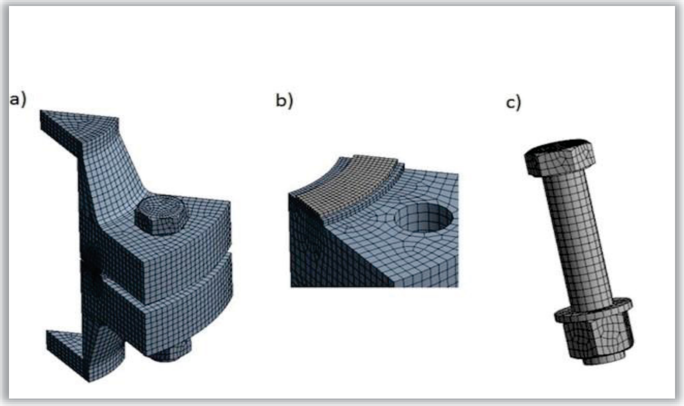

Figure 1.5 The computational mesh of the joint a) whole assembly
b) discretized region of the gasket and flange c) fastener

them using an analytical developed model, a finite element model, and a simple beam on elastic foundation model.

The approach taken involved developing an analytical solution to evaluate the circumferential distribution of gasket contact stress based on flange deflections. Three-dimensional finite element models were then developed to validate the analytical model. The study aimed to understand the factors that affect contact stress and provide insight into the behavior of flanges and gaskets under different conditions. The effect of the number of bolts, gasket thickness, and flange thickness on contact stress and the distribution of contact stress in linear gaskets were also considered.

The results of the study showed that the analytical model predictions compared well with the results obtained from the finite element models and the simple beam on elastic foundation model. The developed model based on the theory of circular ring on elastic foundation confirmed that Koves simple beam on elastic foundation model is accurate for large diameter

flanges used with gasket linear elastic behavior assumption. However, there were relatively larger differences observed in the radial location of the average contact stress, which varied along the circumference due to flange rotation variation in the same direction.
The findings of this study contribute to improving the understanding of the factors that affect contact stress in bolted flange joints. This model has the potential to be used to improve bolt spacing designs and investigate the effect of in-service bolt replacement and hot retorque.

1.2.4 Tightening methods in bolted flange joints

Tightening methods in bolted flange joints are crucial for ensuring the integrity and safety of pressure vessels and rotating equipment. However, achieving uniform bolt preload in these joints can be challenging due to factors such as elastic interaction and cross talk, which can lead to preload scatter. There are two optimization methods, the elastic interaction coefficient method and the inverse sequence method, which can be used to address these issues. The article "A Method to Reduce the Number of Assembly Tightening Passes in Bolted Flange Joints" by Linbo Zhu, Abdel-Hakim Bouzid and Jun Hong, presents a new approach to optimize the tightening sequence in bolted flange joints to achieve bolt load uniformity while minimizing the number of passes required for tightening. The approach is based on an analytical model using the theory of circular beams on a linear elastic foundation to simulate elastic interaction during tightening. The elastic interaction coefficient method (EICM) and inverse sequence method (ISM) are known optimization methods, but EICM cannot be used with nonlinear gasket materials. The report presents a two-pass tightening sequence using criss-cross or sequential clockwise patterns to achieve uniformity in final tension. The approach calculates the tensions caused by elastic interaction from other bolts and applies them to each bolt to achieve different initial loads for each bolt. Results show that the method unifies bolt final tensions with less passes, and the optimum overshooting ratio is assessed and compared between criss-cross and sequential methods.

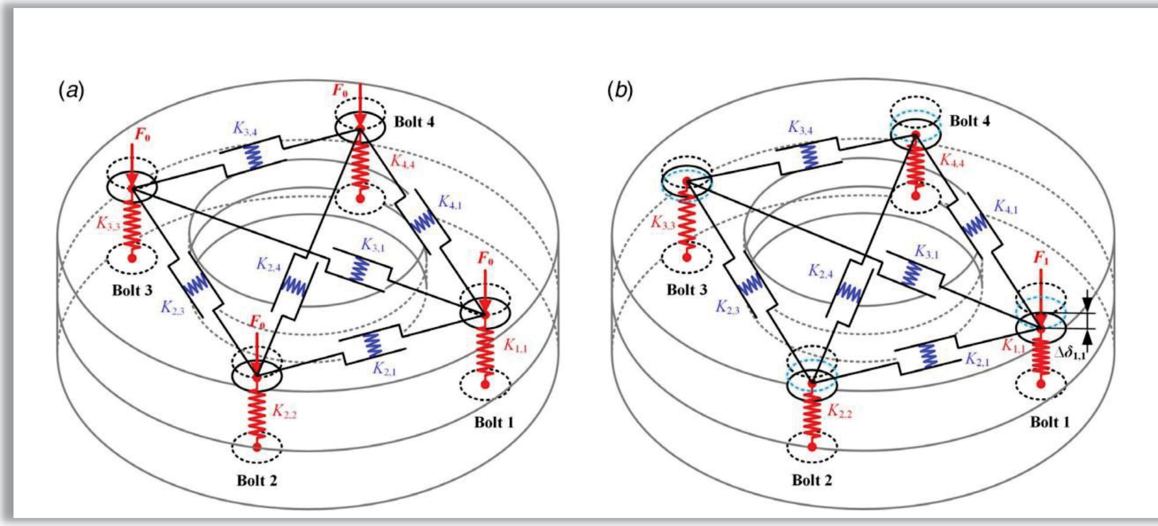

Figure 1.6 Schematic of elastic interaction for four bolts: (a) tightening all bolts to a small preload F0 and (b) tightening bolt 1 to a preload F1 sequentially

The approach uses an analytical model based on the theory of circular beams on a linear elastic foundation to simulate elastic interaction during tightening. The maximum load during tightening is considered, and if it exceeds the yield value, a two-pass tightening sequence is used. The criss-cross or sequential clockwise patterns are used to achieve uniformity in final tension. The approach calculates the tensions caused by elastic interaction from other bolts and applies them to each bolt to achieve different initial loads for each bolt.

The approach was tested by comparing the results of a three-pass non-optimized method with a two-pass optimized method using FE models and experiments. The optimized method showed more accurate bolt final tensions with less passes. The optimum overshooting ratio was also assessed and compared between criss-cross and sequential methods. The new method presented in this report can reduce the number of passes required for tightening while achieving bolt load uniformity. However, its practicality for use in industry requires further development. The analytical model and equations presented in this report can be used to predict the tension in other bolts when untightening one bolt in nonlinear gaskets. The equations used in this method can also be used in reverse calculation for untightening. The new method can have significant implications in reducing assembly time and costs for bolted flange joints.

1.3 Numerical studies of bolted flange joints in operating conditions

1.3.1 Mechanics of Re-torque in bolted flange joints

Understanding the mechanics of re-torquing in bolted flange joints is important for ensuring the reliability and safety of equipment in various industries, including oil and gas, chemical, and aerospace. By accurately modeling the behavior of viscoelastic materials and investigating the effect of re-torquing on gasket performance, researchers and engineers can develop effective maintenance strategies and improve the design of bolted flange joints.

The paper, titled "Mechanics of Re-Torquing in Bolted Flange Connections," by Gordon et al., focuses on the concept of gasket relaxation in Polytetrafluorethylene (PTFE) gaskets and its impact on tightening flanges in high-temperature and high-pressure conditions. The authors' goal is to provide a detailed understanding of the amount and importance of relaxation and re-torque in such conditions.

To achieve this goal, the authors accurately model the behavior of viscoelastic materials, which is a crucial element in predicting gasket material performance. Four common models, namely, Maxwell, Voigt (also referred to as Kelvin), Linear, and Burger, are used to correlate the response of this class of solids.

Constitutive modeling is employed to simulate gasket creep relaxation response for the initial step load. The paper then extends these models for applicability to subsequent torques. The authors investigate the re-torque behavior of a glass-filled PTFE material under re-torque and consider the influence of dwell period duration, gasket thickness, and torque/re-torque level. Additionally, an analytical representation of the gasket material response introduced in the literature is modified for simulating creep relaxation response after a series of torques.

The results of this study are significant in supporting the GUCP assembly procedure for the STS and future RLVs. The authors' findings provide valuable insights into the impact of gasket relaxation and re-torque behavior on flange bolting. Furthermore, the analytical representation of the gasket material response can help in designing gasket flanges that are resistant to creep relaxation.

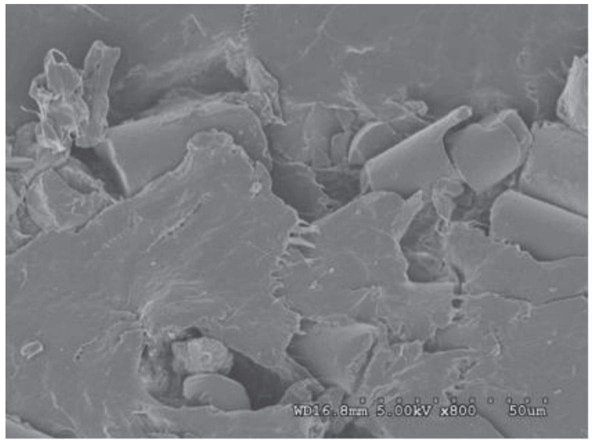

Figure 1.7 Microstructure of PTFE-based gasket with 25% fiberglass prior to application of mechanical loading

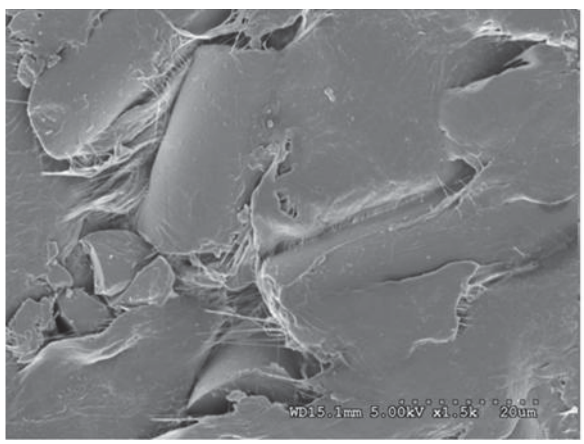

Figure 1.8 Microstructure of PTFE-based gasket with 25% fiberglass after 20hr of loading

1.3.2 Stress Analysis in Operating Conditions

Stress analysis of bolted flange joints in operational conditions involves determining the stresses and deformations in the joint due to the applied load and internal pressure. This analysis is important to ensure the safety and reliability of the joint during its operation. This includes the use of equations and models to calculate stresses and deformations in the joint. These approaches are based on various assumptions and simplifications, which are made to simplify the problem and make the calculations more manageable.

The analytical approach involves the following steps:
Determining the bolt loads: The first step in stress analysis is to determine the bolt loads. This involves calculating the external loads acting on the joint and then using these loads to determine the required bolt loads.
Determining joint stiffness: The joint stiffness is a measure of the joint's ability to resist deformation under load. It is dependent on the geometry and material properties of the joint. The stiffness can be determined analytically by using joint geometry and material properties.
Determining the joint stress: The joint stress can be calculated by applying the bolt loads and internal pressure to the joint stiffness. The joint stress can then be compared to the material yield strength to determine if the joint is safe.
Determining the joint deformation: The joint deformation can be calculated by applying the bolt loads and internal pressure to the joint stiffness. The joint deformation can be compared to allowable limits to determine if the joint is safe.
However, the analytical approach is based on various assumptions and simplifications and may not provide an accurate representation of the actual behavior of the joint. Therefore, it is important to validate the results obtained using analytical approaches with experimental data.
It is worth noting that, to date, no specific research has been conducted on stress analysis of bolted flange joints under operational conditions. While there have been studies conducted in similar conditions for different purposes, there is a lack of research on this particular topic. As a result, there is a gap in knowledge regarding the behavior of bolted flange joints in

operational conditions, and further investigation is warranted to understand the behavior of these joints in service.

1.4 Experimental studies and practical approaches

1.4.1 Bolt Stress in Heat Exchangers

Heat exchanger flanges, as complex components, have been found to exhibit a susceptibility to leakage, particularly in joints that connect large diameter channels to tubesheets. Leakage is often observed during heat exchanger startups or shutdown or following a thermal transient event. This finding aligns with a survey conducted by J. H. Bickford, which reported that most instances of gross leakage occur during or shortly after thermal events.

The article "Heat Exchanger Bolt Stress Measurements" by Michael W. Guillot, Matthew Findlay, and Corey T. Grimsley aimed to present the data obtained from instrumented studs and thermocouples over a period of five months and to summarize the lessons learned. The paper discussed an assessment of the error in various bolting techniques, the benefit of bolting techniques such as multiple jack bolt tensioners, and the nature and effect of thermal gradients in flanges, the effects of spring washers on the magnitude of thermally induced loads, and problems arising from gasket quality control.

Figure 1.9 Heat exchanger bolt stress measurements

The study illustrating several cases where leakage had occurred, and the causes of leakage in each case were explained. The instrumentation, which included 26 thermocouples to document temperature profiles and 8 strain gauges to document stress in bolts, was then described. The researchers considered obtaining accurate preload, the gasket material, and protecting the rigidity of the flange.

The results of the study showed that the final issue was the reduction in preload, which could mean the effect of relaxation, highlighting the importance of uniformity of preload in bolted joints. The study emphasized the significance of considering various factors that might affect the process of hot bolting in heat exchangers, including thermocycling, bolt behavior, gasket behavior, and gasket material of heat exchangers. The unification of the contact stress in gaskets and bolts was considered important, and new methods were proposed to achieve more uniform preloads. Temperature distribution was also identified as an important factor in heat exchangers and should be considered.

