

DESIGN VALIDATION AND FATIGUE PERFORMANCE ASSESSMENT OF MECHANICAL FASTENER ASSEMBLIES USED IN POWER TRANSMISSION

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Abstract - Mechanical fastener assemblies play a critical role in ensuring the structural integrity and reliability of power transmission systems subjected to cyclic and dynamic loading conditions. However, long-term exposure to fluctuating loads such as wind-induced vibrations and operational stresses often leads to bolt loosening, fatigue damage, and eventual joint failure. This study presents a comprehensive approach for the design validation and fatigue performance assessment of mechanical fastener assemblies used in power transmission applications. A combined methodology involving finite element analysis (FEA) and experimental testing is adopted to evaluate the structural response and durability of bolted joints under cyclic loading. The numerical model incorporates detailed contact interactions, preload conditions, and material nonlinearity to simulate realistic operating scenarios. Experimental investigations are conducted using a fatigue testing setup with varying configurations, including the number of bolts, presence of washers, and preload levels. The load-displacement behavior, stress distribution, and energy dissipation characteristics are analyzed to assess fatigue performance. The results demonstrate strong agreement between simulation and experimental findings, validating the proposed modeling approach. Furthermore, the study identifies key parameters influencing fatigue life and joint stability, providing practical insights for improving fastener design and reliability in power transmission structures.

Key Words: Mechanical fasteners; Fatigue performance; Finite element analysis; Bolted joints; Power transmission; Design validation

1. INTRODUCTION

1.1 Background

1.1.1 Importance of Mechanical Fasteners in Power Transmission Structures

Mechanical fasteners, particularly bolted joints, are fundamental components in power transmission structures such as towers, frames, and supporting assemblies. These fasteners ensure load transfer, structural continuity, and ease of assembly and maintenance. Due to their widespread use, the reliability of such systems is highly dependent on the integrity of fastener assemblies. In transmission structures, bolts connect angle sections and plates, enabling

the structure to resist complex loading conditions while maintaining flexibility and modularity. The performance of these connections directly influences the global stability and service life of the structure (Jiang et al., 2011).

1.1.2 Exposure to Cyclic Loads (Wind, Vibration, Thermal Effects)

In real operating environments, power transmission structures are continuously subjected to cyclic and dynamic loads, including wind-induced vibrations, mechanical oscillations, and thermal expansion-contraction effects. These fluctuating loads generate alternating stresses within fastener assemblies, causing repeated micro-slip at contact interfaces. Over time, such cyclic actions lead to degradation of preload and changes in contact conditions, significantly affecting joint behavior. Wind-induced pulsating loads, in particular, are identified as a dominant factor contributing to alternating stress cycles in transmission towers, thereby accelerating damage accumulation (Guo et al., 2021).

1.1.3 Risk of Loosening, Fatigue Failure, and System Reliability Issues

The repeated application of cyclic loads can result in progressive bolt loosening, reduction in clamping force, and eventual fatigue failure. Loosening alters load distribution and increases stress concentration in critical regions, making the joint more susceptible to crack initiation and propagation. Fatigue failure of fasteners is particularly critical because it often occurs without significant prior deformation, leading to sudden and catastrophic structural failure. Consequently, ensuring the fatigue resistance and stability of fastener assemblies is essential for maintaining the long-term reliability and safety of power transmission systems (Kong et al., 2022).

1.2 Literature Review

1.2.1 Studies on Bolted Joint Behavior Under Static Loading

A significant portion of existing research has focused on the static behavior of bolted joints, including strength, stiffness, and load transfer mechanisms. These studies have contributed to the understanding of joint slip, bearing capacity, and semi-rigid behavior under monotonic loading

conditions. Analytical and experimental approaches have been widely used to evaluate static performance, providing design guidelines for structural applications. However, such studies often neglect the effects of repeated loading and time-dependent degradation.

