

Failure Analysis of Bolted Connection Subjected to Torsional Loading

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Abstract

In mechanical engineering, the integrity of bolted connections under stress is critical. This study focuses on the failure mechanisms of these connections under torsional loading. The objective was to simulate the mechanical performance of a particular failed bolted joint under varying torsional loads. Using SolidWorks for 3D modelling and ANSYS for finite element analysis, the research methodically evaluates the performance of the failed bolted joint under various torsional loads ranging from 2.5 to 20 Nm. Key findings reveal excessive stress distribution patterns and specific failure points. The study concludes with design recommendations for an optimized bolt joint, ensuring that stress and strain values remain well below the material's failure benchmarks.

1. Introduction

Bolted connections have played a pivotal role in engineering since the dawn of the Industrial Revolution, marking a significant advancement in the construction and assembly of mechanical systems and structures [1]. The invention and widespread adoption of bolted connections revolutionised how components could be fastened together, offering a combination of strength, durability, and ease of assembly and disassembly. This innovation was instrumental in developing complex machinery, skyscrapers, bridges, and many other structures and devices that form the backbone of modern infrastructure.

Despite their widespread use and inherent strengths, bolted connections are challenging, particularly when subjected to torsional loads. Torsional stress, the twisting force that acts on an object, is a common yet potentially detrimental phenomenon in mechanical engineering. The impact of torsional stress on bolted connections is profound, as it can lead to various failure modes, such as shear failure, tensile overload, and joint loosening [2]. For instance, in the automotive industry, the failure of bolted connections in engine components due to torsional vibrations can lead to catastrophic engine failure. In the realm of civil engineering, bridges and high-rise buildings subjected to dynamic loads, including wind and seismic activity, experience torsional forces that can compromise the integrity of bolted joints.

The objectives of this study stem from the urgent need to address these challenges. While the basic design of bolted connections has remained relatively unchanged over the years, modern engineering applications' increasing complexity and demands necessitate re-evaluating their performance under various loading conditions, especially torsion [3, 4]. This study aims to thoroughly investigate the failure mechanisms of standard bolted connections under torsional loads, focusing on identifying key areas of weakness and proposing design improvements. The ultimate goal is to enhance these connections' overall reliability and safety, ensuring they are better suited to withstand the dynamic and often unpredictable forces they encounter in real-world applications.

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By achieving this, the study seeks to contribute to advancing mechanical engineering practices, setting new standards for the design and application of bolted connections in various industries.

Nomenclature

T	torque
F	Applied force
σ	Stress
ϵ	Strain
E	Modulus of Elasticity

1.1 Failure Analysis of Bolted Connections under Torsional Stress

The performance of bolted connections under torsional loads is a key factor in ensuring mechanical systems' overall safety and functionality [3, 5]. Failures in these connections can lead to catastrophic consequences, including system malfunctions, structural failures, and safety hazards.

Understanding the behaviour of these connections (Fig. 1) under torsional stress is essential for designing safer and more efficient mechanical systems [6, 7]. It helps predict potential failure modes and develop more robust designs. Fig. 2 shows a schematic diagram of the actual bolted assembly.