1.4.2 Standards

Standards play an important role in the design, manufacturing, and maintenance of bolted flange joints. One such standard is the ASME PCC-1-2019 "Guidelines for Pressure Boundary Bolted Flange Joint Assembly," which provides recommendations and best practices for the assembly, disassembly, and reassembly of bolted flange joints.

This standard covers a wide range of topics, including bolted joint design, bolt selection, tightening methods, lubrication, and torque specifications. It also provides guidelines for the use of gaskets, including the selection and installation of appropriate gasket materials and the calculation of gasket stress.

ASME PCC-1-2019 also covers topics related to joint assembly and disassembly, including joint preparation, bolt lubrication, and tightening procedures. It provides recommendations for bolt tightening methods, including torque and tensioning, and guidelines for the use of hydraulic tensioning equipment.

Furthermore, this standard addresses the importance of joint inspection and maintenance, including visual inspections, leak detection, and torque checks. It also provides guidelines for the repair of damaged or leaking joints.

By following the recommendations outlined in ASME PCC-1-2019, manufacturers and operators of pressure equipment can ensure the safe and reliable performance of bolted flange joints in a wide range of applications.

1.4.2.1 ASME PCC-1 and PCC-2 guidance for Hot Bolting

ASME PCC-1 and PCC-2 are two guidance documents that provide recommendations for hot bolting procedures in bolted flange joints.

ASME PCC-1, "Guidelines for Pressure Boundary Bolted Flange Joint Assembly," provides guidance for the installation, inspection, maintenance, and repair of bolted flange joints in pressure vessels and piping systems. This standard includes a section on hot bolting, which refers to the process of tightening or loosening bolts in a flange joint while the equipment is in operation at high temperatures. The standard recommends that hot bolting procedures be performed by qualified personnel using appropriate tools and equipment. It also provides guidance on temperature limits, torque values, and tensioning techniques for hot bolting operations.

ASME PCC-2, "Repair of Pressure Equipment and Piping," provides guidance for the repair of pressure equipment and piping systems that have been damaged or degraded. This standard includes a section on hot bolting, which provides guidance on the use of hot bolting to repair flange joints that have loosened due to thermal cycling or other factors. The standard recommends that hot bolting procedures be performed by qualified personnel using appropriate tools and equipment. It also provides guidance on temperature limits, torque values, and tensioning techniques for hot bolting operations.

Overall, both standards emphasize the importance of proper training, equipment, and procedures for hot bolting operations to ensure the safety and reliability of bolted flange joints in pressure equipment and piping systems.

The replacement of aging equipment is a common challenge faced by many industries. The article Application of PCC-2 in Real World Situations by Jaan Taagepera, Chad Magyar, Matt Greenfield, and Nathan Tyson examines the replacement of a gate valve that had been in service for over 50 years. The replacement process was carried out using the nitrogen freeze plug method, which presented several challenges, including health and safety risks, high costs, and the novelty of the method. The article presents the approach used to overcome these challenges and the impact of this study on future projects.

The replacement process involved several steps, including the evaluation of alternatives, the decision to use the nitrogen freeze plug method, planning, risk assessment, and mitigation. The nitrogen freeze plug was set up in the pipe, and several modifications were made to the system to minimize the potential risks. The plan was executed successfully, and the gate valve was replaced without any incidents.

Figure 1.10 Frost developing on jacket during freezing operation

The replacement process was successful, and the old gate valve was replaced with a new one using the nitrogen freeze plug method. The project demonstrated the importance of proper planning, risk assessment, and mitigation in executing such projects successfully. The study also highlighted the impact of unexpected risks on such projects and the need to address them appropriately.

The successful replacement of the gate valve using the nitrogen freeze plug method demonstrated the feasibility of using this method in similar projects. The study highlighted the importance of proper planning, risk assessment, and mitigation in executing such projects. The impact of this study on future projects is significant, as it provides valuable insights into the challenges faced during equipment replacement projects and the importance of addressing them appropriately.

This case study provides valuable insights into the replacement of aging equipment using the nitrogen freeze plug method. The study demonstrates the importance of proper planning, risk assessment, and mitigation in executing such projects successfully. The impact of this study on future projects is significant, as it provides valuable lessons that can be applied to similar projects in the future. The study also highlights the importance of addressing unexpected risks appropriately in such projects to ensure their success.

1.4.2.2 European standards for managing the integrity of bolted joints

European standards and guidelines play a significant role in ensuring the integrity and safety of bolted joints in various industries. These standards provide a framework for managing the integrity of bolted joints through regular inspection and maintenance activities. The European Pressure Equipment Directive (PED) and the Machinery Directive provide the legal basis for ensuring the safety of bolted joints in pressure vessels and rotating machinery, respectively. The PED sets out requirements for design, manufacture, and conformity assessment of pressure equipment while the Machinery Directive requires equipment to be designed and manufactured to meet safety requirements.

The European Standard EN 1591 provides guidelines for the design and calculation of flanges and bolted joints. This standard defines procedures for calculating the bolt preload and the gasket stress required to achieve a leak-tight seal in bolted joints. The standard also provides guidelines for selecting appropriate materials and specifying the necessary torque values for tightening bolts.

The European Industrial Gases Association (EIGA) provides guidelines for managing the integrity of bolted joints in gas systems. These guidelines cover the design, construction, inspection, and maintenance of bolted joints in gas systems. EIGA guidelines also specify the minimum requirements for bolt material, torque values, and gasket types.

European standards and guidelines play a vital role in ensuring the safety and integrity of bolted joints in various industries, providing a framework for managing the integrity of bolted joints and specifying minimum requirements for bolted joint design, construction, inspection, and maintenance.

The main objective of the article "Update on European Standards and Guidelines for Managing the Integrity of Bolted Joints" by Robert Noble is to present the changes in the European Standards and Guidelines for managing the integrity of bolted joints, as well as their alignment with ASME PCC-1-2013 and ASME PCC-2-2011. The paper reviews the activity in three key sections: Management Guidelines, Training and Competence, and Technical and Engineering Standards.

The article starts by discussing the Management Guidelines section, where the author identified areas that needed an update to provide improved guidance. This section includes management processes, technology and practice, integrity testing, hot-bolting and bolt replacement, lessons learned, ownership, support, and integration, criticality assessment, training and competence, records, data management, and tagging, in-service inspection, management of leaks, and analysis, learning, and improvement.

Furthermore, the article discusses the Training and Competence section, which is based on the principle of establishing core knowledge topics and awareness level topics. The candidate is expected to demonstrate the required knowledge level and practical competence by carrying out various technical tasks under the assessment of a responsible person.

Finally, the article discusses the Technical and Engineering Standards section, which emphasizes bolt load calculation standards, bolting, and the pressure equipment directive guideline.

This article provides a valuable source of information for professionals working in the field of hot bolting. By comparing European and ASME standards, readers can gain a better understanding of the practical aspects of hot bolting and the factors that must be considered when managing the integrity of bolted joints. This paper can also serve as a reference for engineers and technicians who are involved in the maintenance and repair of industrial equipment, ensuring that their work is compliant with the latest industry standards and guidelines.

1.4.3 Single Stud Replacement in bolted flange joints

One of the maintenance techniques used to address these issues is Single Stud Replacement (SSR), which involves replacing one stud at a time in a bolted flange joint. SSR is a practical approach for joint maintenance, as it enables replacement of worn or damaged studs without shutting down the entire system. However, proper execution of SSR requires careful consideration of factors such as temperature, pressure, gasket stress, and external loads, to ensure the joint remains safe and reliable. In this report, we will explore the methodology and criteria for executing SSR, including engineering analysis, risk assessment, and the limits under which SSR can take place. We will also examine the implications of SSR on the performance and integrity of bolted flange joints.

The article “The how and when to execute single stud replacement (SSR) of bolted flanged joints by Clay D. Rodery, Scott Hamilton, Neil Ferguson and Gonghyun Jung presents a comprehensive analysis of three critical factors to consider when executing SSR: Temp-Pressure allowable, external loads and bending moments, and gasket contact stress. The paper discusses the need to redefine the PCC-2 method, which lacks clarity and needs further explanation. For instance, the article highlights that applying a safety margin of 50% pressure

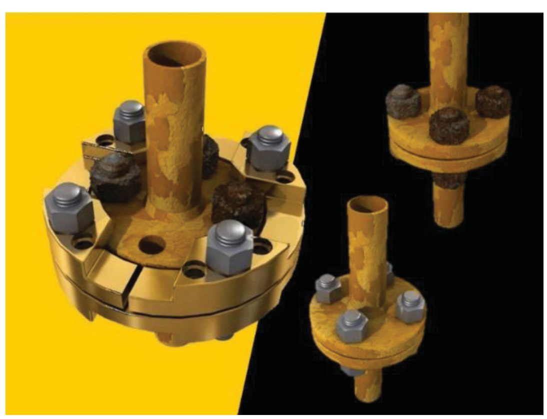

Figure 1.11 Hot Bolting and Single Stud Replacement by ENERPAC

in the PCC-2 method is based on an experience criterion and requires more accurate calculations.

The paper describes the hot bolting process, which is an effective method for executing SSR. The process involves several steps, including engineering and risk analysis, determining the desired stud load and torque value, gathering necessary materials, and lubrication, and checking nuts' freedom. The bolts are replaced one by one in a sequential pattern, and the process concludes with a final tightening pass on the remaining bolts in sequential order.

To define the limits under which SSR might take place, the authors propose three methods. The first is evaluating gasket stress using minimum gasket stress criteria from ASME PCC-1 Appendix O, which provides insight into the requirements for different conditions and flange sizes. The second is evaluating gasket stress using FEA, which involves several specific calculations, such as assessing the risk for different classes of flanges. However, the authors note that accurately calculating 50% stress using FEA is necessary. The third is exploring pressure limits using pressure testing, which helps approve the FEA data. The results of 24 experiments showed no leakage, which confirms the accuracy of FEA and PCC-1 methods in ideal conditions.

In conclusion, the paper emphasizes that to execute SSR successfully, several unknowns, including existing bolt load magnitude and consistency, gasket and gasket sealing surface condition, and the effect of external loads, must be considered. These factors must be carefully analyzed before executing SSR. The paper's findings have significant implications for improving the safety and reliability of bolted flanged joints in industrial applications.

1.4.4 Safety considerations

Safety considerations are critical when performing hot bolting activities. Proper planning, risk assessments, training, and following established procedures are essential to ensure that the hot bolting work is carried out safely and efficiently. This can help prevent accidents, equipment damage, and even fatalities. In this section, we will discuss the various safety considerations that should be taken into account when performing hot bolting activities.

Stud bolt thread engagement is a critical factor in ensuring the integrity of bolted assemblies,

Figure 1.12 Bolt thread engagement

particularly in high-stress applications. The paper “Stud Bolt Thread Engagement: A Fitness for Service Approach” by Colton M. Cranford aims to review the key considerations for fastener strength and propose a post-construction evaluation technique to assess the fitness for service of less-than-fully engaged fastener assemblies. The importance of this matter is highlighted, and existing design evaluation techniques are discussed, including simple design formula and The Authoritative Method. The lack of engagement assessment techniques such as thread geometry, nut and stud geometry, and material strength value calculation is also emphasized. The impact of temperature effects and the Consolidated LOTE Assessment Technique are explored in detail.

The paper reviews previous works and identifies the need for an assessment technique for less-than-fully engaged fastener assemblies. The lack of engagement assessment techniques and methods to calculate material strength values are discussed. The paper suggests using material test reports to calculate fastener strengths accurately and recommends published strength data as an alternative in the absence of material test reports. The impact of temperature on fastener strength is also discussed, and the Consolidated LOTE Assessment Technique is proposed as an effective fitness-for-service assessment technique for determining the strength of fastener assemblies with less-than-full thread engagement.

The paper concludes that although there is uncertainty in performing thread strength calculations for less-than-fully engaged fasteners, proper risk considerations and measurement techniques can be used to predict fastener assembly static failure strength adequately. The LOTE Assessment Technique can be incorporated into fitness-for-service assessments to determine the strength of a fastener assembly with less-than-full thread engagement.

The paper provides a valuable perspective on the assessment of fastener assemblies with less-than-full thread engagement. It proposes several methods for calculating fastener strengths accurately and highlights the importance of material test reports in such assessments. The paper's focus on the Consolidated LOTE Assessment Technique provides a useful reference for assessing fastener assemblies' fitness for service. The study's findings and methods proposed can be incorporated into the design and evaluation of bolted assemblies in high-stress applications, providing greater confidence in the assemblies' safety and reliability.

1.4.5 Tools and equipment needed for Hot Bolting

Hot bolting is a specialized maintenance technique that involves the removal and replacement of flanged joint bolting on live piping and equipment. To perform hot bolting, certain tools and equipment are needed to ensure the safety and efficiency of the process. Here are some of the tools and equipment typically used in hot bolting:

Hot Bolting Clamps: Hot bolting clamps are designed to be used in conjunction with hot bolting. These clamps are used to apply a compressive force to the flange, which keeps the joint tight during the bolt removal and replacement process.

Hydraulic Torque Wrenches: Hydraulic torque wrenches are used to apply a precise amount of torque to the bolts during the tightening process. These wrenches can be powered by electric or hydraulic motors and are available in various sizes to fit different bolt diameters.

Impact Wrenches: Impact wrenches are used to remove and install bolts quickly and efficiently. These wrenches use a rotational force to tighten or loosen bolts, making them ideal for use in hot bolting applications.

Gasket Cutting Tools: Gasket cutting tools are used to cut new gaskets to fit the flange during the hot bolting process. These tools can be manual or electric and are available in various shapes and sizes to fit different flange configurations.

Bolt Tensioning Equipment: Bolt tensioning equipment is used to apply a precise amount of tension to the bolts during the tightening process. This equipment can be manual or hydraulic and is available in various sizes to fit different bolt diameters.