1.2.2 Research on Cyclic Loading and Energy Dissipation

More recent investigations have explored the response of bolted joints under cyclic loading, particularly focusing on load–displacement behavior and energy dissipation characteristics. Under cyclic loads, joints exhibit hysteresis loops, where the enclosed area represents the energy dissipated during each loading cycle. This energy dissipation is closely related to frictional slip and material deformation at contact interfaces. Experimental studies combined with finite element modeling have shown that parameters such as bolt preload, number of bolts, and use of washers significantly influence the hysteretic response and energy absorption capacity of joints (Zhang et al., 2025).

1.2.3 Existing Fatigue Assessment Approaches

Fatigue performance of fastener assemblies is commonly assessed using stress–life (S–N) methods, strain-based approaches, and fracture mechanics concepts. These methods aim to predict fatigue life based on stress amplitudes, material properties, and loading conditions. In addition, energy-based approaches have gained attention due to their ability to capture the effects of cyclic plasticity and frictional dissipation. Despite these advancements, fatigue prediction in bolted joints remains complex due to nonlinear contact behavior and varying preload conditions.

1.2.4 Limitations in Current Design Validation Methods

Current design validation practices often rely on simplified assumptions and do not fully account for the combined effects of cyclic loading, contact nonlinearity, and preload loss. While finite element analysis (FEA) is widely used, many models lack experimental validation, limiting their reliability. Furthermore, most studies emphasize static properties, whereas dynamic and fatigue behaviors are relatively underexplored. The attached study clearly indicates that although static characteristics of bolted joints are well documented, their performance under dynamic cyclic loading conditions requires further investigation (Zhang et al., 2025).

1.3 Research Gap

Despite considerable progress in understanding bolted joint mechanics, several critical gaps remain. There is a lack of integrated frameworks that combine design validation with accurate fatigue life prediction for fastener assemblies. Additionally, limited studies have effectively coupled finite

element simulations with experimental fatigue testing to validate numerical models under realistic loading conditions. Another significant gap is the insufficient understanding of the influence of key assembly parameters—such as preload, number of nuts, washers, and bolt configuration—on fatigue performance. Addressing these gaps is essential for developing reliable and optimized fastener designs.

1.4 Objectives

The primary objective of this study is to develop a comprehensive methodology for the design validation and fatigue performance assessment of mechanical fastener assemblies used in power transmission structures. Specifically, the study aims to validate the structural design of fastener assemblies using finite element analysis, evaluate their fatigue performance under cyclic loading conditions, and investigate the influence of critical assembly parameters on joint behavior. Furthermore, the study seeks to establish a correlation between numerical simulations and experimental results to enhance the accuracy and reliability of predictive models.

2. MATERIALS AND METHODS

2.1 Fastener Assembly Description

2.1.1 Geometry and Configuration

The fastener assembly considered in this study consists of standard mechanical components including bolts, nuts, washers, and connected steel members typically used in power transmission structures. The geometry is modeled based on practical configurations found in transmission towers, where angle sections are connected using high-strength bolts. The bolt–nut assembly ensures clamping force, while washers are incorporated to improve load distribution and reduce localized stress concentration. The configuration also accounts for clearance between the bolt shank and hole, which plays a significant role in slip behavior under loading. The assembly is designed to replicate real-world conditions, including alignment constraints and load transfer paths, ensuring that the mechanical interaction between components is realistically captured. Such configurations are widely used in lattice-type transmission structures where multiple bolted joints contribute to overall structural stability.

2.1.2 Material Properties

The material properties of the fastener components and connected members are defined based on standard structural steel and high-strength bolt specifications. Key parameters include elastic modulus, yield strength, Poisson's ratio, density, and fatigue characteristics. To accurately simulate the behavior under cyclic loading, a bilinear elastoplastic material model is adopted, which captures both the elastic response and strain hardening behavior beyond

yield. This approach allows for realistic representation of material nonlinearity during repeated loading cycles. The properties used in the study are summarized in Table 1.