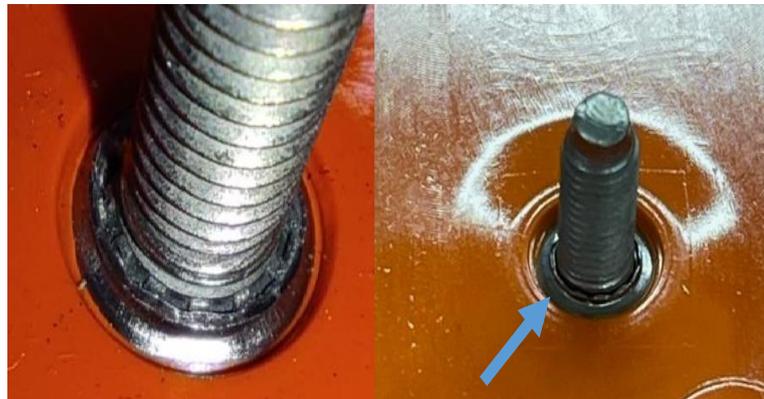


Fig. 1 Actual images of bolt failure

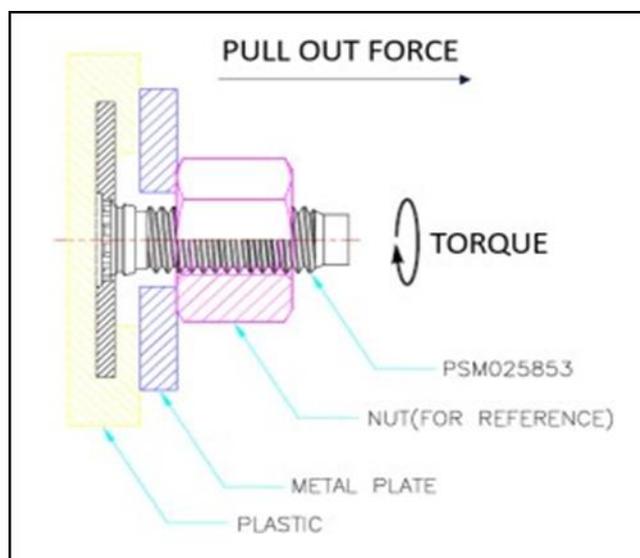


Fig. 2 Schematic diagram of the actual bolted assembly, Failure specimen

2 Methodology

In this study, a two-phase technical approach was employed. The first phase involved detailed 3D modelling using SolidWorks, where the geometrical representations of bolted connections, including bolts, nuts, and support plates, were accurately constructed. This process aimed to mirror real-world configurations of bolted joints in mechanical systems. Table 1 and Table 2 show the parameters of the 3D parts and materials' properties, respectively.

The second phase involved applying finite element analysis (FEA) using ANSYS. Here, the SolidWorks models were subjected to a series of torsional loads, varying from 2.5Nm to 20Nm. This FEA simulation [8] enabled the identification and analysis of stress distributions, deformation patterns, and potential failure mechanisms under the applied loads. The focus was on dissecting the influence of design parameters such as support plate dimensions and bolt arrangement on the mechanical integrity and performance of the connections.

Combining SolidWorks modelling with ANSYS-based FEA, this methodology provided an in-depth understanding of bolted connections' mechanical behaviours and failure characteristics under different torsional stresses. The research employs SolidWorks for detailed 3D modelling of the M5 stud bolt and nut, ensuring accurate thread geometry representation and material properties integration. Table 3 shows the Ansys Parameter.

Table 1 Parameter 3D parts

No	Part	Parameters
1.	M5 STUD BOLT	M5 x 0.8, 25mm Pitch: 0.8 Length: 25mm
2.	Hex Nut	M5 standard
3.	Support Plate initial design (Failure specimen)	Diameter hole 14mm
4.	Support Plate corrected design (Solution Case)	Diameter hole 7mm
5.	Mating Part	Diameter hole 6.5mm

Table 2 Material Properties [9]

Properties	Material	
	Carbon Steel	LEXAN 925U Polycarbonate
Young' Modulus (GPa)	203.4	2.27
Poison ratio	0.2998	0.35
Bulk Modulus (GPa)	169.33	2.52
Shear Modulus (GPa)	78.243	0.84

Table 3 Ansys Parameters

Torque, Nm	Preload, N	Friction coefficient		
		Bolt and nut Friction coefficient	Support plate & Mating Part	Mating Part & Nut
2.5	2000	0.25	0.25	0.15
5	4000			
7.5	6000			
10	8000			
15	12000			
20	16000			

In the study of bolted connections under torsional loads, the methodology incorporated the 3D modelling of both the initial and modified designs using SolidWorks, with subsequent simulations performed in ANSYS to analyse mechanical performance. The initial design replicated a failing model from a production plant where bolts designed to withstand 15N were breaking at just 7.5Nm. The assembly was composed of an M5 stud bolt and nut, a mating plate with a 6.5mm hole, and a support plate made of carbon steel, except for the support plate, which was constructed of LEXAN 925U polycarbonate. Fig. 3 shows the initial and modified design.

In the initial design, the support plate's centre diameter was oversized, leading to high pull-out forces and failure when a torque of 7.5Nm was applied. This was a critical observation from the failure analysis phase, which sought to understand the components and conditions leading to failure. The SolidWorks models of the bolted connection assembly, which included precise specifications and material properties, were then exported to ANSYS for finite element analysis (FEA). The simulations aimed to replicate the torque loading conditions to determine the stress distribution and identify the cause of failure.