Flange Spreaders: Flange spreaders are used to separate the flanges during the hot bolting process. These tools can be hydraulic or mechanical and are available in various sizes to fit different flange configurations.

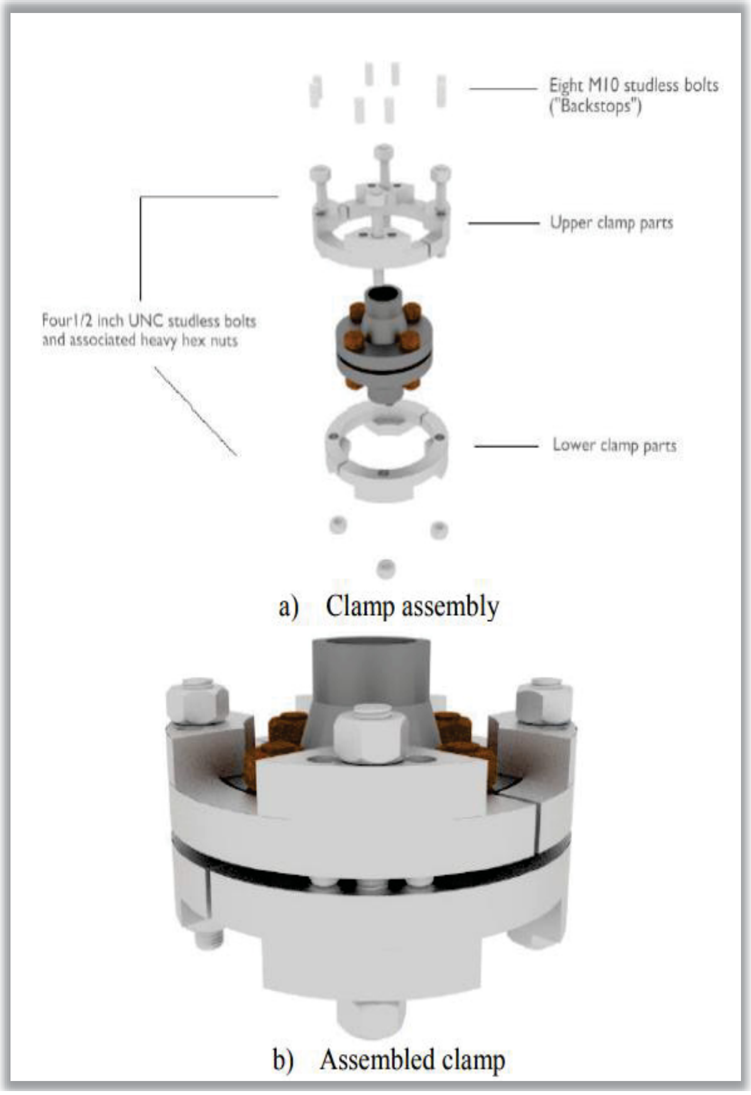

Figure 1.13 Hot bolting clamp™ from Irgens Engineering AS

Alignment Tools: Alignment tools are used to align the flanges during the hot bolting process. These tools can be manual or electronic and are used to ensure that the flanges are properly aligned before tightening the bolts.

Safety Equipment: Safety equipment, such as gloves, safety glasses, and ear protection, is essential when performing hot bolting. This equipment protects the operator from hot surfaces, flying debris, and loud noise associated with the process.

Integrity assessment of hot bolting tool refers to the process of evaluating the safety and effectiveness of a tool used for hot bolting, which is a technique used to replace or tighten bolts on live piping and equipment without shutting down the system. The assessment typically involves analyzing the mechanical properties of the tool and the components it interacts with, as well as evaluating the procedure for using the tool to ensure that it is safe and effective. In the context of the article by Guomin Ji et al., the integrity assessment focused on the use of hot bolting clamps designed by Irgens Engineering AS and involved finite element analysis (FEA) to model the behavior of the tool and the components it interacted with, as well as assessing the gasket's contact stress and the effects of the hot bolting operation on the flange and ring gasket.

The article discusses the hot bolting operation and its application using tools or without tools. The authors refer to the EEMUA published sheet in 1999, which restricted the application of hot bolting without tools on flange joints with less than eight bolts or with bolt materials weaker than grades B7/2H. To overcome this restriction, hot bolting clamps designed by Irgens Engineering AS were introduced in 2011.

The authors emphasize that controlling gasket contact stress is a key factor during hot bolting operations, which is achieved using FEA modeling. This modeling differs from traditional flanged joints bolting due to complex loading procedures, increased non-linear contact pairs, modeling of backstops, and the challenge of achieving convergence with increased model size.

The article outlines a step-by-step process for the hot bolting operation that includes initializing surface-surface contact interactions, applying pre-tension loads at flange bolts, applying hydrostatic pressure inside the flange, applying partial clamp loading, applying backstop loading, applying full clamp loading, removing and rebolting flange bolts, and removing clamps.

The authors used ABAQUS to assess the gasket's contact stress by pressure vs. closure modes, allowing the modeling of very complex non-linear elasticity gaskets. The stresses at the contact area between the flange and ring gasket exceeded the yield stress and entered the plastic regime, indicating the flow of the operation.

However, the authors note that there is a lot of stress at the other bolts' area during the "bolt removing step," which can be optimized using new methods. The authors emphasize that safety factors are considered high in this test, and no leakage occurred during the operation. Finally, the authors concluded that hot bolting is operable for 8" flanges.

1.5 Conclusion

The present literature review has provided valuable insights into the concept of elastic interaction of bolted flange joints, hot bolting and related practices. By analyzing a wide range of articles, A comprehensive understanding of the subject matter gained, including the importance of this topic in the industry and the innovative nature of this concept. The review has also highlighted various methods that can be employed to advance the project, enabling me to develop precise solutions to the problem.

Furthermore, the literature review has emphasized the significance of adhering to industry standards to mitigate potential risks associated with hot bolting. By examining relevant literature, I recognized the importance of adopting standardized practices in the field to ensure safety, reliability, and efficiency.

It is important to acknowledge the limitations of this literature review and the need for continued research to achieve a more comprehensive understanding of the subject matter. Future research should build upon the findings of this review, explore additional perspectives, and identify potential areas for improvement.

1.6 Research Gap and Motivation

While extensive studies have addressed the assembly behavior and sealing performance of bolted flange joints, there remains a notable gap in understanding the elastic interaction behavior during the untightening phase, particularly under hot bolting conditions. Furthermore, comparative studies that explore the influence of different gasket materials, untightening patterns, and initial preload levels on elastic redistribution are scarce.

Most of the current literature either focuses exclusively on analytical or FEM studies without experimental validation or generalizes findings without accounting for material variability.

Moreover, industry practices continue to rely on conservative guidelines due to the absence of predictive tools validated by comprehensive data.

1.7 Objective of the Study

The primary objective of this study is to investigate the elastic interaction of bolted flange joints during the untightening process, with a specific focus on scenarios such as regular disassembly and hot bolting. The study aims to improve understanding of how bolt tension redistributes, how gasket contact stress evolves, and how the overall joint behaves mechanically during bolt unloading. This objective can be accomplished through the following specific sub-objectives:

To adapt an existing analytical model capable of predicting bolt load redistribution and elastic interaction during sequential and criss-cross bolt tightening sequences to hot bolting and disassembly of bolted flange joints.

To validate the analytical predictions using both finite element modeling (FEM) and controlled experimental testing on NPS 4 Class 900 flange joints, equipped with different gasket types (PTFE, graphite, metallic), under controlled tightening and untightening conditions.

To assess the influence of gasket stiffness and bolt preload levels on bolt tension behavior, joint displacement, and gasket contact stress distribution during bolt removal.

To evaluate the effectiveness and risks associated with different untightening patterns and provide recommendations for safer and more reliable hot bolting practices based on experimental evidence and simulation results.

1.8 Summary

The literature review underscores the importance of understanding the mechanical response of bolted flange joints during untightening. Although existing studies have explored bolt load distribution, gasket behavior, and flange deformation during tightening, the dynamic elastic interaction during bolt untightening remains insufficiently addressed particularly in relation to practical variables such as gasket type and preload strategy.

This thesis addresses this gap by conducting a systematic experimental and numerical investigation of bolted flange joints behavior during untightening. The work evaluates flange displacement, bolt tension variation, and gasket compression across different untightening patterns and preload configurations. The results are validated against analytical models and FEM simulations, offering new insights for improving hot bolting safety and reliability.

CHAPITRE 2

EXPERIMENTAL SETUP

2.1 Introduction

Experimental investigation of the untightening of bolted joints is essential to ensure the reliability, safety, and longevity of these joints in practical applications. It enables the examination of bolt untightening in realistic conditions, such as dynamic loading, and pressure fluctuations. Analytical models or simulations alone may not fully capture the complexities of the hot bolting behavior in real-world environments. Experimental data helps validate analytical and numerical models that predict the conditions under which bolted joints untightened, which leads to improved predictive capabilities for engineers. Also, the parameters, such as materials, component dimensions and design features influence the susceptibility to untightening process, and experimental investigations help identify the optimal combinations to mitigate this risk.

The test rig in this project must be capable of measuring displacement and preload of all bolts during untightening, while maintaining other key parameters constant such as transverse displacement. With these considerations, a dedicated experimental test rig was developed at Static and Dynamic Sealing Laboratory of ÉTS, based on an existing spiral wound gasket buckling test rig. The test rig shown in Figure 2.1 comprises the following components:

1. Structural support pipe with a plate or pedestal bolted to the ground.
2. Two NPS 4 class 900 raised face welding neck flanges with a sheet gasket in between.
3. Eight LVDTs (Linear Variable Differential Transformers) fixed at the flange OD to measure axial displacement.
4. Eight instrumented studs with full bridge strain gauges bounded to the outside machined surfaces to measure tension and nuts.
5. A data acquisition system that measures tension, displacement, temperature and time.

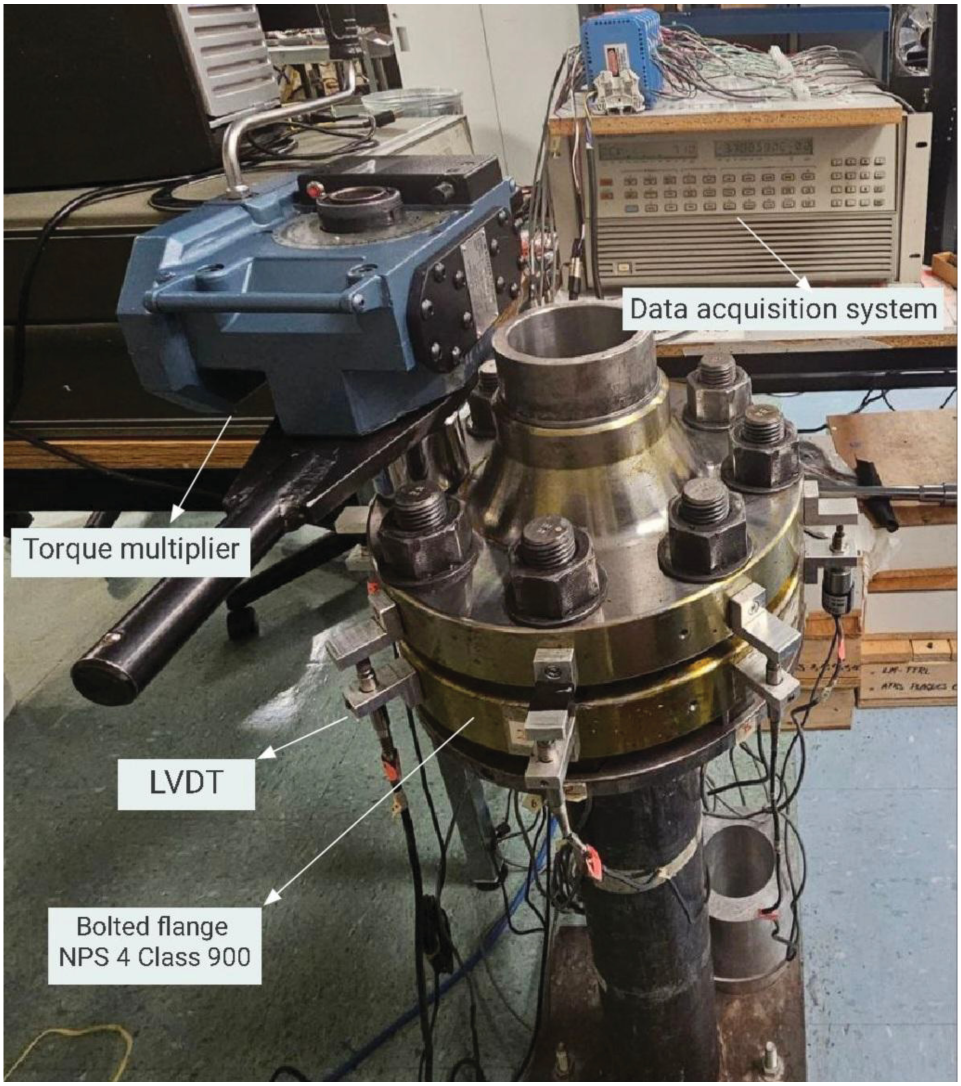

Figure 2.1 Buckling test rig used in this study

A digital torque multiplier with a 1/800 turn ratio was used to apply the preloads to the required levels.

The torque multiplier was also used to untighten the bolts gradually to reduce the chance of lateral movement.

The data acquisition system is integrated with the rig to capture outputs and display them through LabView software.

The test specimens (bolts, flanges, gasket, and nuts) are mounted on a pedestal bolted to the ground.

