

Failure Analysis and Optimization of Epoxy Insulating Sleeves in Preloaded Flange Joints

Pruthviraj Ambadas Hatkar¹

¹B. E. Mechanical Engineering

from SNJB's Late Sau. K. B. Jain College of Engineering, Chandwad (Maharashtra)

Abstract - Electrically insulated flange joints are essential in cathodically protected pipeline systems, as they interrupt electrical continuity between metallic components and reduce the risk of galvanic corrosion. These joints typically utilize non-conductive elements such as insulating sleeves, washers, and gaskets made from epoxy-based composites. Despite being designed to sustain specified bolt preload levels, repeated cracking of epoxy insulating sleeves was observed during controlled torque-based assembly. These failures occurred even when recommended torque values and cross-pattern tightening sequences were carefully followed, indicating the presence of additional factors affecting the stress distribution within the assembly.

This study investigates the root cause of sleeve failure through a systematic approach involving geometric compatibility analysis, load transfer assessment, contact stress evaluation, and bending stress modelling. Special attention is given to the interaction between metallic washers and epoxy sleeves, particularly in situations where dimensional inconsistencies influence load distribution.

A numerical case study based on an M20 bolted joint is presented to quantify stress intensification resulting from washer outer diameter variation, inner diameter misalignment, and inadequate sleeve support. Analytical results reveal that deviations from concentric loading significantly increase localized contact pressure and bending stresses. Given the brittle behavior and limited tensile capacity of epoxy materials, such stress concentrations can readily initiate cracking.

The results confirm that the observed failures were primarily caused by geometric misalignment and uneven stress distribution rather than excessive preload. Design modifications ensuring proper alignment and uniform load transfer effectively eliminated sleeve damage without altering torque requirements. The study emphasizes the importance of dimensional precision and symmetric load distribution in bolted assemblies incorporating brittle insulating components.

Key Words: Electrically insulated flange joints, Epoxy insulating sleeves, Bolt preload, Failure analysis, Contact stress, Bending stress

1. INTRODUCTION

• 1.1 Background

Pipeline systems in the oil and gas sector are frequently exposed to harsh environmental conditions such as moisture, chemically active soils, and stray electrical currents. These factors significantly accelerate corrosion, leading to material degradation, reduced structural integrity, and increased risk of failure. If left unaddressed, corrosion can compromise safety, cause environmental damage, and result in substantial economic losses.

To mitigate these effects, **cathodic protection (CP)** systems are widely adopted. These systems operate by modifying the electrochemical behavior of pipeline surfaces, thereby suppressing corrosion reactions. As a result, cathodic protection plays a crucial role in enhancing durability, maintaining structural reliability, and extending the operational lifespan of pipeline infrastructure.

• 1.2 Role of Insulated Flange Joints

Electrically insulated flange joints are critical components within cathodic protection systems. Their primary function is to ensure electrical separation between different sections of a pipeline, which is essential for maintaining the effectiveness of corrosion control measures.

These joints serve several important purposes:

- Electrically isolating pipeline segments to support controlled CP operation
- Minimizing the impact of stray electrical currents
- Safeguarding connected equipment from electrochemical damage

In addition to electrical isolation, insulated flange joints must satisfy multiple engineering requirements, including:

- Adequate mechanical strength to withstand bolt preload and operational forces
- Reliable sealing performance to prevent leakage under pressure
- Long-term stability of insulating properties under service conditions

• **1.3 Components and Load Interaction**

An electrically insulated flange joint consists of several interconnected components, including flanges, bolts, insulating gaskets, insulating sleeves, insulating washers, and metallic washers. The overall performance of the joint depends on how these components interact under mechanical loading.

The **insulating sleeve** is a key element within this assembly, contributing to both electrical isolation and mechanical behavior. Its primary functions include:

- Preventing electrical contact between the bolt shank and the flange bore
- Enabling the transmission of compressive forces through adjacent components within the bolted joint assembly

During installation and service, the sleeve is subjected to a combination of compressive, tensile, and bending stresses. Since it is typically made from epoxy-based composite material, which exhibits brittle characteristics and relatively low tensile strength, it is particularly vulnerable to stress concentrations and uneven loading. Consequently, the performance of the sleeve is highly dependent on proper load distribution and geometric alignment within the joint.