The modified design involved changes to the support plate; specifically, the centre hole diameter was reduced from 14mm in the initial design to 7mm in the corrected design. This modification aimed to improve bolt security and efficiency under the same loads. The SolidWorks modelling process detailed the steps from sketching the bolt shaft, adding features such as the head and chamfers, extruding the sketch to form the stud bolt, and refining the model to match the exact specifications. Each part was verified and validated against technical drawings and industry standards to ensure accuracy [10].

$$T = K d_b F_i \quad (1)$$

Where;

T – tightening torque (N-m)
K – nut factor (unitless)
 d_b – bolt diameter (m)

Given;

T = 7.5 Nm
 d_b = 5 mm = 0.005 m
 F_i = preload
K = 0.25

$$T = K d_b F_i \quad F_i = \frac{T}{K d_b}$$

$$F_i = \frac{7.5Nm}{0.25 \times 0.005m}$$

$$F_i = 6000N$$

For the assembly, friction coefficients between the support plate, mating part, and nut were determined to be critical for preload calculation. A conservative approach was taken by selecting higher friction coefficients to ensure a secure joint, with a nut factor of 0.25 chosen for the preload calculation, resulting in a preload of 6000N.

The ANSYS software simulations were meticulously set up to replicate the assembly's conditions, with particular attention paid to the support plate and mating part's material properties, friction coefficients, and applied torque loads. The study aimed to determine the minimal allowable diameter of the mating parts to prevent failure under torsional loading, providing insights into structural performance and guiding design optimisation for enhanced reliability in real-world applications.

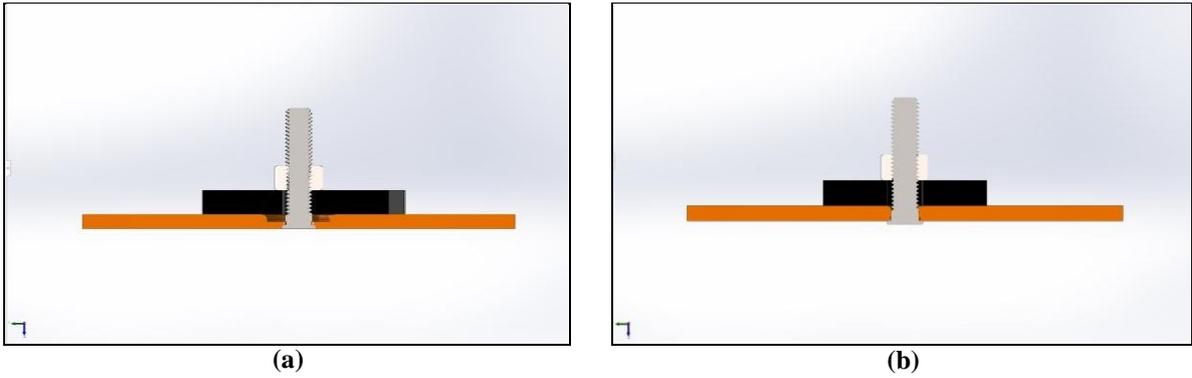


Fig. 3 Initial Design(a); (b) Modified Design

3. Meshing Size in Finite Element Analysis

In the simulation analysis conducted for the failure analysis of bolted connections subjected to torsional loading, mesh quality was identified as a critical factor affecting the accuracy and reliability of Finite Element Analysis (FEA)[11, 12]. The mesh quality was evaluated based on the skewness of the mesh elements, which measures mesh element distortion.

A mesh size of 1.5 mm (Fig. 4) was selected, and the average skewness value obtained was 0.477. This value falls within the acceptable range of 0.25 to 0.50, according to established standards in mesh quality assessment, including those outlined by Ozen (2014). This range is considered acceptable for engineering simulations, indicating that the mesh elements, while not ideally shaped, do not possess a level of distortion that would significantly compromise the simulation's accuracy.

The average skewness value suggests that the mesh is sufficiently accurate for most analysis purposes in this simulation, providing reliable FEA results with a good balance between computational efficiency and accuracy. It's also noted that there is potential for further mesh refinement to achieve even lower skewness values, which could enhance the precision of the simulation results.