Eight LVDTs are positioned around the flange on the same radius as the studs to measure the axial displacements of the flanges during each untightening steps. The strain gauges bounded to the surface of the studs are calibrated to measure continuously the load tension applied to the bolt and its variation during tightening and untightening process.

Figure 2.2 LVDTs placed radially on the flange face

2.2 Axial Displacement Measurement Using LVDTs in Bolted Flange Joints

Axial displacement refers to the movement of the flange in the axial direction, typically expressed in millimeters (mm) or inches (in.). Monitoring axial displacement is critical during the untightening procedure, as it reflects changes in flange separation, gasket compression, and overall structural deformation. Accurate measurement of these displacements provides essential data for assessing elastic interaction among bolts and predicting potential integrity loss.

LVDTs are robust, electromagnetic displacement transducers that offer virtually infinite resolution and exceptional repeatability. They operate on the principle of electromagnetic induction, where a movable ferromagnetic core alters the magnetic coupling between a primary coil and two secondary coils. As the core moves linearly, the amplitude and phase of the resulting AC voltage vary in proportion to its position. This enables precise detection of both the magnitude and direction of displacement.

As illustrated in Figure 2.2, the experimental setup for the NPS 4 Class 900 flange joint included eight LVDTs mounted radially at the flange OD. These sensors were positioned adjacent to the bolt holes to monitor axial displacement during bolt untightening. The LVDTs were securely bracketed to the lower flange, while the core movement corresponded to vertical shifts in the upper flange caused by the release of the bolt preload.

LVDTs were chosen for several key reasons:

Non-contact measurement ensures no mechanical wear, making them suitable for repeated high-precision testing.

High resolution and linearity in the central range provide accurate data for both small and large displacements.

Phase-sensitive output allows for identification of displacement direction, critical in evaluating asymmetric deformation or tilting during sequential bolt release.

Compatibility with signal conditioning electronics enabled real-time acquisition and logging of displacement data using LabVIEW software and integrated DAQ systems.

The LVDT signal was conditioned using phase-sensitive demodulation, converting the AC output into a proportional DC voltage. This voltage was recorded in sync with bolt preload changes and gasket contact stress measurements. By comparing displacement patterns under different untightening sequences (sequential vs. criss-cross) and gasket types (PTFE, graphite, metallic), the study identified distinct elastic interaction behaviors. Notably, the data revealed flange lift-off patterns, cross-talk between bolts, and loss of gasket compression near the untightened zones.

2.2.1 LVDT Calibration Procedure

Prior to data collection, all LVDTs were individually calibrated to ensure measurement accuracy. Calibration was performed using a high-precision micrometer stage, which allowed for controlled, incremental displacements of the LVDT core. Each sensor core was moved in both directions from its electrical zero position, and the corresponding output voltage was recorded at known displacement intervals (typically in 0.1 mm steps across the full measurement range).

The calibration process followed these steps:

Setup: Each LVDT was mounted in a rigid fixture aligned with a micrometer-driven translation stage.

Reference Measurement: The stage was zeroed, and displacement was applied in both positive and negative directions from the electrical center.

Data Acquisition: Output voltage was measured at each position using the signal conditioning system and recorded via LabVIEW.

Linearity Check: The output was plotted against known displacements to verify linearity within the working range.

Curve Fitting: A linear regression or polynomial model was fitted to the calibration data to generate a calibration factor for real-time displacement conversion.

The resulting calibration factors were stored and used to convert raw voltage readings into precise displacement values during bolt untightening. An example of the calibration curve for stud 2 is shown in Fig 2.3. The calibration ensured measurement accuracy within ±0.01 mm, enabling fine-resolution analysis of flange lift-off, gasket compression loss, and bolt-induced deformation.

By carefully calibrating the LVDTs and arranging them in a symmetrically across the flange face, this study captured detailed deformation profiles and significantly enhanced understanding of elastic interactions in bolted flange joints.

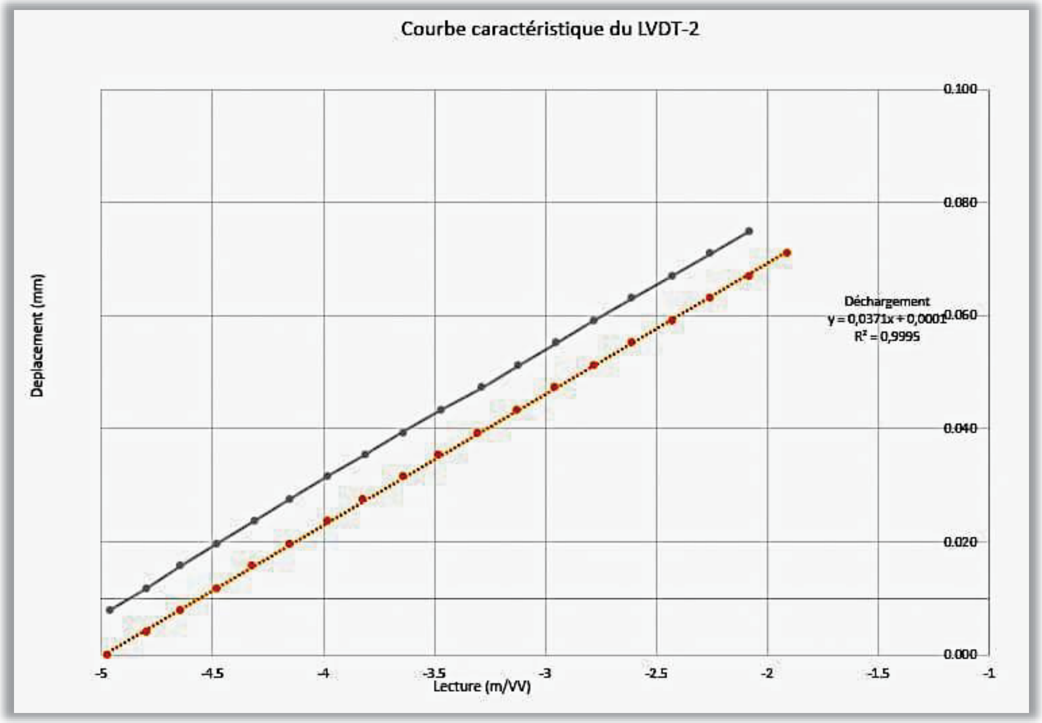

Figure 2.3 LVDT 2 calibration graph

In summary, LVDTs played a central role in quantifying flange displacement during bolt untightening, enabling a comprehensive understanding of how untightening one bolt impacts surrounding bolt tensions and flange geometry. These insights directly contributed to the development of safer, more efficient hot bolting strategies by correlating physical deformation with bolt load redistribution and gasket stress.

2.3 Strain Gauges for Bolt Tension Measurement

Accurate measurement of bolt tension during the untightening process is essential for analyzing load redistribution and elastic interaction in bolted flange joints. In this study, strain gauges were embedded within the studs to provide real-time data on preload variation throughout the untightening process.

Figure 2.4 strain gauges embedded within the bolts

As shown in Figure 2.4, each bolt was instrumented with a full-bridge strain gauge configuration. The gauges were mounted internally at the mid-length of the bolts. This configuration ensured that the measured strain corresponded directly to axial tension in the bolt shaft, providing a linear relationship between electrical output and bolt load.

2.3.1 Working Principle of Strain Gauges

Strain gauges operate based on the principle that electrical resistance changes proportionally to the deformation of the gauge material. When the bolt is subjected to tensile or compressive forces, it elongates or contracts accordingly. This deformation is captured by the strain gauge, whose resistance changes are translated into voltage signals through a Wheatstone bridge circuit.

For this study, each bolt utilized a full-bridge setup, enhancing measurement sensitivity and compensating for temperature-induced drift. The full-bridge configuration also provided an improved signal-to-noise ratio and linearity, which are critical for monitoring subtle tension variations during controlled bolt loosening.

2.3.2 Calibration Procedure

Prior to use in the flange joint assembly, the stud strain gauge bridges were carefully calibrated using a servo-hydraulic tensile machine equipped with a load cell. The calibration process involved:

Controlled Application of Load: A known preload by the tensile machine to the stud in a stepwise manner.

Recording Gauge Output: Corresponding bridge voltage outputs were recorded at load level.

Establishing Calibration Curves: The measured voltage was plotted against theoretical bolt tension, allowing the creation of accurate calibration curves for each bolt.

Verification: Calibration was validated by comparing strain-derived preload values with those measured directly by the torque meter. The deviation was found to be within acceptable limits (typically <2%), confirming the reliability of the strain gauge system.

2.3.3 Untightening Sequences

During testing, stud tension were continuously monitored as bolts were untightened using either sequentially or criss-cross patterns. At each stud untightening step, the measured tension and displacement were corelated to the FEM predictions. This approach enabled:
Identification of localized preload increases in adjacent bolts due to elastic interaction,
Tracking of tension loss in remote bolts caused by untightening steps.
Quantitative validation of analytical and simulation models.
The strain gauge system is essential for understanding the redistribution of preload during hot bolting procedures and revealed tension spikes in adjacent bolts following single-bolt removal.

2.4 Data acquisition system

To monitor and record data from the experimental setup, a data acquisition system was used in this project and consists of a main analog to digital board converter (Figure 2.6). All measuring devices are connected to a computer via the HP 3852A data acquisition unit. The electrical signals measured from all bolt strain gauges and conditioned LVDTs (Fig. 2.4) attached to different positions of the bolted flange joint are monitored every 10 seconds to record bolt tension and lateral displacement respectively during each untightening step.

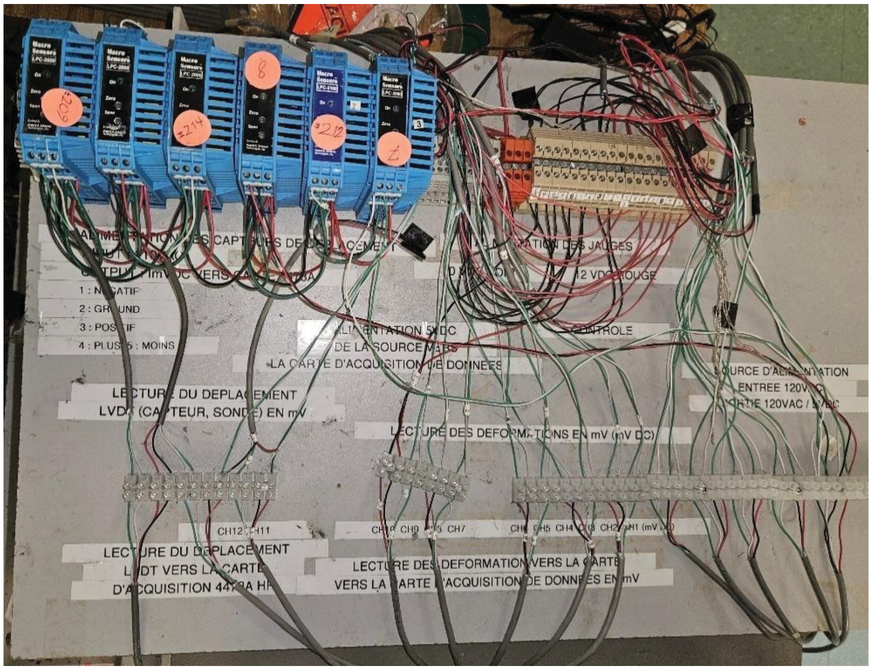

Figure 2.5 Data acquisition unit's main board and components

Figure 2.6 HP 3852A Data Acquisition/control Unit

The system is programmed using LabView software, the user interface of which is shown in Figure 2.7. The program continuously tracks and captures real-time data from all sensors connected to the test rig every 10 seconds. In addition to automatic periodic logging, a manual save point button was designed to record data at specific moments during testing.

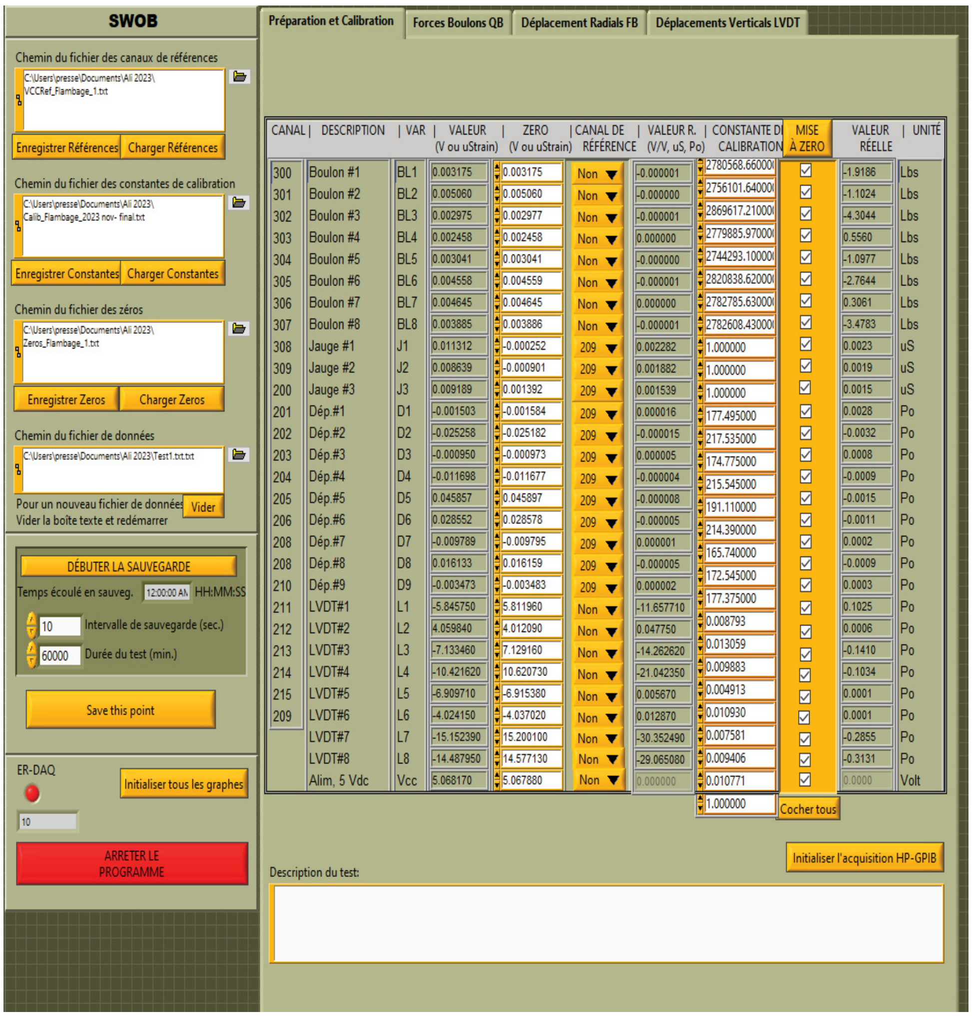

Figure 2.7 LabVIEW Interface

2.5 Conclusion

This chapter detailed the experimental framework developed to investigate the untightening behavior of bolted flange joints under controlled conditions. A custom test rig equipped with calibrated LVDTs and strain-gauged studs, enabled precise, real-time monitoring of axial displacement and bolt tension throughout various untightening sequences. The integration of a high-resolution data acquisition system allowed for synchronized measurement and analysis of mechanical responses, supporting the validation of analytical and numerical models. By replicating realistic flange configurations and loading conditions, the experimental setup provided critical insights into elastic interactions, preload redistribution, and gasket compression loss during bolt removal. These findings lay the groundwork for safer and more efficient bolt untightening strategies in bolted flange joints applications.