• **1.4 Problem Statement**

During the assembly of insulated flange joints in an oil and gas pipeline application, repeated failures of epoxy insulating sleeves were observed. These failures occurred despite following recommended assembly procedures, including controlled torque application and cross-pattern tightening to achieve uniform preload.

The following key observations were noted:

- Cracking of insulating sleeves during bolt tightening
- Failure occurring before reaching the specified design torque
- Consistent recurrence of failure across multiple assemblies

These patterns suggest that the issue is not due to random defects or improper procedures, but rather indicates a systematic problem related to joint design, geometry, or load transfer behavior.

• **1.5 Research Gap**

Existing research on bolted flange joints has primarily focused on aspects such as gasket sealing efficiency, preload distribution, and stress behavior in metallic components. While these studies provide valuable insights into joint performance, they often overlook the mechanical response of non-metallic insulating elements. Specifically:

- The internal stress distribution within insulating sleeves has not been extensively studied
- The impact of dimensional inconsistencies between washers and sleeves remains underexplored
- The influence of load path deviations on brittle insulating materials is not well understood

This highlights a significant gap in current research, particularly in applications where insulating components play a critical functional role.

• **1.6 Objective of the Study**

The main objective of this study is to investigate the failure mechanism of epoxy insulating sleeves in electrically insulated flange joints and to develop a clear understanding of the factors contributing to their premature cracking.

The specific objectives are:

- To determine the root cause of sleeve failure during torque-controlled assembly
- To develop an analytical explanation based on load transfer and stress distribution
- To assess the effect of geometric compatibility on joint performance
- To propose and validate design improvements that ensure uniform load distribution and prevent failure

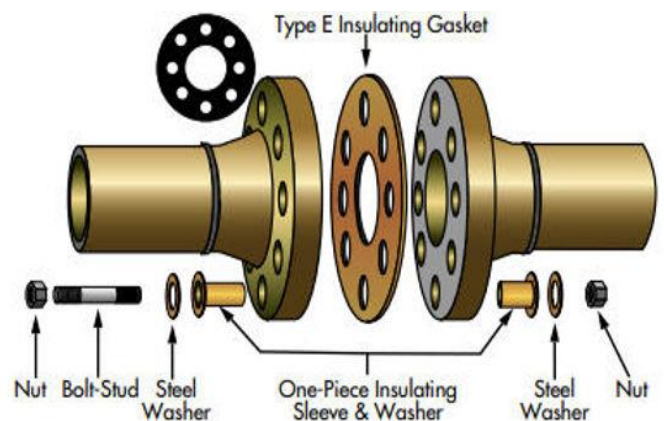


Fig -1: Assembly of Two Insulated Flanges using Sleeve

2. Literature Review:

Bolted flange joints have been extensively researched due to their critical function in maintaining both structural integrity and leak-tight performance in pressure-containing systems. The behaviour of these joints is primarily governed by the relationship between applied torque, resulting bolt preload, and the distribution of contact stresses across the interface. Early contributions by J. H. Bickford laid the foundation for understanding bolted

joint mechanics, highlighting that achieving adequate preload and maintaining its uniform distribution are essential for reliable joint performance.

Further studies have explored the influence of geometric parameters on the mechanical response of flange joints. Research by M. Koch, S. Böhm, and F. Klein demonstrated that even small deviations in geometry can significantly alter stress distribution patterns and increase fatigue loading in bolts. These findings emphasize that bolted assemblies are highly sensitive to dimensional variations, making precise component compatibility crucial for optimal performance.

Finite Element Analysis (FEA) has been widely adopted to study stress behaviour in bolted flange joints under various loading conditions. Investigations by H. Fukuoka and T. Nomura showed that flange rotation and non-uniform contact conditions can generate uneven stress fields within the joint. Similarly, M. Daidie and J. Bouchard reported that assembly-related factors, such as misalignment and inconsistent tightening, can lead to unequal preload distribution among bolts. Such irregularities often result in localized stress concentrations, which may initiate damage or failure.

The sealing behaviour of flange joints and the performance of gasket materials have also received considerable attention. Studies by K. Sawa and T. Hirose, along with S. Abid and M. Khan, highlighted that maintaining consistent contact pressure across the flange interface is essential for ensuring both sealing effectiveness and structural stability. Variations in contact conditions or stiffness can create localized regions of high stress, increasing the likelihood of leakage or component failure.