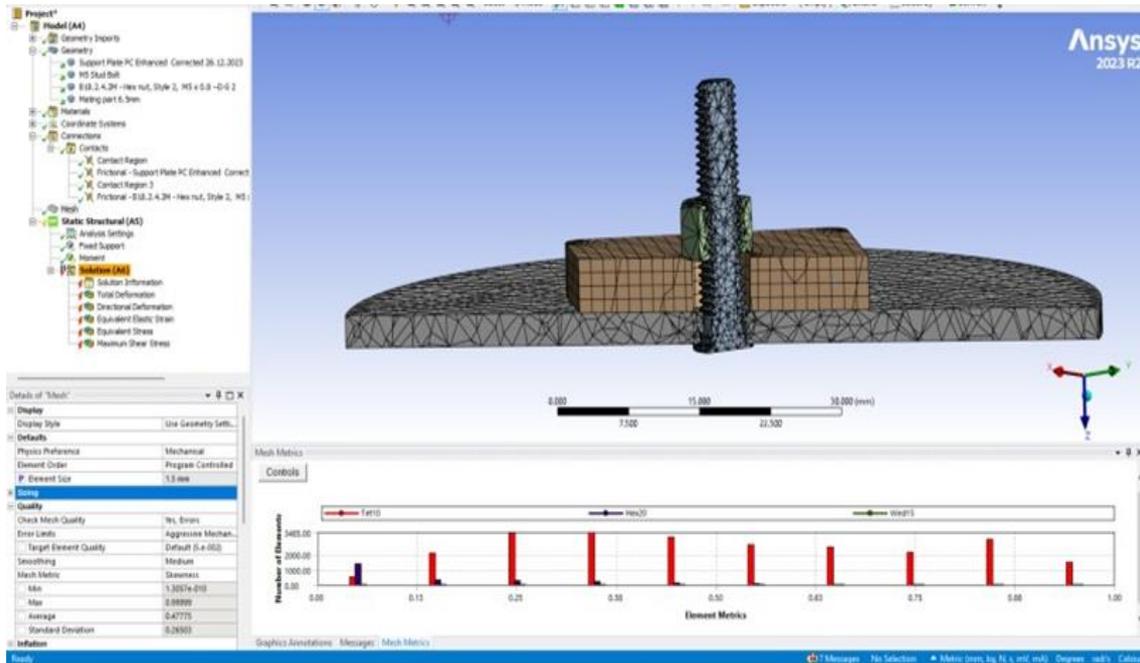


Fig. 4 Meshing size of 1.5 mm

Table 4 Mesh analysis table

Torque	Mesh Size, mm	Number of Nodes	Number of Elements
7.5Nm	0.5	356404	147615
	1	98191	46518
	1.5	56461	26502
	2	46146	23272
	2.5	42125	21931
	3	40803	20833

The selected meshing size and skewness value suit the study's requirements, providing a reliable and computationally efficient simulation. The chosen mesh parameters ensure that the behaviour of the bolted connection under torsional loads is accurately represented in the simulation, allowing for a credible assessment of its performance and potential failure points.

4. Simulation Results

The simulation results revealed that standard bolted connections typically fail due to excessive pull-out forces, particularly under torsional loads of 7.5Nm and above. This failure was primarily attributed to the oversized diameters of the support plates. An improved design featured reduced gap sizes and increased contact areas between the bolts and plates.

The simulation results for the initial and modified bolted connection designs under a torsional loading of 7.5Nm reveal significant differences in their performance, particularly in terms of deformation, strain, stress, and shear stress:

4.1 Initial Design (Failure Specimen)

Fig. 5, Fig. 6 and Fig. 7 show the initial design results. The deformation for the initial design was considerably high at 6.5743 mm, far exceeding the benchmark of 0.22 mm set by the JIS B 1051:2000 standard. The strain recorded was 0.003886 mm/mm, which, while not exceeding the benchmarks, is substantial for the loading condition. The stress reached a maximum value of 285.3 MPa, surpassing the yield strength of steel bolts (240 MPa as per EN 1993-1-8 standard) by approximately 18.8%, indicating that the design was not robust enough to handle the applied load without failing. The shear stress in the failure specimen was 158.12 MPa, higher than the solution case's shear stress and exceeding the benchmark of 145 MPa suggested by the British Steel Association, suggesting a risk of shear failure.