Table 1 Material Properties of Fastener Assembly Components

Component	Elastic Modulus (GPa)	Yield Strength (MPa)	Poisson's Ratio
Structural Steel	200–210	300–350	0.3
High-strength Bolt	200–210	450–500	0.3
Washer	200–210	250–300	0.3

2.2 Finite Element Modeling

2.2.1 Model Development

A three-dimensional finite element model of the fastener assembly is developed using advanced simulation software (e.g., ANSYS or Abaqus). The model includes detailed geometric representation of bolts, nuts, washers, and connected plates. Special attention is given to the inclusion of thread geometry, as it significantly influences stress distribution and contact behavior. Solid elements are used to discretize the geometry, ensuring high accuracy in stress and deformation prediction. Mesh refinement is applied in critical regions such as the bolt-hole interface and thread engagement zones to capture stress concentration effects. The developed model aims to replicate real assembly conditions as closely as possible, providing a reliable basis for subsequent analysis.

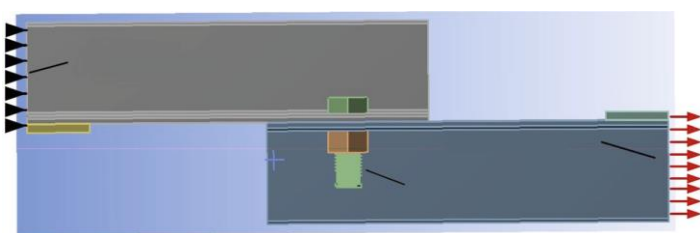


Figure 1 Finite element model of bolt joint

2.2.2 Contact and Boundary Conditions

Accurate representation of contact interactions is essential for simulating the behavior of fastener assemblies. Contact pairs are defined between bolt and hole surfaces, nut and plate interfaces, and between connected plates. Frictional contact is considered to model slip behavior and energy dissipation during cyclic loading. Bolt preload is introduced using appropriate simulation techniques such as pretension

elements or equivalent contact-based methods, which replicate the tightening torque applied during assembly. Boundary conditions are applied to constrain one end of the structure, while allowing controlled displacement or load application at the other end. This setup ensures that the model captures realistic load transfer and deformation characteristics under operating conditions.

2.2.3 Loading Conditions

The fastener assembly is subjected to cyclic or transverse loading to simulate real service conditions encountered in power transmission structures. A displacement-controlled cyclic loading approach is adopted, where the load is applied in repeated cycles with specified amplitude and frequency. The loading parameters are selected to ensure that the joint behavior covers key stages such as elastic deformation, slip, and potential plastic deformation. The amplitude of loading is chosen based on expected service conditions, while the frequency is varied to study its influence on fatigue performance. This approach enables the evaluation of load-displacement behavior, hysteresis characteristics, and energy dissipation capacity of the joint. The use of cyclic displacement loading combined with detailed contact modeling ensures a realistic simulation of joint response, consistent with established experimental and numerical methodologies in similar studies.

2.3 Experimental Methodology

2.3.1 Specimen Preparation

The experimental program involves the preparation of fastener assembly specimens that replicate practical configurations used in power transmission structures. Each specimen consists of structural steel members connected using high-strength bolts, nuts, and washers. To investigate the influence of assembly parameters on fatigue performance, different configurations are considered, including single-nut and double-nut arrangements, with and without washers, and varying numbers of bolts. All specimens are fabricated with consistent geometric dimensions and material properties to ensure comparability of results. During assembly, a controlled tightening torque is applied using a calibrated torque wrench to establish the desired preload condition. Care is taken to ensure proper alignment of components and uniform contact between surfaces. Multiple specimens are prepared to represent different combinations of parameters, enabling a systematic parametric study under cyclic loading conditions, consistent with prior experimental approaches.