Material characteristics play a vital role in determining the failure response of joint components, particularly when non-metallic materials are involved. The principles of contact mechanics, as described by K. L. Johnson, explain how stress levels can increase significantly when loads are transmitted through reduced or uneven contact areas. This phenomenon is especially critical for brittle materials such as epoxy composites, which exhibit limited tensile strength and are highly susceptible to cracking under bending or tensile stresses.

Research on composite and non-metallic bolted joints further reinforces the importance of uniform load transfer. Work by C. McCarthy, M. McCarthy, P. Camanho, and C. Davila showed that non-uniform load distribution in composite joints leads to stress concentrations, particularly near edges and discontinuities, ultimately resulting in premature failure. These observations are directly relevant to insulating sleeves, which share similar mechanical characteristics due to their composite nature.

Additional investigations have examined the effects of design parameters such as gasket thickness, stiffness variation, and thermal loading. Studies by R. C. Singh and P. K. Jain demonstrated that geometric changes can significantly influence internal stress distribution, while Y. Zhang and X. Liu highlighted that temperature variations can alter load paths and redistribute stresses within the joint. Together, these findings indicate that both design features and operating conditions must be carefully considered to ensure reliable joint performance.

Despite the substantial body of research on bolted flange assemblies, most existing work concentrates on metallic components, gasket behaviour, and overall sealing performance. In contrast, the mechanical behaviour of insulating elements, such as epoxy sleeves, has received comparatively limited attention, particularly under assembly-induced loading conditions. Furthermore, the effect of dimensional incompatibility between washers and sleeves on stress distribution has not been thoroughly investigated.

Accordingly, the present study addresses this gap by examining how washer-sleeve geometric mismatch influences load transfer mechanisms and stress concentration within the joint. Through a combination of analytical modelling and a practical case study, this work aims to provide a clearer understanding of failure mechanisms in insulated flange joints and to propose design improvements that enhance their reliability and performance.

3. Problem Definition:

A detailed case study was carried out on an electrically insulated flange joint used in an oil and gas pipeline system, where repeated failures of epoxy insulating sleeves were observed during assembly. The purpose of this investigation was to systematically document the joint configuration, assembly conditions, and failure characteristics in order to determine the root cause of the observed damage.

The flange assembly consisted of standard pipeline flanges connected using M20 bolts. A complete insulation kit was installed within the joint, comprising an epoxy-based insulating sleeve, insulating washers, metallic washers, and an insulating gasket. Stainless steel bolts were used, and tightening was performed using a calibrated torque wrench. A cross-pattern tightening sequence was followed to ensure uniform preload distribution, in accordance with standard assembly practices.

The specified torque range for the M20 bolts was 250–300 Nm. However, despite strict compliance with the recommended torque values and tightening procedure, consistent cracking of the epoxy insulating sleeves was observed during assembly. Notably, the failure occurred

before reaching the upper limit of the specified torque, indicating that excessive tightening was not the primary cause.

A detailed examination of the failed sleeves revealed that cracks were predominantly located near the neck region. The fracture surfaces exhibited characteristics typical of brittle failure, suggesting that the epoxy material experienced stress levels beyond its tensile or flexural capacity during installation.

To further investigate the issue, dimensional measurements of the assembly components were conducted. The analysis revealed a mismatch between the outer diameter of the metallic washer and that of the insulating sleeve, with the washer having a smaller outer diameter. This discrepancy resulted in incomplete contact between the washer and the sleeve, causing uneven load transfer and localized stress concentration.

The observations from this case study demonstrate that the failure was consistent and repeatable under the given assembly conditions. Based on these findings, it can be inferred that the root cause is associated with geometric incompatibility and non-uniform load distribution within the joint, rather than material defects or improper assembly procedures.

4. Methodology

The present study adopts a systematic and multi-stage methodology to investigate the failure of epoxy insulating sleeves in electrically insulated flange joints. The approach combines field observations, dimensional verification, analytical modelling, and design validation to develop a comprehensive understanding of the failure mechanism and its underlying causes.