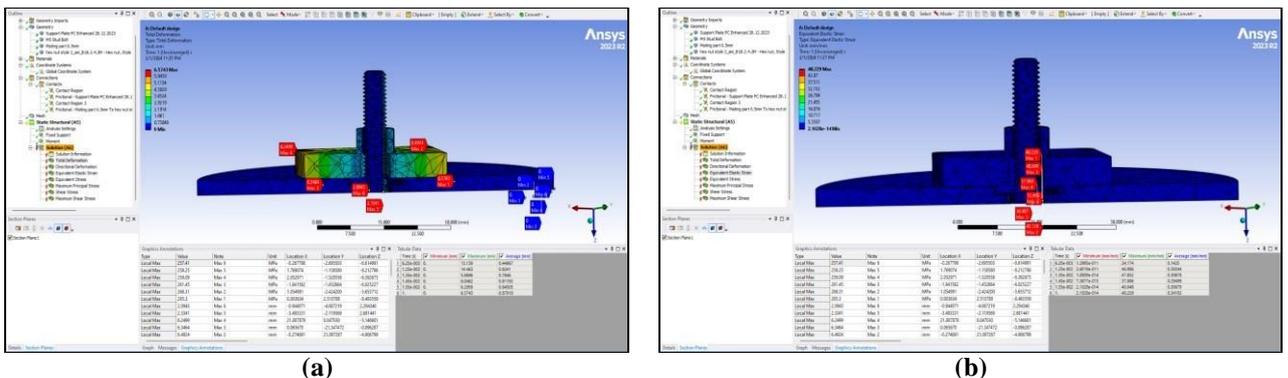


Fig.5 Deformation(a); (b) Equivalent Elastic Strain; for initial design with 7.5Nm loading

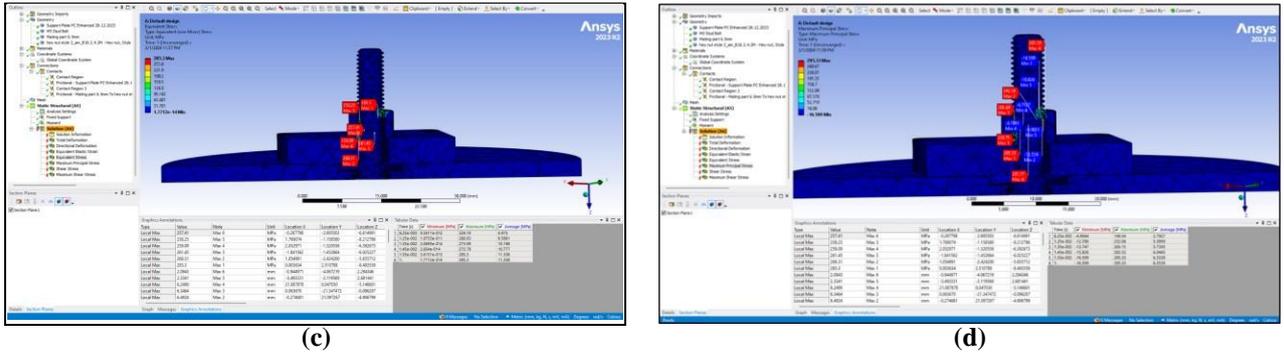


Fig.6 (c) Equivalent Stress;(d) Maximum Shear Stress for initial design with 7.5Nm loading

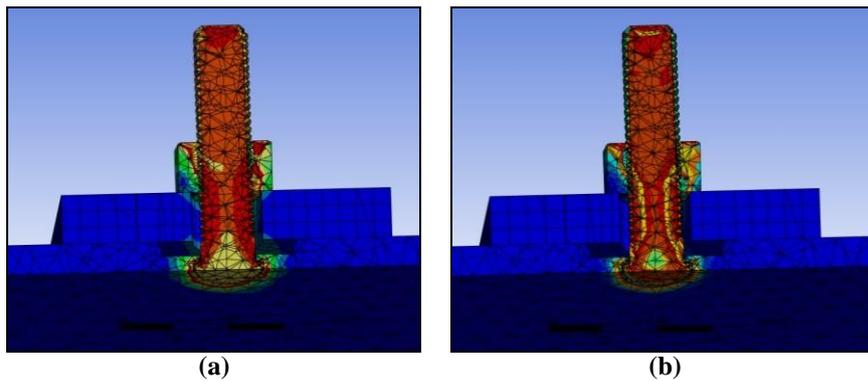


Fig.7 Detailed view of excessive Stress (a); (b) Detailed view of excessive Shear stress for initial design with 7.5Nm loading

4.2 Modified Design (Solution Case)

Fig. 8 and Fig. 9 shows the modified design results. The deformation was significantly reduced to 0.043575 mm, well within safe limits and demonstrating a much more rigid bolted connection. The strain was reduced to a minimal 0.003886 mm/mm, highlighting the improved material behaviour under the same loading conditions. The stress was reduced to 138.1 MPa, comfortably below the yield strength of the bolt material, indicating a safe margin for the modified design.