Table 2 Specimen Configurations

Specimen ID	Number of Bolts	Nut Configuration	Washer Presence	Loading Frequency (Hz)
S1	1	Single nut	No	1
S2	1	Double nut	No	1
S3	1	Single nut	No	2
S4	1	Single nut	Yes	1
S5	2	Single nut	No	1
S6	2	Double nut	No	1

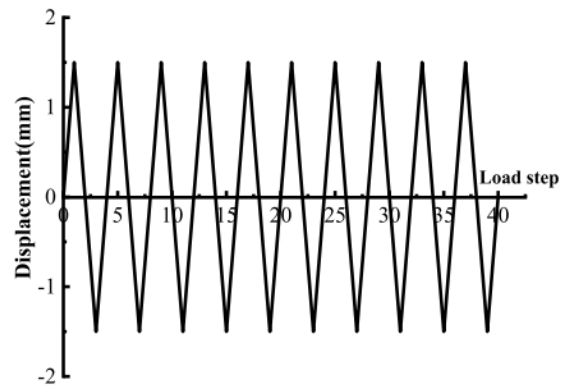


Figure 2: Cyclic Loading Profile

2.3.2 Test Setup

The fatigue performance of the prepared specimens is evaluated using a servo-controlled fatigue testing machine capable of applying cyclic loads with precise control over amplitude and frequency. The specimens are mounted securely between the grips of the testing machine to ensure axial alignment and eliminate unwanted bending effects. Instrumentation is employed to measure key response parameters, including applied load and corresponding displacement. Load cells are used to record the applied forces, while displacement sensors (such as LVDTs) capture the deformation of the joint during loading cycles. Data acquisition systems are integrated with the testing setup to continuously record the load-displacement response throughout the experiment. This setup allows for accurate monitoring of joint behavior, including slip, stiffness degradation, and energy dissipation under cyclic loading.

2.3.3 Testing Procedure

The testing procedure involves subjecting each specimen to controlled cyclic loading based on a predefined protocol. A displacement-controlled loading scheme is adopted, where cyclic displacement is applied with a specified amplitude representative of service conditions. Each test is conducted for a fixed number of cycles, typically ranging from tens to several hundred cycles, depending on the study requirements. The loading frequency is varied for selected specimens to examine its effect on fatigue behavior. During testing, load-displacement data are recorded for each cycle to analyze hysteresis behavior and energy dissipation characteristics. Observations are also made regarding bolt loosening, reduction in preload, and visible damage. This systematic procedure enables a comprehensive evaluation of fatigue performance across different fastener configurations, as demonstrated in similar experimental studies involving cyclic loading of bolted joints.

2.4 Fatigue Assessment Approach

2.4.1 Stress-Life (S-N) Method

The stress-life (S-N) approach is employed to estimate the fatigue life of fastener assemblies under cyclic loading. This method relates the applied stress amplitude to the number of cycles to failure, providing a practical means of predicting fatigue performance. Stress values obtained from finite element analysis or experimental measurements are used in conjunction with material S-N curves to estimate fatigue life. The approach is particularly suitable for high-cycle fatigue conditions where stresses remain within the elastic or near-elastic range. By comparing stress levels across different configurations, the relative fatigue resistance of each fastener assembly can be evaluated.

2.4.2 Energy-Based Approach

In addition to the S-N method, an energy-based approach is used to assess fatigue performance by analyzing the hysteresis behavior of the joint. Under cyclic loading, the load-displacement response forms hysteresis loops, where the enclosed area represents the energy dissipated during each cycle. This energy dissipation is associated with frictional slip, material deformation, and microstructural damage within the joint. A reduction in hysteresis loop area over successive cycles indicates degradation in energy dissipation capacity, often due to bolt loosening or stiffness loss. Therefore, energy dissipation serves as a reliable indicator of fatigue damage and structural degradation, as demonstrated in prior studies on bolted joints.