- **4.1 Failure Inspection and Documentation**

The investigation began with a detailed visual examination of failed insulating sleeves collected from the assembly site. The objective was to determine the nature, location, and pattern of failure, and to identify any recurring characteristics.

The following steps were undertaken:

- Visual inspection of cracked sleeves
- Identification of crack initiation and propagation regions
- Documentation of fracture characteristics
- Photographic recording for further analysis

The inspection revealed that cracks consistently originated near the neck region of the sleeve. The uniformity in failure location indicated the presence of localized stress concentration rather than random material defects.

- **4.2 Dimensional Measurement and Verification**

To assess possible geometric incompatibilities, all critical components of the insulation assembly were measured using precision instruments such as vernier callipers and micrometres.

The parameters evaluated included:

- Outer diameter (OD) of the epoxy insulating sleeve
- Inner diameter (ID) of the sleeve
- Inner and outer diameters of the metallic washer
- Thickness of washers
- Diameter of the flange bolt hole

The measurements revealed a significant mismatch between the outer diameter of the metallic washer and the insulating sleeve. Specifically, the washer outer diameter was smaller than that of the sleeve, resulting in incomplete contact and an uneven load transfer interface.

- **4.3 Assembly Condition Evaluation**

The assembly procedure was reviewed in detail to verify whether the observed failures could be attributed to installation errors or procedural inconsistencies.

The following conditions were confirmed:

- Use of a calibrated torque wrench
- Torque applied within the specified range of 250–300 Nm
- Adoption of a cross (star) tightening sequence
- Proper lubrication of bolt threads

Since all assembly practices adhered to standard guidelines, the possibility of human error or improper tightening was effectively ruled out.

- **4.4 Load Path Analysis**

A qualitative load path analysis was conducted to understand how bolt preload was transmitted through the joint components under both ideal and actual conditions.

Ideal Condition:

- Load is transferred uniformly from the bolt head → metallic washer → insulating washer → flange surface

Actual Condition:

- Due to the smaller outer diameter of the metallic washer, a portion of the load was transferred directly to the edge of the insulating sleeve

This deviation in load transfer resulted in:

- Reduction in effective contact area
- Development of localized compressive stresses
- Induction of bending stresses within the sleeve, particularly near the neck region

- **4.5 Analytical Stress Modelling**

To quantify the stresses acting on the insulating sleeve, an analytical approach was adopted.

Step 1: Bolt Preload Estimation

The preload generated in the bolt was estimated using standard torque-preload relationships, considering frictional effects and tightening conditions.

Step 2: Contact Stress Evaluation

Contact stresses were calculated based on the reduced load-bearing area caused by the washer-sleeve mismatch. This reduction significantly increased localized pressure.

Step 3: Bending Stress Estimation

Due to eccentric load transfer, bending stresses were evaluated at the sleeve neck, where failure was consistently observed.

Step 4: Combined Stress Assessment

The combined effect of compressive and bending stresses was assessed and compared with the allowable strength of the epoxy material.

The analysis demonstrated that the resulting stress levels exceeded the material's permissible limits, leading to crack initiation and propagation.

- **4.6 Root Cause Identification**

Based on the combined findings from inspection, measurement, and analytical evaluation, the root cause of failure was identified as:

- Dimensional incompatibility between the metallic washer and insulating sleeve
- Resulting in non-uniform load transfer and localized stress concentration

This confirmed that the failure mechanism was design-related rather than material- or process-induced.

- **4.7 Design Modification and Validation**

To validate the identified root cause, a series of design modifications were implemented and tested under the same assembly conditions.

Modification 1: Increase in Washer Outer Diameter

- **Change:** Use of a metallic washer with an outer diameter equal to or greater than the sleeve outer diameter
- **Issue Addressed:** Reduced contact area and localized compressive stress
- **Outcome:**
 - Uniform load distribution achieved
 - No cracking observed

Modification 2: Alignment of Washer Inner Diameter

- **Change:** Use of a washer with an inner diameter closely matching the sleeve inner diameter
- **Issue Addressed:** Misalignment between washer and sleeve leading to eccentric loading
- **Outcome:**
 - Improved concentric load transfer
 - Elimination of uneven stress distribution
 - No failure observed

Modification 3: Geometric Compatibility with Flange Hole

- **Change:** Ensuring proper matching between the flange hole radius and the sleeve neck radius
- **Issue Addressed:** Excessive clearance and improper seating of the sleeve within the flange
- **Outcome:**
 - Improved fit and alignment
 - Reduction in unintended movement and stress concentration
 - No cracking observed

The successful elimination of failure after implementing these modifications confirms that the issue was primarily due to geometric incompatibility and improper load distribution. The study demonstrates that relatively simple design corrections can significantly enhance the reliability of insulated flange joint assemblies.