The shear stress was significantly lower at 79.649 MPa, below the benchmark and indicative of a design that can handle the applied loads without nearing failure (Table 5).

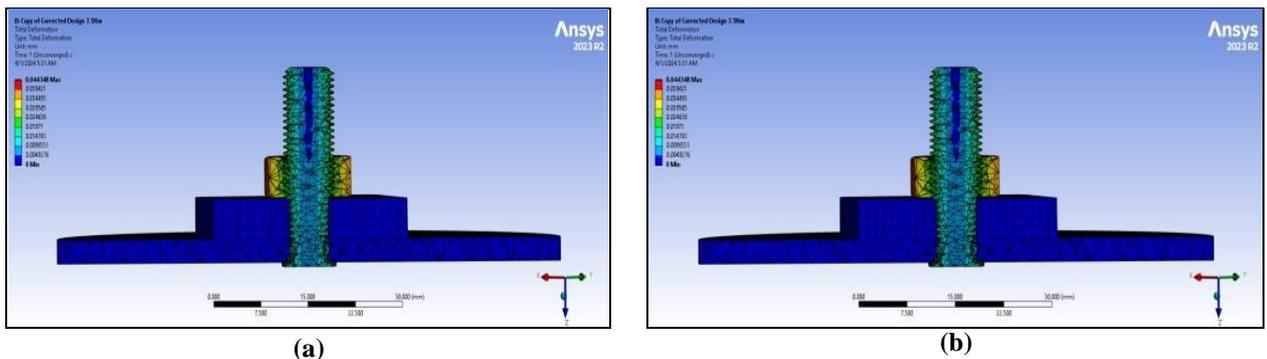


Fig. 8 Deformation(a); (b) Equivalent Elastic Strain; for modified design with 7.5Nm loading

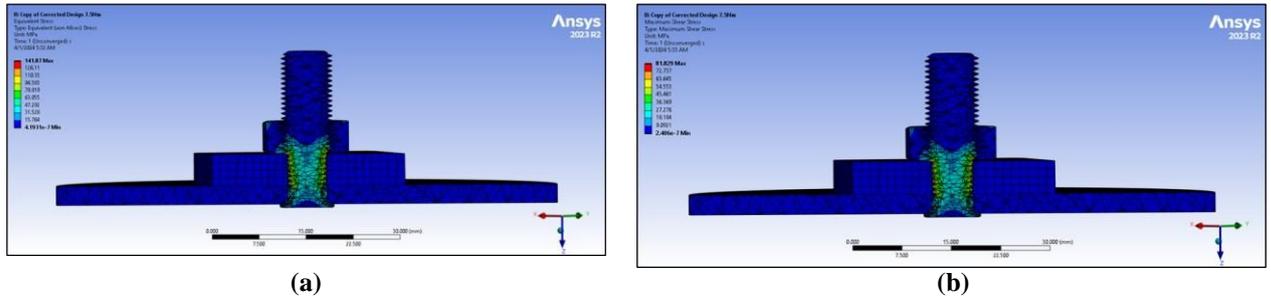


Fig. 9 (a) Equivalent Stress;(b) Maximum Shear Stress for modified design with 7.5Nm loading.

Table 5 Simulation results of the Modified Design (Proposed Solution) tested with various torque loading

Torque, Nm	Deformation, mm	Equivalent Elastic Strain mm/mm	Equivalent Stress Von-mises, Mpa	Shear Stress, Mpa
2.5	0.042132	0.003561	128.96	75.19
5	0.042802	0.003724	134.03	77.42
7.5	0.043575	0.0038869	138.1	79.649
10	0.044348	0.0040463	141.87	81.829
15	0.048734	0.0045869	149.65	86.374
20	0.050049	0.0050127	159.56	92.032

In summary, the simulation results validate the improved performance of the modified design over the initial one. The failure specimen consistently displayed higher values for deformation, stress, and shear stress, exceeding safe limits and leading to failure. In contrast, the solution case-maintained values within the allowable range, demonstrating the effectiveness of the design modifications. The ANSYS simulation results confirm the practical outcomes, showcasing the reliability of the simulation approach in predicting and preventing bolt failure.