2.4.3 Failure Criteria

The failure of fastener assemblies under cyclic loading is evaluated based on multiple criteria to capture different modes of degradation. Crack initiation is considered as the onset of fatigue damage, typically occurring at stress concentration regions such as thread roots or contact interfaces. Bolt loosening is another critical failure mode, characterized by a reduction in preload and increased joint slip, which significantly affects load transfer and stiffness.

Final failure is identified by fracture of the bolt or connected members, often resulting from progressive crack growth under repeated loading. By combining these criteria, a comprehensive assessment of fatigue performance is achieved, enabling a better understanding of the mechanisms governing failure in mechanical fastener assemblies.

3. RESULTS

3.1 Finite Element Results

3.1.1 Stress Distribution

The finite element analysis (FEA) results indicate that stress concentrations are primarily located at the bolt–thread interface, bolt shank near the shear plane, and the contact edges of the connected plates. The maximum von Mises stress is observed at the first engaged thread of the bolt, followed by the bearing region around the bolt hole. Under cyclic loading, stress redistribution occurs due to contact interactions and progressive slip. The magnitude of peak stress varies with preload and assembly configuration, with higher preload conditions showing relatively lower stress amplitudes in critical regions.

3.1.2 Deformation and Slip Behavior

The deformation results show that the fastener assembly undergoes initial elastic deformation followed by localized slip between contact surfaces. The displacement contours indicate that slip initiates at the plate–plate interface when the applied load exceeds the frictional resistance provided by bolt preload. After slip initiation, the bolt shank comes into bearing with the hole surface, resulting in increased stiffness. The total deformation remains within acceptable limits for most configurations, although increased displacement is observed in cases with lower preload or absence of washers.

3.1.3 Contact Pressure Analysis

Contact pressure distribution across the interfaces reveals non-uniform patterns, with peak pressures concentrated around the bolt hole edges and under the nut–washer region. The application of preload significantly increases the initial contact pressure, enhancing frictional resistance and delaying slip. During cyclic loading, a gradual reduction in contact pressure is observed, particularly in configurations with single nuts or without washers. This reduction indicates loss of clamping force and potential loosening of the joint.

3.2 Experimental Results

3.2.1 Load–Displacement Curves

The experimental load–displacement curves exhibit nonlinear hysteresis behavior under cyclic loading. Each cycle forms a closed loop, representing energy dissipation

within the joint. Initially, the curves show a steep slope corresponding to elastic behavior, followed by a plateau region indicating slip. With increasing number of cycles, the slope of the curves decreases slightly, and the loop area reduces, indicating stiffness degradation and reduced energy dissipation capacity.

3.2.2 Fatigue Life Observations

The fatigue life of the specimens varies depending on the fastener configuration. Specimens with higher preload, double nuts, or washers demonstrate improved fatigue resistance and sustain a greater number of cycles before significant degradation occurs. In contrast, specimens with single nuts and no washers show earlier signs of loosening and reduced fatigue life. The number of cycles to noticeable performance degradation is summarized in Table 3.

Table 3 Fatigue Performance of Specimens

Specimen ID	Configuration Description	Cycles to Degradation	Observed Behavior
S1	Single nut, no washer	~40–50 cycles	Early loosening, high slip
S2	Double nut	~60–70 cycles	Improved stability
S3	Higher frequency (2 Hz)	~45–55 cycles	Similar to S1 behavior
S4	With washer	~70–80 cycles	Reduced slip, stable response
S5	Two bolts	~75–85 cycles	Higher stiffness
S6	Two bolts + double nuts	~90+ cycles	Best performance

3.2.3 Failure Modes

The experimental observations reveal multiple failure modes depending on the configuration. The most common failure mode is bolt loosening, characterized by a reduction in preload and increased joint slip. In some cases, localized plastic deformation is observed around the bolt hole due to bearing stresses. Crack initiation is detected near thread roots and contact edges after repeated loading cycles. Final failure occurs either through bolt fracture or excessive deformation of connected members in extreme cases.