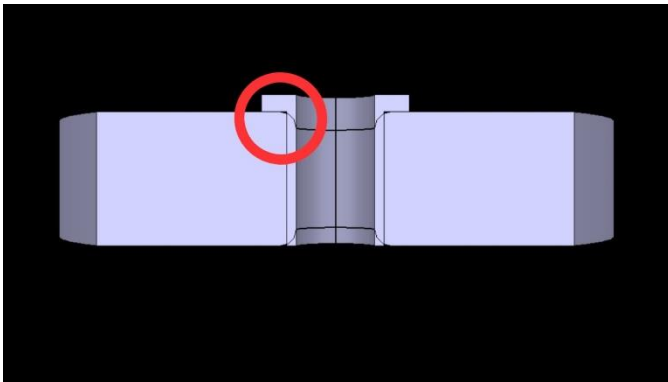


Fig -2: Assembly Before Modification 3

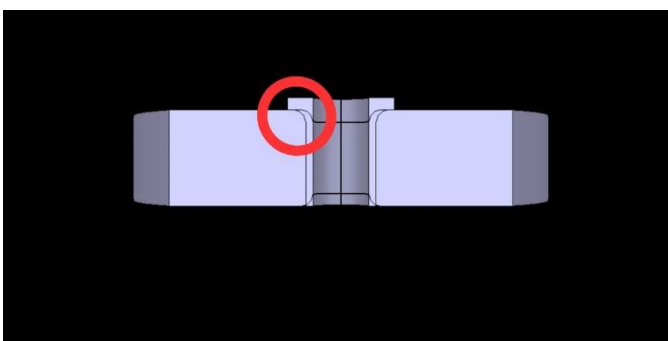


Fig -3: Assembly After Modification 3

5. Validation:

Following the identification of the root cause and implementation of the corrective design—specifically, increasing the outer diameter of the metallic washer to match or exceed that of the insulating sleeve—a series of validation trials were conducted. The purpose of these trials was to evaluate the effectiveness of the proposed modification under practical assembly and service conditions.

• 5.1 Reassembly and Torque Testing

The flange joint was reassembled using the modified washer configuration while keeping all other parameters unchanged. Tightening was performed using a calibrated torque wrench in a controlled, multi-stage cross-pattern sequence to ensure uniform preload distribution.

- The assembly was successfully tightened up to **400 Nm**, exceeding the original specified torque range of 250–300 Nm.
- No visible cracking or damage to the epoxy insulating sleeves was observed during or after tightening.
- The sleeves maintained structural integrity throughout the process, demonstrating improved resistance to assembly-induced stresses.

These results indicate that the modified configuration can safely withstand higher preload levels without failure.

• 5.2 Hydrostatic Pressure Testing

To assess the performance of the modified joint under operating conditions, a hydrostatic pressure test was conducted after assembly.

- The joint was pressurized as per standard pipeline testing requirements.
- No leakage, pressure drop, or instability was observed during the test.
- The insulating components remained intact, confirming that the design modification did not compromise sealing performance.

This verifies that the joint maintains both mechanical integrity and leak-tightness under pressure.

• 5.3 Contact and Seating Verification

A detailed post-assembly inspection was carried out to evaluate load distribution and seating conditions of the joint components.

- Uniform contact was observed between the metallic washer, insulating washer, and flange surface.
- No evidence of localized indentation, edge loading, or uneven contact was found.
- The epoxy sleeve was properly supported along its circumference, indicating effective and balanced load transfer.

These findings confirm that the revised design eliminates stress concentration caused by improper contact.

• 5.4 Repeatability and Reliability Assessment

To ensure the robustness of the proposed solution, multiple assembly trials were performed under identical conditions.