4.3 Graphical Representation of Results

This new design demonstrated a significant increase in strength and efficiency, effectively addressing the issue of pull-out forces. Compared with industry standards, notably EN 1993-1-8, the optimised design exhibited enhanced performance, maintaining lower stress levels and reducing deformation under similar load conditions. This comparison highlighted the superior mechanical reliability of the proposed design in real-world applications. Fig. 10 and Fig. 11 display the findings of the modified design, which includes deformation, strain, stress and shear stress behaviour of the bolted connection.

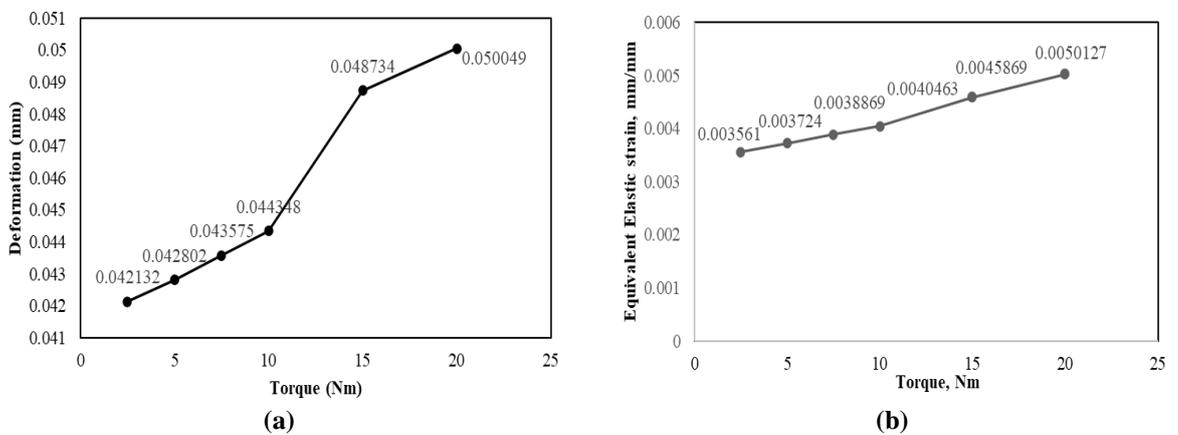


Fig. 10 Deformation vs. Torque (a); (b) Equivalent elastic strain vs Torque

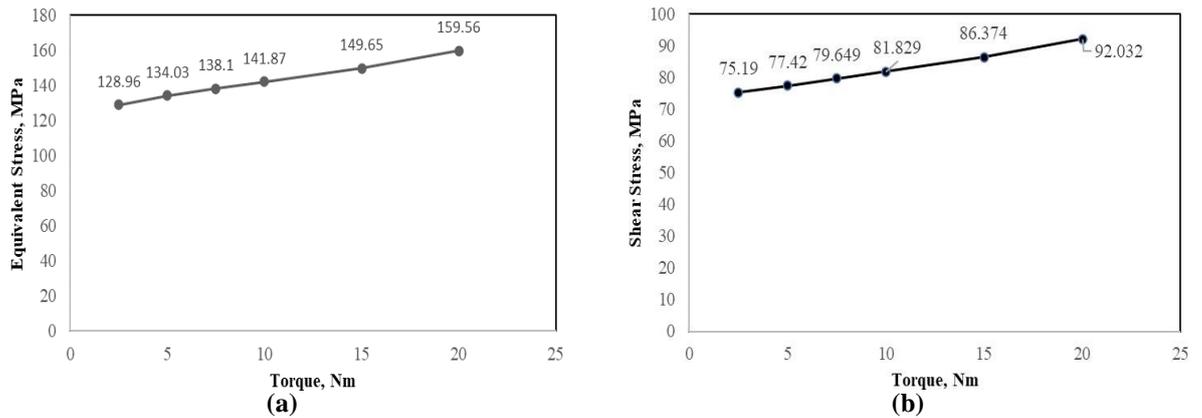


Fig. 11 Equivalent Stress vs. Torque (a); (b) Shear Stress vs. Torque

Fig. 10a shows the deformation vs. torque graph. This graph displays a curve that starts with a gradual slope and then progresses to a steeper increase. The deformation values, measured in millimetres, increase as the torque, measured in Newton meters (Nm), is applied. The plotted points show a clear trend where deformation is minimal and becomes more pronounced as the torque increases. This is consistent with elastic behaviour transitioning into plastic deformation, where the material begins to deform permanently.