3.3 Validation of Numerical Model

3.3.1 Comparison of FEA and Experimental Results

The comparison between finite element and experimental results shows close agreement in terms of load-displacement behavior and deformation characteristics. Both approaches capture key features such as initial stiffness, slip behavior, and hysteresis response under cyclic loading. The simulated curves closely match the experimental curves in shape and trend, confirming the accuracy of the numerical model.

3.3.2 Error Analysis

A quantitative comparison of key parameters such as peak load and displacement indicates that the variation between FEA and experimental results is within an acceptable range. Minor discrepancies are attributed to experimental uncertainties, such as variations in applied preload and material inconsistencies. The overall error is found to be within 5–10%, demonstrating the reliability of the simulation approach.

Table 4 Comparison of FEA and Experimental Results

Parameter	FEA Result	Experimental Result	Error (%)
Maximum Load (kN)	25.0	23.5	6.0
Maximum Displacement (mm)	1.50	1.60	6.7
Initial Stiffness (kN/mm)	18.0	17.2	4.5

3.4 Parametric Study Results

3.4.1 Effect of Preload

Higher bolt preload results in increased contact pressure and reduced slip, leading to improved joint stiffness and fatigue performance. Lower preload conditions show earlier slip initiation and faster degradation.

3.4.2 Effect of Washers

The presence of washers enhances load distribution and reduces stress concentration under the nut. Specimens with washers exhibit higher energy dissipation capacity and improved stability under cyclic loading.

3.4.3 Effect of Number of Bolts/Nuts

Increasing the number of bolts or using double-nut configurations significantly improves joint performance. These configurations provide higher clamping force, reduced loosening, and increased fatigue life compared to single-bolt or single-nut setups.

3.4.4 Effect of Loading Frequency

Variation in loading frequency shows relatively minor influence on overall fatigue performance within the tested range. The load-displacement behavior and energy dissipation characteristics remain largely consistent across different frequencies.

4. CONCLUSIONS

This study presents a comprehensive investigation on the design validation and fatigue performance of mechanical fastener assemblies used in power transmission structures through a combined numerical and experimental approach. The finite element model developed in this work successfully captured the nonlinear behavior of bolted joints, including contact interactions, preload effects, and cyclic slip characteristics. The experimental results demonstrated nonlinear hysteresis behavior with progressive stiffness degradation and reduction in energy dissipation under repeated loading cycles. A strong correlation between the numerical and experimental findings was observed, with prediction errors remaining within acceptable limits, thereby validating the reliability of the simulation methodology.

The results indicate that stress concentration is primarily localized at thread roots and bolt-hole interfaces, which are critical regions for fatigue crack initiation. It was also observed that bolt preload, number of nuts, and use of washers significantly influence the fatigue performance of fastener assemblies. Configurations with higher preload, double-nut arrangements, and washers exhibited improved resistance to loosening, enhanced energy dissipation capacity, and longer fatigue life. In contrast, joints with lower preload or simpler configurations showed early slip and rapid degradation. The influence of loading frequency was found to be relatively minor within the investigated range. Overall, the study provides valuable insights into the mechanical behavior and durability of fastener assemblies, offering practical guidelines for improving the reliability and safety of power transmission structures.

5. FUTURE SCOPE OF RESEARCH

Future research can focus on developing advanced fatigue prediction models incorporating multiaxial stress states and variable amplitude loading conditions to better simulate real service environments. The integration of damage mechanics and fracture-based approaches may further improve the

accuracy of fatigue life estimation. Additionally, the effect of environmental factors such as corrosion, temperature variations, and long-term aging on fastener performance should be investigated. Real-time monitoring techniques, including smart sensors and structural health monitoring systems, can be explored for early detection of bolt loosening and fatigue damage. Furthermore, the application of machine learning and data-driven models for predictive maintenance of fastener assemblies presents a promising direction for enhancing the reliability of power transmission systems.

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