- No cracking or damage to the insulating sleeves was observed across repeated trials.
- The joint exhibited stable and consistent behaviour in all cases.
- The performance remained predictable and reliable under repeated assembly conditions.

This demonstrates the repeatability and practical applicability of the design improvement.

• 5.5 Validation Summary

The validation results clearly demonstrate that correcting the washer geometry effectively eliminates the stress concentration responsible for sleeve failure. The improved design ensures uniform load distribution, enhances assembly reliability, and maintains both mechanical strength and sealing performance under operational conditions.

Overall, the study highlights the importance of geometric compatibility in bolted assemblies incorporating brittle insulating materials and confirms that appropriate design modifications can significantly improve system reliability.

7. Results and Discussions:

The results obtained from this investigation provide a clear and consistent understanding of the failure mechanism associated with epoxy insulating sleeves in electrically insulated flange joints. The analysis confirms that the observed failures were not caused by material deficiencies or improper assembly practices, but were primarily driven by an inherent issue in load transfer arising from geometric incompatibility within the joint components.

Dimensional evaluation revealed that the outer diameter of the metallic washer was smaller than that of the insulating sleeve. This mismatch significantly reduced the effective contact area available for load transfer during bolt tightening. From the standpoint of contact mechanics, a reduction in contact area leads to a corresponding increase in localized stress, which was further substantiated through analytical calculations performed in this study.

The load path assessment provided additional insight into the failure mechanism. Under ideal conditions, bolt preload is expected to be transferred uniformly through the metallic washer and insulating washer to the flange surface. However, due to the dimensional mismatch, part of the applied load was diverted toward the outer edge of the epoxy sleeve. This resulted in the development of localized compressive stresses at the contact interface, along with bending stresses induced at the sleeve neck region due to eccentric loading conditions.

Given the brittle nature of epoxy materials and their relatively low tolerance to tensile and bending stresses, this combined stress state exceeded the material's allowable limits. Consequently, crack initiation occurred at the most critical region, which aligns with the failure patterns observed during inspection.

The outcomes of the validation trials strongly support this interpretation. After modifying the washer geometry to ensure full and uniform contact with the sleeve, the load transfer became more evenly distributed. This eliminated stress concentration zones and prevented the development of excessive localized stresses. The absence of cracking, even under higher-than-design torque levels, clearly demonstrates that the root cause of failure was related to design and geometry rather than operational conditions.

Overall, the findings of this study emphasize the critical importance of geometric compatibility and proper load path design in bolted assemblies, particularly when brittle, non-metallic components are involved. The results also highlight that even relatively small dimensional inconsistencies can significantly alter stress distribution and lead to premature failure if not properly addressed.

8. Conclusion:

This study presented a comprehensive failure analysis of epoxy insulating sleeves used in electrically insulated flange joints under torque-controlled assembly conditions in an oil and gas pipeline application. The investigation established that the recurring sleeve failures were not attributed to material defects or improper assembly procedures, but were primarily caused by geometric incompatibility within the insulation kit components.

Detailed analysis revealed that the mismatch between the outer diameter of the metallic washer and the insulating sleeve resulted in an uneven load transfer mechanism. This geometric inconsistency reduced the effective contact area and led to significant stress concentration during bolt tightening. Analytical modelling further showed that, in addition to elevated contact stresses, eccentric load transfer introduced bending stresses at the sleeve neck region. Due to the brittle nature and limited tensile capacity of epoxy materials, the combined stress state exceeded allowable limits, leading to crack initiation and propagation.

The proposed design modification—ensuring that the metallic washer outer diameter is equal to or greater than that of the insulating sleeve—successfully restored uniform load distribution across the joint interface. Validation trials confirmed that the modified configuration eliminated sleeve cracking, even under torque levels exceeding the original design range. This clearly demonstrates that the failure was design-induced and can be effectively mitigated through appropriate geometric correction.

Overall, the study highlights the critical importance of dimensional compatibility and load path alignment in bolted assemblies incorporating brittle, non-metallic components. It emphasizes that even minor geometric deviations can significantly influence stress distribution and lead to premature failure. The findings provide practical design recommendations for insulation kits and contribute to improving the reliability, safety, and long-term performance of electrically insulated flange joints in pipeline systems.

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