CHAPITRE 3

ELASTIC INTERACTION IN BOLTED FLANGE JOINTS DURING HOT BOLTING AND DISASSEMBLY

Ali Tofighi [a], Linbo Zhu [b], Abdel-Hakim Bouzid [c],

[a] Department of Mechanical Engineering, École de technologie supérieure,
1100 Notre-Dame St. West, Montreal, Quebec, H3C 1K3
[b] School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an, Shaanxi, P.R.China
[c] ASME Fellow, Department of Mechanical Engineering, École de technologie supérieure,
1100 Notre-Dame St. West, Montreal, Quebec, H3C 1K3

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3.1 Abstract

The sequential removal or replacement of bolts of a bolted flange joints while being considered a simple operation that involves untightening of bolts can lead to failure of the remaining untighten bolts, damage the gasket, and harm other associated components. Additionally, challenges persist in ensuring system reliability and safety during hot bolting or single replacement of bolts.

This paper aims to provide a deeper understanding of the elastic interactions within bolted flange joints during the unloading of bolts such that conducted during disassembly or hot bolting process. By analyzing the elastic interaction, common issues such as flange integrity loss and component damage can be effectively mitigated. Furthermore, the research seeks to enable more accurate predictions of flange behavior during untightening. This enhanced understanding could facilitate the development of more efficient tools or potentially enable the process to be performed safely without additional tools, provided safety factors are meticulously calculated. Ultimately, this study aims to improve the safety, efficiency, and reliability of systems that utilize hot bolting procedures.

Keywords: Hot bolting, bolted flange joints, untightening bolted flange joints, finite element modeling, pipeline safety, post construction maintenance, contact stress, elastic interaction

Nomenclature

A_b	nominal area of the bolt cross section, mm^2
C_b	elastic compliance of the bolt, mm/N
$C_{i,j}$	amount of vertical compressive displacement of the gasket and flanges at the axis of bolt i due to a unit load in bolt j, mm/N
E_b	elastic modulus of bolt material, MPa
E_f	elastic modulus of flange material, MPa
E_g	elastic modulus of gasket material, MPa
L_e	effective bolt length, mm
F_0	snug fit preload in each bolt, N
F_b	bolt tension, N
F_i^m	preload in bolt i after tightening all bolts in pass m, N
F_i^{m-1}	preload in bolt i after tightening all bolts in pass m-1, N
$F_{i,j}^m$	preload in bolt i after tightening bolt j in pass m, N
$F_{i,j-1}^m$	preload in bolt i after tightening bolt j-1 in pass m, N
F_j	preload in bolt j, N
$F_{j,j-1}^{m-1}$	preload in bolt j after tightening bolt j-1 in pass m-1, N
i, j	bolt number
n	total number of bolts
m	pass number
w_i	displacement of flange at periodic bolt spacing, mm
$[C]$	elastic compliance matrix
$\Delta F_{i,j}$	the corresponding bolt tension increment in bolt i after tightening bolt j, N
ΔF_j	bolt tension increment in bolt j, N

$\Delta\delta_{i,j}$ displacement increments of gasket and flanges at bolt i location after tightening bolt j, mm

$\Delta\delta_{bi,j}$ displacement increments of bolt j, mm

3.2 Introduction

The untightening of bolts is a common operation during the disassembly of mechanical components, particularly in bolted flange connections. This procedure is essential for separating flanged parts during maintenance. However, when bolts are untightened, the load distribution among the remaining bolts changes due to elastic interactions, potentially increasing stress in some bolts while reducing it in others. In extreme cases, this redistribution can lead to plastic collapse or even failure of the clamped components.

Replacing corroded or damaged bolts in bolted flange joints is another critical maintenance task in pressure vessels and piping systems, especially in high-pressure and high-temperature environments with harsh, corrosive conditions. Performing this operation without halting system operations (referred to as hot bolting) is crucial to minimizing downtime and ensuring service continuity. Hot bolting is addressed in the PCC-1 Guidelines for Pressure Boundary Bolted Flange Joint Assembly and the ASME PCC-2 Repair of Pressure Equipment and Piping [1,2]. Despite these guidelines, industries often use specialized tools and clamps [3] and apply high safety margins due to the uncertainties surrounding bolt behavior under extreme conditions.

Ji et al. [4] referenced an information sheet published by the EEMUA Engineering Equipment and Materials Users Association in 1999, titled Guidance Procedures for the Removal and Replacement of Flanged Joint Bolting on Live Piping and Equipment [5], which imposed strict safety factors on hot bolting applications. Their study introduced the use of hot bolting clamps, first utilized in 2011, where gasket contact stress was a key variable controlled through finite element analysis (FEA). The analysis revealed that stresses at the flange-ring gasket contact area exceeded the yield stress. In metal-to-metal contact scenarios, ensuring a reliable seal often requires localized plastic deformation of the flange groove in contact with the gasket's outer surface.

Addressing these uncertainties and improving our understanding of bolted flange joint behavior during hot bolting is essential for enhancing safety and operational efficiency. Gordon et al. [6] explored gasket relaxation in polytetrafluoroethylene (PTFE) gaskets, emphasizing the significance of re-torquing in high-pressure, high-temperature applications; a crucial factor in hot bolting. Rodery et al. [7] outlined operational limits for hot bolting and recommended evaluating gasket stress using the minimum gasket stress criteria from ASME PCC-1 Appendix O. This appendix defines key parameters such as maximum permissible gasket stress, minimum gasket seating stress, and minimum operating gasket stress. Garcia et al. [8] investigated how these variables influence gasket performance across different materials and thicknesses. Subsequently, they proposed minimum requirements for hot bolting based on flange size, class, and gasket contact stress evaluation. Despite these studies, accurately assessing contact stress distribution requires a deeper understanding of bolt interactions during the untightening process, a key focus of this research. Lutkiewicz [9] analyzed the impact of flange type on hot bolting safety, comparing an API 6F flange with a BX gasket and a NORSOK L-005 compact flange with an IX seal ring.

To mitigate risks and prevent catastrophic failures, a thorough evaluation of safety measures in hot bolting is imperative. Understanding how different gasket materials and bolt untightening sequences affect joint behavior allows for improved risk management and maintenance planning. By analyzing the joint response under varying conditions, this study aims to enhance hot bolting procedures, ensuring maintenance is conducted with minimal risk and maximum efficiency.

This paper presents a comprehensive investigation into bolted flange joint behavior during the untightening of multiple bolts, focusing on load redistribution in adjacent bolts. Two untightening patterns sequential clockwise and criss-cross are compared. Key factors such as contact stress and bolt displacement are analyzed to provide data-driven insights for safe and reliable bolt unloading. The findings contribute to optimizing hot bolting practices and advancing the broader knowledge of pressure vessel and piping system maintenance.

3.3 Analytical Modeling

The analytical model that simulates the effect of elastic interaction on bolt tension and clamp load scatter in a bolted flange joint is based on the one developed by Zhu et al. in [10-13]. As shown in the model of a four-bolt flange joint of Figure 3.1, the variations of the bolt tension result mainly from the axial displacement change at the bolt location due to the combined flange, gasket and bolt axial stiffness at that same location.

All bolts are initially tightened to a preload F_0. It is assumed that the bolts, the gasket, and the two flanges deform elastically in the axial direction. Subsequently, when a bolt is untightened, the axial displacements of the gasket, bolt and flange change leading to a change of preload in other bolts. If bolt j is untightened to a preload F_j=0 from F_0, the elastic vertical displacement increments of the gasket and flanges at bolt i locations can be defined as:

$$\Delta\delta_{i,j} = C_{i,1}\Delta F_{1,j} + \mathrm{K} + C_{i,i}\Delta F_{i,j} + \mathrm{K} + C_{i,j}\Delta F_{j} + \mathrm{K} + C_{i,n}\Delta F_{n,j} \quad (3.1)$$

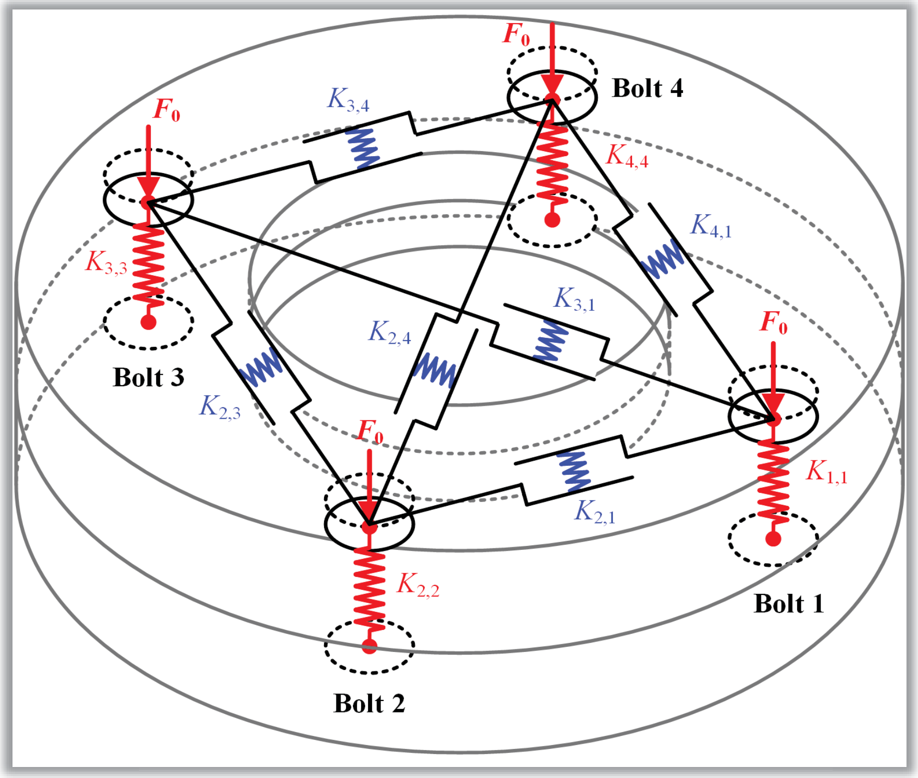

Figure 3.1 Analytical Model

Where n is the number of bolts, $C_{i,j}$ is the elastic compliance and represents the axial displacement of the gasket and the flange at bolt i due to a unit load of bolt number j. $\Delta F_{i,j}$ is the corresponding bolt tension change in bolt i. ΔF_j is the bolt tension change in bolt j, $\Delta F_j = F_j - F_0$.

Because of symmetry with respect to the diameter line passing through the untightened bolt, the compliance of any two symmetrical bolts is the same such that:

$$C_{i-k,i} = C_{i,i-k} = C_k \quad (k = 1, \ldots, i-1;\ i = 2, \ldots, n) \tag{3.2}$$

$$C_{i,i} = C \quad (i = 1, \ldots, n) \tag{3.3}$$

Based on the displacement compatibility condition of bolt i, we have

$$\Delta\delta_{i,j} + \Delta\delta_{bi,j} = 0 \tag{3.4}$$

Where $\Delta\delta_{bi,j}$ is the displacement increment of bolt i that can be obtain by

$$\Delta\delta_{bi,j} = C_b \Delta F_{i,j} \tag{3.5}$$

In which, C_b is the elastic compliance of the bolt defined as

$$C_b = \frac{L_e}{E_b A_b} \tag{3.6}$$

Where L_e is the effective bolt length, A_b is the nominal area of the bolt cross section, and E_b is the elastic modulus of bolt material. Substituting Eqs.(3.1) and (3.5) into Eq.(3.4), the corresponding compatibility equation of displacement can be written as:

$$C_{i,1}\Delta F_{1,j} + \cdots + (C_{i,i} + C_b)\Delta F_{i,j} + \cdots + C_{i,j}\Delta F_j + \cdots + C_{i,n}\Delta F_{n,j} = 0 \tag{3.7}$$

Extending the deformation compatibility condition to other bolts based on Eq.(3.8), the bolt tension increments of a joint with n bolts after untightening pass $m=1$ can be defined as:

$$\begin{bmatrix} C_{1,1}+C_b & \cdots & C_{1,i} & \cdots & C_{1,j} & \cdots & C_{1,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ C_{i,1} & \cdots & C_{i,i}+C_b & \cdots & C_{i,j} & \cdots & C_{i,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ C_{j,1} & \cdots & C_{j,i} & \cdots & C_{j,j}+C_b & \cdots & C_{j,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ C_{n,1} & \cdots & C_{n,i} & \cdots & C_{n,j} & \cdots & C_{n,n}+C_b \end{bmatrix} \begin{Bmatrix} \Delta F_{1,j}^m \\ \vdots \\ \Delta F_{i,j}^m \\ \vdots \\ \Delta F_j^m \\ \vdots \\ \Delta F_{n,j}^m \end{Bmatrix} = \{0\} \tag{3.8}$$

Or simply in a matrix form:

$$[C]\{\Delta F\} = 0 \tag{3.9}$$

In Eq.(3.9), the positions of $C_{i,j}$ and $\Delta F_{i,j}^m$ are determined by the untightening pattern. The subscript j refers to the untightening of bolt j and the superscript m refers to the untightening pass number and is equal to 1 here. Taking the NPS4 class 900 flange joint with 8 bolts as an example and using Eq.(3.9), the bolt tension changes after tightening pass $m=1$ using the criss-cross pattern can be obtained as:

$$[C]\begin{Bmatrix} \Delta F_{1,j}^{m} \\ \Delta F_{5,j}^{m} \\ \Delta F_{3,j}^{m} \\ \Delta F_{7,j}^{m} \\ \Delta F_{2,j}^{m} \\ \Delta F_{4,j}^{m} \\ \Delta F_{6,j}^{m} \\ \Delta F_{8,j}^{m} \end{Bmatrix} = \{0\} \tag{3.10}$$

where matrix C is:

$$[C] = \begin{bmatrix} C_{1,1}+C_b & C_{1,5} & C_{1,3} & C_{1,7} & C_{1,2} & C_{1,6} & C_{1,4} & C_{1,8} \\ C_{5,1} & C_{5,5}+C_b & C_{5,3} & C_{5,7} & C_{5,2} & C_{5,6} & C_{5,4} & C_{5,8} \\ C_{3,1} & C_{3,5} & C_{3,3}+C_b & C_{3,7} & C_{3,2} & C_{3,6} & C_{3,4} & C_{3,8} \\ C_{7,1} & C_{7,5} & C_{7,3} & C_{7,7}+C_b & C_{7,2} & C_{7,6} & C_{7,4} & C_{7,8} \\ C_{2,1} & C_{2,5} & C_{2,3} & C_{2,7} & C_{2,2}+C_b & C_{2,6} & C_{2,4} & C_{2,8} \\ C_{6,1} & C_{6,5} & C_{6,3} & C_{6,7} & C_{6,2} & C_{6,6}+C_b & C_{6,4} & C_{6,8} \\ C_{4,1} & C_{4,5} & C_{4,3} & C_{4,7} & C_{4,2} & C_{4,6} & C_{4,4}+C_b & C_{4,8} \\ C_{8,1} & C_{8,5} & C_{8,3} & C_{8,7} & C_{8,2} & C_{8,6} & C_{8,4} & C_{8,8}+C_b \end{bmatrix} \tag{3.11}$$

The bolt tension change of the NPS 4 class 900 flange joint using a sequential clockwise pattern can be obtained using Eq.(3.10) with the compliance matrix C is replaced by C' such that:

$$[C'] = \begin{bmatrix} C_{1,1}+C_b & C_{1,2} & C_{1,3} & C_{1,4} & C_{1,5} & C_{1,6} & C_{1,7} & C_{1,8} \\ C_{2,1} & C_{2,2}+C_b & C_{2,3} & C_{2,4} & C_{2,5} & C_{2,6} & C_{2,7} & C_{2,8} \\ C_{3,1} & C_{3,2} & C_{3,3}+C_b & C_{3,4} & C_{3,5} & C_{3,6} & C_{3,7} & C_{3,8} \\ C_{4,1} & C_{4,2} & C_{4,3} & C_{4,4}+C_b & C_{4,5} & C_{4,6} & C_{4,7} & C_{4,8} \\ C_{5,1} & C_{5,2} & C_{5,3} & C_{5,4} & C_{5,5}+C_b & C_{5,6} & C_{5,7} & C_{5,8} \\ C_{6,1} & C_{6,2} & C_{6,3} & C_{6,4} & C_{6,5} & C_{6,6}+C_b & C_{6,7} & C_{6,8} \\ C_{7,1} & C_{7,2} & C_{7,3} & C_{7,4} & C_{7,5} & C_{7,6} & C_{7,7}+C_b & C_{7,8} \\ C_{8,1} & C_{8,2} & C_{8,3} & C_{8,4} & C_{8,5} & C_{8,6} & C_{8,7} & C_{8,8}+C_b \end{bmatrix} \tag{3.12}$$

Based on Eq.(3.2), the elastic compliances in Eqs.(3.12) and (3.13) are given as:

$$\begin{gathered} C_{1,1} = C_{2,2} = C_{3,3} = C_{4,4} = C_{5,5} = C_{6,6} = C_{7,7} = C_{8,8} \\ C_{1,2} = C_{2,3} = C_{3,4} = C_{4,5} = C_{5,6} = C_{6,7} = C_{7,8} = C_{8,1} \; C_{1,3} = C_{2,4} = C_{3,5} = C_{4,6} = C_{5,7} = C_{6,8} = C_{7,1} = C_{8,2} \\ C_{1,4} = C_{2,5} = C_{3,6} = C_{4,7} = C_{5,8} = C_{6,1} = C_{7,2} = C_{8,3} \; C_{1,5} = C_{2,6} = C_{3,7} = C_{4,8} \end{gathered} \tag{3.13}$$

To determine the changes in bolt tension after sequentially untightening each bolt, a MATLAB code has been developed. The calculation process is divided into five key steps. The input parameters include flange, gasket, and bolt dimensions, material properties, bolt count, untightening pass number, and initial bolt preload. The steps are as follows:

1. Input Definition: The geometry, material properties of the flange, bolts, and gasket, as well as the untightening strategy, are specified.
2. Elastic Compliance Calculation: Using either the first or second method, the elastic compliances of the combined flange and gasket at each bolt position are determined as described in references [8,9].
3. Compliance Matrix Construction: The compliance matrix [C] is assembled based on the selected untightening pattern (criss-cross, sequential clockwise, or another sequence). Compatibility conditions for each bolt are established using Equation (3.8).
4. *Bolt Load Redistribution*: The load variation in bolt i due to the untightening of bolt j is calculated using Equation (3.9). The resulting bolt tension is then obtained from Equation (3.11).
5. Compliance Matrix Update & Iteration: The compliance values associated with the untightened bolt are set to zero, affecting all corresponding row and column elements. The process is then repeated from Step 3 until all bolts are untightened.

3.4 Experimental Set-up and FEM Validation

For this investigation, an NPS 4 Class 900 welding neck flange joint was tested with three gasket types: metallic, PTFE, and graphite sheets. These materials were chosen to evaluate their impact on elastic interaction and cross-talk behavior in the bolted joint under unloading conditions. The untightening process was conducted using a single pass with both sequential and criss-cross patterns.

Sequential Pattern: Bolts were untightened in numerical order: 1, 2, 3, 4, 5, 6, 7, 8.

Criss-Cross Pattern: Bolts were untightened in order: 1, 5, 3, 7, 2, 6, 4, 8.

During the experimental phase, bolts were systematically untightened following these patterns while monitoring bolt load changes, gasket contact stress distribution, bolt displacement, and overall joint stability. High-precision sensors and monitoring equipment ensured accurate and detailed data collection throughout the tests.

To complement the experiments, finite element modeling (FEM) was used to validate the observed behavior. FEM simulations provided deeper insight into the mechanics involved, enabling the visualization of stress distribution and deformation patterns that were not easily captured experimentally. A comparison between the experimental and numerical results showed a high degree of agreement, confirming the effectiveness of FEM as a predictive tool for hot bolting. Any discrepancies were thoroughly analyzed and attributed to material properties and experimental constraints.

3.4.1 Experimental set-up

The test rig used for experimentation consists of an instrumented bolted joint, comprising a pair of NPS 4 Class 900 welding-neck flanges secured by eight instrumented studs. Bolt tension is measured using full-bridge strain gauges, embedded at the mid-length of each machined stud where the threads have been removed. The gauges are calibrated on an MTS servo-hydraulic tensile machine to ensure accuracy. To analyze elastic interaction and cross-talk, axial displacements are measured at eight locations on the flange face adjacent to the studs. This is achieved using eight linear variable differential transformers (LVDTs), mounted

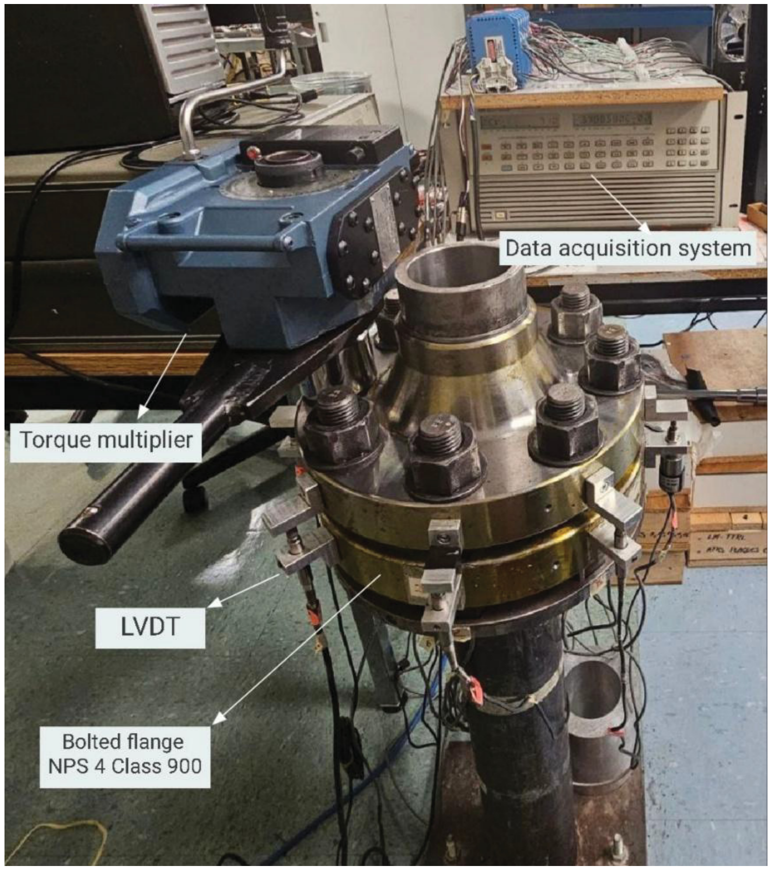

Figure 3.2 Experimental Set-Up

on brackets fixed to the lower flange. The LVDTs capture flange movement due to gasket compression, flange rotation, and elastic interactions. Prior to testing, the LVDTs are calibrated using a micrometer.

A digital power torque multiplier is used for tightening and untightening the studs. This device can apply up to 1200 lb.ft of torque with a rotation angle ratio of 1/800. The criss-cross pattern is employed for tightening, using multiple steps to achieve a uniform preload of up to approximately 120 kN per stud, corresponding to 275 MPa (40 ksi). All instruments are connected to a data acquisition system, with real-time monitoring and data transfer to a computer running LabView software. Measurements are recorded every 10 seconds or as needed. To evaluate the effect of gasket stiffness, tests are conducted using PTFE, graphite, and metallic gaskets.

3.4.2 Finite Element Model

The bolted joint consists of three primary components: the flange, bolts, and gasket, as shown in Figure 3.4, The flange comprises three distinct parts: the shell, hub, and flange ring. It is an NPS 4 Class 900 flange made of SA105 with a Young's modulus of 210 GPa and a Poisson's ratio of 0.3. The studs are made of SA193 B7, with a Young's modulus of 200 GPa and a Poisson's ratio of 0.3. The bolted joint dimensions are detailed in Table 3.1.

The untightening process of the bolted flange joint is simulated using ANSYS finite element software. Since the assembly involves identical flanges, only one flange and half of the gasket thickness are modeled to leverage symmetry. Although the full flange is considered in the analysis, Figure 3.4 presents only half of it for better visualization [7].

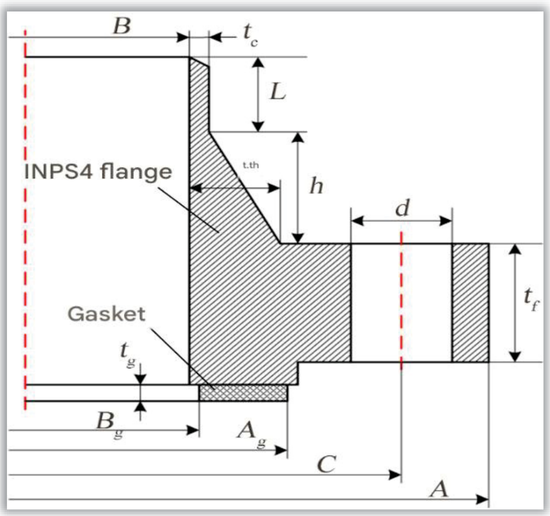

Figure 3.3 Flange Dimensions

Table 3.1 Bolted Joint Dimensions

A	B	C	t_c	t_h	h	t_f	n_b	d	A_g	B_g
mm	mm	mm	mm	mm	mm	mm		mm	mm	mm
290	102	235	6	25.4	44.5	44.5	8	29	149	124

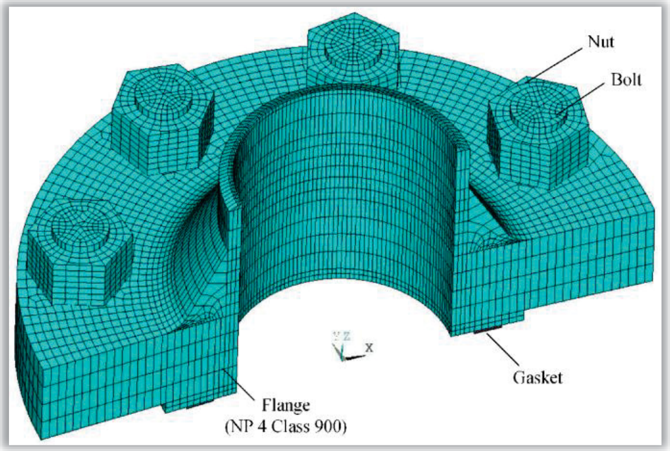

Figure 3.4 FE Model of The Bolted Joint

The flange and studs are modeled in 3D using isoparametric eight-node SOLID185 elements. Interface gasket elements simulate the gasket's linear material behavior for simplification. The model consists of 57,979 elements and 68,227 nodes, with contact elements capturing interactions at the flange-nut interfaces. While washers were included in the experimental setup, they were excluded from the simulation due to their negligible impact on the study. A friction coefficient of 0.15 is assigned to all contact surfaces. The gasket-flange interface is modeled using contact elements with a no-slip condition. Symmetry constraints are applied by meshing only one full flange, with the symmetry plane passing through the mid-gasket thickness. Nodes along this plane, including those of the gasket and studs, are restricted from axial displacement. The simulation process begins by simultaneously tightening all studs to achieve a preload of 120 kN per stud. Untightening is then performed following criss-cross or sequential patterns, using the element birth and death (EKILL) method.

3.5 Results and Discussion

This section presents the analytical, numerical (FE), and experimental results on the elastic interactions of an NPS 4 Class 900 bolted flange joint during the untightening process using both criss-cross and sequential patterns for different gasket styles. The analysis includes a comparative assessment of experimental results with finite element (FE) and analytical predictions, specifically for a sequential clockwise untightening pattern using a PTFE gasket. Key factors evaluated include bolt tensions, displacements, and stress distributions, which are critical indicators of elastic interactions in bolted flange joints.

To assess the impact of gasket stiffness on elastic interactions, experimental results for three gasket materials—PTFE, metallic, and graphite—are compared. The influence of gasket type on bolt tensions and displacements during untightening is reported, with particular attention to variations observed at each bolt unloading step. A key focus is placed on identifying critical levels of bolt tension and gasket contact stress, particularly in the context of single bolt replacement (hot bolting) and complete untightening scenarios.

3.5.1 Untightening using sequential pattern:

The change in bolt tension is analyzed using analytical, finite element (FE), and experimental methods, as described earlier. The bolts are numbered sequentially, and each untightening step involves loosening one bolt at a time until all bolts are fully released. A PTFE gasket is used across all experimental, analytical, and FE tests.

As shown in Figure 3.5, loosening the first bolt leads to a tension increase in the adjacent bolts (2 and 8). This increase is approximately 33% of the target load in the FE model, 28% in the analytical method, and no more than 17% in the experimental test. For both analytical and experimental results, this represents the highest tension value, and for the FE results, it is nearly

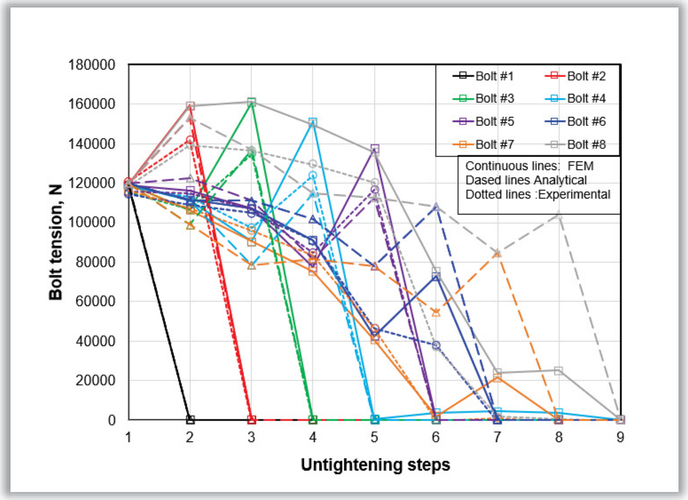

Figure 3.5 Bolt Tension Comparison During Sequential Untightening

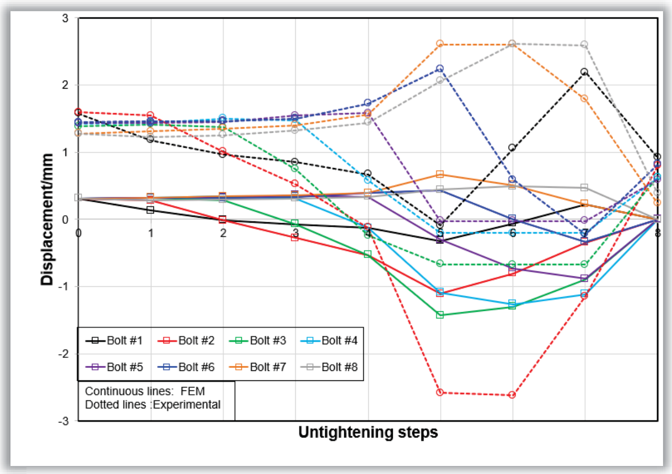

Figure 3.6 Displacement Comparison During Sequential Untightening

the highest. These findings suggest that the maximum tension occurs after untightening the first bolt, reaching 33% of the preload in this NPS 4 Class 900 flange. Thus, to prevent yielding during untightening, bolts should be preloaded at least 33% below their yield stress.

The bolts that experience the most tension loss are the adjacent bolts (3 and 7) to bolts 2 and 8, respectively, with a reduction of just under 10%. Figure 3.5 also demonstrates strong agreement between the analytical, FE, and experimental results regarding elastic interaction. However, larger differences between the three methods are observed when untightening the two bolts before the last one, likely due to gasket material stiffness evaluation and flange tilting or cross-talk effects.

Figure 3.6 presents the joint displacement during the untightening process. A shift of approximately 1 mm is observed even before untightening begins, attributed to flange rotation and the positioning of the LVDTs. In the experimental setup, LVDTs are placed a few centimeters away from the flange, whereas the FE model computes values directlyat the flange radius. Despite this, the FEM and experimental results show overall alignment.

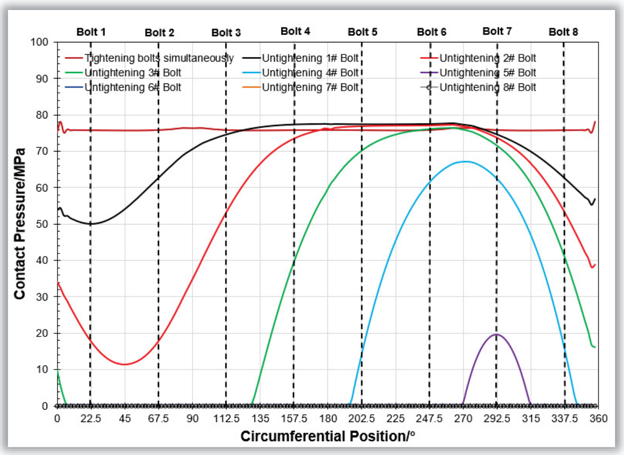

Figure 3.7 Gasket Contact Stress at Inner Radius
During Sequential Untightening

Figures 3.7 and 3.8 illustrate the FE gasket contact stress distributions at the inner and outer gasket radius after each untightening step. These results indicate that when the first bolt is untightened, the gasket loses over 37% of its contact stress at the inner radius and more than 50% at the outer radius, particularly at the location of the untightened bolt (bolt 1). Subsequent untightening, especially of bolt 5, causes a contact stress increase of over 57%.

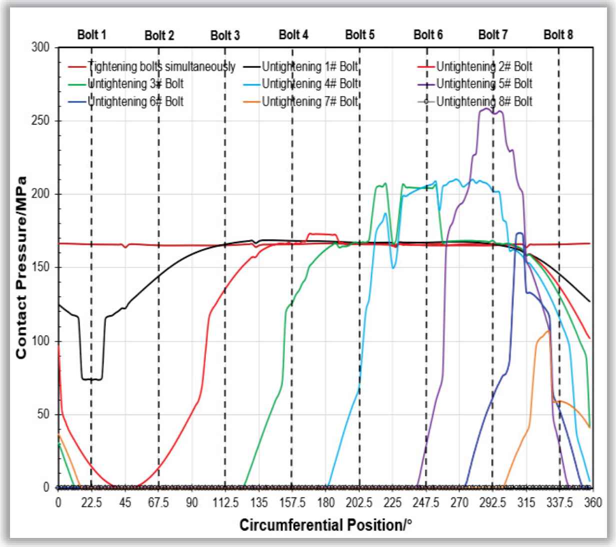

Figure 3.8 Gasket Contact Stress At Outer Radius
During Sequential Untightening

3.5.2 Criss-Cross Untightening Pattern:

Although the criss-cross pattern is more commonly used for tightening, it was applied here for untightening to compare its effectiveness against the sequential pattern and provide recommendations. The results from experimental tests were compared with finite element (FE) and analytical models.

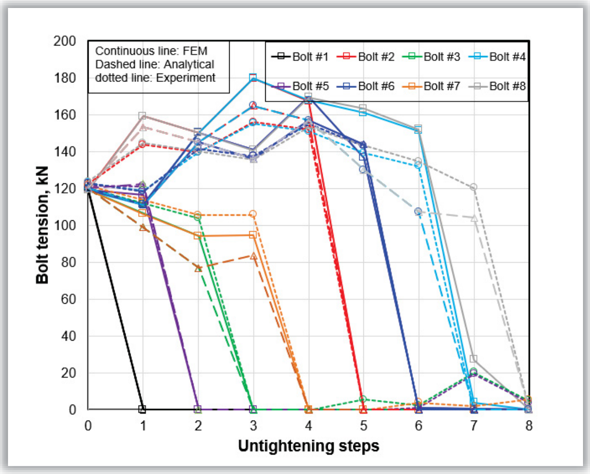

Figure 3.9 Bolt Tension Comparison During Criss-Cross Untightening

As shown in Figure 3.9, the bolt tension changes due to elastic interactions exhibit good agreement across the three methods. The criss-cross pattern results in higher tension increases than the sequential pattern. Specifically, FE simulations recorded a 50% increase, while analytical and experimental methods showed increases of 37% and 30%, respectively, in bolts 2 and 4. This suggests that if the initial tightening force is high, yielding could occur during untightening. The discrepancy between experimental and numerical results is likely due to the nonlinear, non-elastic behavior of the gasket material.

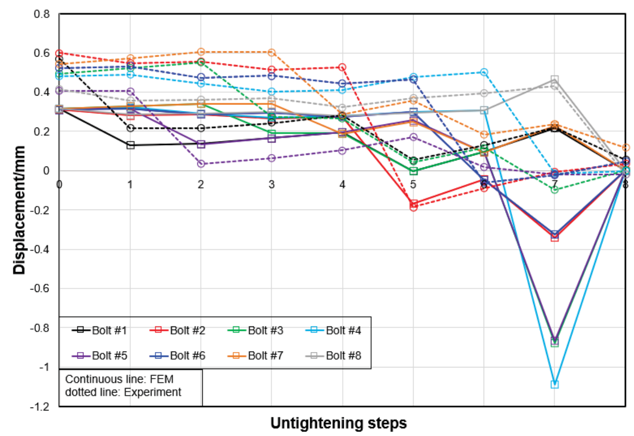

Figure 3.10 Displacement Comparison During Criss-Cross Untightening

Figure 3.10 presents the axial flange displacement observed during untightening. A 0.2 mm difference between the FE model and measured values is evident at the start, before untightening begins. As discussed earlier, this difference is likely due to flange rotation and the positioning of LVDTs in the experimental setup. Despite this, the overall displacement patterns align well. Compared to the sequential pattern, displacements in the criss-cross pattern are more uniform, except for a spike at the penultimate bolt. In contrast, the sequential pattern results in maximum displacement across the last three untightened bolts before the final one.

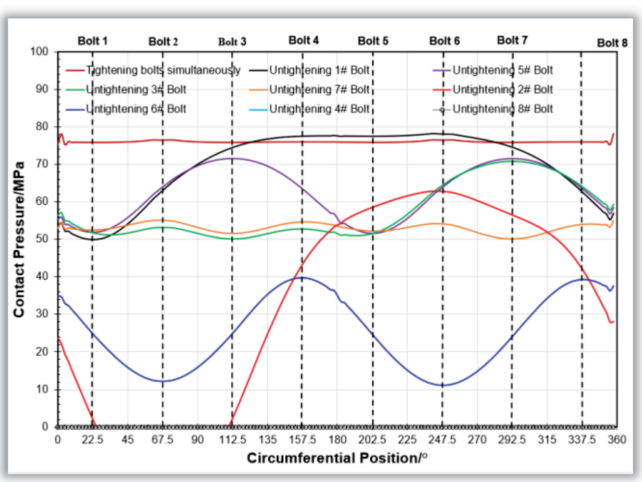

Figure 3.11 Gasket Contact Stress at Inside During Criss-Cross Untightening

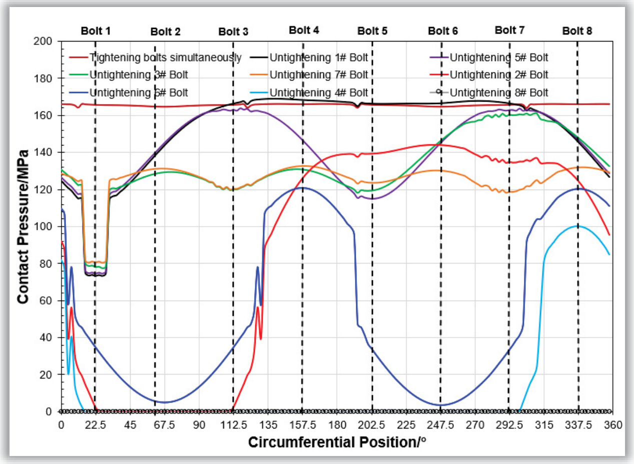

Figure 3.12 Gasket Contact Stress at Outside
During Criss-Cross Untightening

Figures 3.11 and 3.12 indicate that the criss-cross pattern helps the gasket maintain higher minimum contact stress values, especially in cases requiring multiple bolt replacements. Additionally, unlike the sequential pattern, this method does not cause an increase in gasket contact stress, which is beneficial if gasket reuse is necessary. Therefore, the criss-cross pattern is recommended when more than one bolt needs to be untightened simultaneously.

3.5.3 Gasket Stiffness Effect

Gasket stiffness plays a crucial role in the tightening and untightening behavior of bolted flange joints, significantly influencing elastic interactions during these processes. Figure 3.13 compares bolt tensions for graphite and metallic gaskets. The results indicate that the graphite gasket generates slightly higher bolt tensions up to step 4, though the differences remain minor. However, beyond step 4, the tension in the graphite gasket drops significantly, while the metallic gasket maintains its tension until just before the final step, demonstrating greater

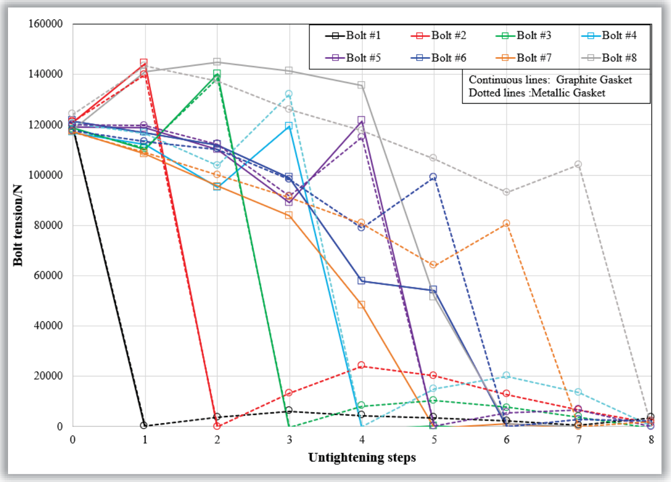

Figure 3.13 Bolt Tension Comparison Between Graphite and Metallic Gaskets During Untightening Steps

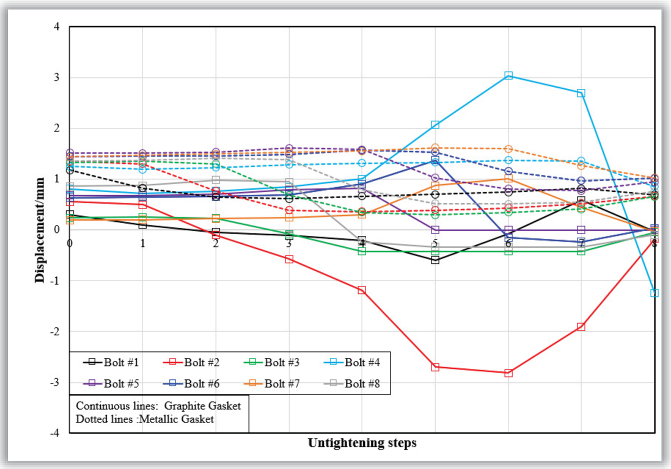

Figure 3.14 Displacement Comparison Between Graphite and Metallic Gaskets During Untightening

stability. This enhanced stability is likely due to the material similarity between the metallic gasket and the flange, reducing the effects of differential deformation.

Figure 3.14 compares the displacement behavior of the two gaskets during untightening. The graphite gasket exhibits fewer fluctuations, which may be attributed to its stiffness characteristics. Additionally, the notable displacement observed in bolts 2 and 4 after step 5 further highlights the tension loss in the graphite gasket, reinforcing its reduced ability to maintain preload compared to the metallic gasket.

3.5.4 Bolt Load Level Effect

The effect of tightening level was investigated by repeating the initial sequential untightening test, which was originally conducted with a 120 kN bolt force (275 MPa bolt stress), using a lower bolt force of approximately 43 kN (100 MPa bolt stress)—about one-third of the original preload. The pattern of bolt tension variation during untightening remained consistent, with bolt 1 experiencing a load increase of 30% in FEM, 28% in the analytical model, and 17% in the experimental test. These

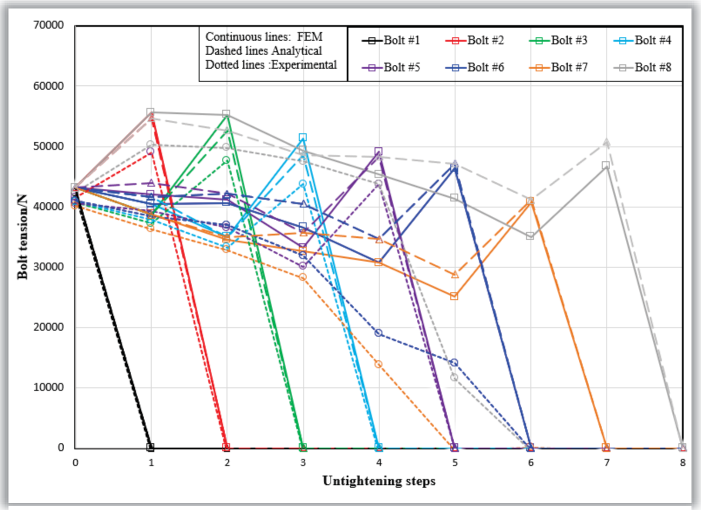

Figure 3.15 Bolt Tension Comparison During Sequential Untightening

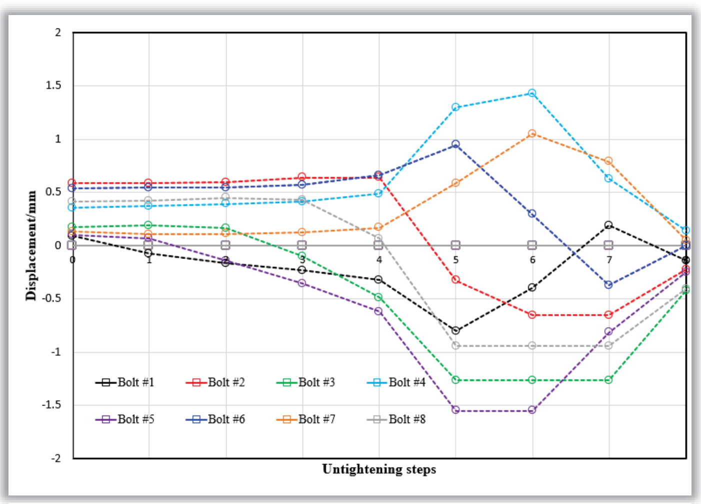

Figure 3.16 Displacement Comparison During Sequential Untightening

values closely match those observed at 275 MPa bolt stress, indicating that the general elastic interaction behavior is independent of preload level within this range.

Figure 3.15 presents the bolt tension variations during the sequential untightening of all bolts. The agreement between the three methods is particularly strong during the untightening of the first four bolts. However, greater deviations appear after the untightening of the last four bolts, likely due to cross-talk effects and the nonlinear behavior of the gasket material.

Figure 3.16 illustrates the experimentally measured flange displacements. While the displacement magnitudes at the flange outer diameter are smaller at the lower preload level, the overall distribution pattern remains the same as in the higher bolt tightening level, reinforcing the consistency of the elastic interaction trends.

3.6 Conclusion

This study delved into the elastic interactions present during the untightening process of bolted flange joints, employing analytical, finite element, and experimental methods. A particular focus was placed on assessing the influence of gasket stiffness. Both sequential clockwise and criss-cross untightening patterns were examined to determine their effects on bolt tension and gasket contact stress.

Notably, in an NPS 4 class 900 flange, untightening a single bolt resulted in over a 30% increase in tension in adjacent bolts. This significant rise suggests that preloading bolts to a certain value below their yield stress is advisable to prevent yielding during untightening depending on the bolted joint size and class. Additionally, the gasket experienced up to a 50% local stress reduction upon untightening a bolt, a factor that could potentially lead to leakage. Future research should aim to evaluate the drop in other bolted joints and correlate the stress drop with leakage occurrences.

The criss-cross untightening pattern exhibited no increase in gasket contact stress, making it particularly suitable when gasket reuse is anticipated. This pattern is also preferable if multiple bolts are to be untightened simultaneously.

The results further revealed that gasket stiffness had a relatively minor influence on bolt tension variations during untightening. However, metallic gaskets exhibited greater stability compared to PTFE and graphite types, suggesting better performance in maintaining preload and contact conditions throughout disassembly.

Additionally, the initial bolt preload level was shown to have only a modest effect on elastic interactions. When one-third of the original preload was applied, the corresponding increases in adjacent bolt tension were approximately 17%, 28%, and 30% for experimental, analytical, and FEM simulations, respectively.

These preliminary findings offer valuable insights into the elastic behavior of bolts during untightening. Such understanding enhances safety measures and bolsters the reliability of systems during hot bolting procedures and general untightening operations. The observations from this study can be extended to applications involving heat exchangers, joints of varying sizes, and other pressure vessel components.

CONCLUSION

The primary objective of this research was to investigate the elastic interaction of bolted flange joints during untightening, with an emphasis on hot bolting operations. This topic is of critical importance for maintenance procedures in pressurized systems, where complete depressurization is often infeasible. The study aimed to improve our understanding of preload redistribution, flange deformation, and gasket stress behavior under untightening scenarios, thereby contributing to the development of safer and more efficient maintenance practices.

A significant focus was placed on quantifying the mechanical response of the joint when a bolt is loosened. The redistribution of preload to neighboring bolts was observed experimentally and numerically, with adjacent bolt tension increasing by approximately 30% in the experimental setup and by 37% and 50% in analytical and FEM analyses, respectively. These findings highlight the importance of maintaining sufficient preload margins below yield limits to prevent bolt overloading during disassembly.

The study also found that untightening one bolt caused locally up to a 50% drop in gasket contact stress posing a potential risk for leakage. This underscores the need for careful planning in hot bolting operations, especially when using softer gasket materials. Furthermore, the criss-cross untightening sequence proved effective in maintaining gasket contact integrity, with negligible increase in contact stress, making it preferable for cases involving gasket reuse or simultaneous loosening of multiple bolts.

Gasket stiffness was shown to have a modest influence on bolt load variation, though metallic gaskets demonstrated superior stability compared to PTFE and graphite alternatives. Additionally, reducing bolt preload to one-third of its original value still resulted in notable load increases in adjacent bolts by 17%, 28 and 30% in experimental, analytical, and FEM simulations confirming that elastic interaction persists even under low initial tension.

Beyond conventional untightening processes, this study explored the predictive behavior of bolts in advanced maintenance scenarios, including the use of velocity washers and half bolting techniques. These strategies, while offering significant efficiency gains, require detailed understanding of bolt interaction dynamics to ensure system integrity. The insights gathered in this work serve as a foundation for engineering guidelines to support these practices.

In summary, this thesis contributes validated experimental, analytical, and numerical data to the field of bolted joint disassembly, emphasizing elastic interactions, preload sensitivity, and the role of gasket behavior. These research studies not only provide a methodology and tools to improve hot bolting safety and reliability but also offer a pathway for refining disassembly strategies in heat exchangers, pipeline connections, and pressure vessel applications. Future studies should extend the developed models to broader flange sizes, elevated temperature and pressure conditions, and more complex loading scenarios to further enhance predictive capability and operational safety during the process of unloading.

RECOMMENDATIONS

This study investigated the elastic interaction and preload redistribution among an NPS 4 class 900 raised face welding neck flange joints during the untightening sequence. While the findings offer valuable insights into joint behavior under controlled conditions, several opportunities exist to expand and deepen this research.

First, future studies should consider replicating the current experimental and numerical framework using flange joints of different materials, nominal sizes and pressure ratings. The mechanical behavior of larger or smaller flanges may exhibit different interaction patterns due to changes in geometry, number of bolts, and flange material. Expanding the scope to include a variety of flange materials and sizes would enhance the generalizability and practicality of the results.

Second, one of the principal objectives of this research was to simulate and understand elastic interactions under conditions representative of service environments. To more accurately reflect real-world operating conditions, future investigations should incorporate elevated temperatures and internal pressures into both experimental testing and finite element modeling. Such conditions are critical in high-stakes industries like oil and gas, chemical processing, and power generation. Studying elastic interactions under combined thermal and pressure loads would significantly improve the predictive accuracy of maintenance planning and risk assessment models.

Finally, to support the development of comprehensive safety protocols for hot bolting and related maintenance operations, future work should focus on calculating safety margins and applying structured reliability methodologies. Specifically, the use of Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) could allow for systematic identification of failure modes, quantification of associated risks, and development of mitigation strategies. Integrating such tools with mechanical modeling and empirical data would contribute to a robust safety framework for bolted joint maintenance under operating conditions.

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