The equivalent elastic strain is plotted against the torque shown in Fig. 10b. The trend is also upward, indicating that as the torque increases, so does the strain. The relationship appears linear, suggesting that the material behaves elastically as expected within the torque range applied, with no significant plastic deformation, as the strain values are relatively low and increase proportionally with torque.

The equivalent stress, measured in megapascals (MPa), is shown against the torque (Fig. 11a). The linearity of the graph indicates that the stress increases proportionally with the torque. This behaviour indicates the material staying within its elastic limit, as there is no disproportionate increase in stress, which would suggest yielding or approaching failure.

Fig. 11b shows shear stress vs. Torque. This graph shows the shear stress response to the torque applied. Like the equivalent stress, shear stress also increases linearly with torque, suggesting that the material is not nearing its shear strength limit. The graph's absence of a sharp turn implies that the bolted connection can withstand the applied torque without immediate danger of failing due to shear.

The bolted connection can withstand the tested torque range without showing signs of failure, as indicated by the linear increase in stress and strain in the graphs. This suggests the material remains elastic and has not reached the plastic deformation phase. Analysing these graphs is essential for evaluating the durability and safety of bolted connections under torsion, aiding in predicting their performance and potential failure, which is critical for ensuring structural integrity and safety.

5. Factor of Safety

In the analysis of bolted connections subjected to torsional loading, the Factor of Safety (FOS) against bolt elongation is a key metric for evaluating the reliability and longevity of the assembly under operational stress conditions. The FOS indicates how much stress a component can withstand beyond the expected loads before failing or yielding (Table 6).

For an M5 bolt of class 4.6, which plays a critical role in the connection, the following specifications were considered:

- Class: 4.6
- Yield Strength: 240 MPa
- Allowable stress: 138.1 MPa

Table 6 Strength Properties for Bolts according to EN 1993-1.8 [13]

Symbol	Description	Bolt Class						
		4.6	4.8	5.6	5.8	6.8	8.8	10.9
f_{yb} (MPa)	Yield Strength	240	320	300	400	480	640	900
f_{ub} (MPa)	Ultimate Tensile Strength	400	400	500	500	600	800	1000

$$FOS_{elongation} = \frac{\text{Yield strength}}{\text{Allowable stress}} \quad (2)$$

$$FOS_{elongation} = \frac{240 \text{ Mpa}}{138.1 \text{ Mpa}}$$

$$FOS_{elongation} = 1.7379$$

The FOS against bolt elongation measures the bolt's ability to resist elongation stresses without experiencing permanent deformation. It is computed by dividing the yield strength of the bolt material by the equivalent stress experienced by the bolt. The equivalent stress is determined using the Von Mises stress criterion, a well-established approach for assessing the yield condition in ductile materials.

The FOS is a vital aspect in the design and analysis of bolted connections, providing an understanding of the safety margin incorporated into the design. It ensures that the bolt will function safely under the given loads and conditions, considering possible uncertainties in the material properties, loading scenarios, and environmental factors.

In the context of the seminar paper, the FOS plays a role in demonstrating the adequacy of the bolt design and the effectiveness of the corrective measures implemented in the modified design to prevent failure. A higher FOS indicates a greater margin of safety, which translates to a more reliable bolted connection in service.

6. Benchmarks

The failure specimen's shear stress was measured at 158.12 MPa, surpassing the solution case's shear stress of 79.649 MPa and exceeding the benchmark of 145 MPa recommended by the British Steel Association [14] by approximately 9%. This excess suggests that the failure specimen was prone to shear failure. The analytical comparison (Fig. 12) also demonstrated that the failure specimen exhibited higher deformation, stress, and shear stress values than the safe limits defined by industry benchmarks, aligning with the practical observations of failure.

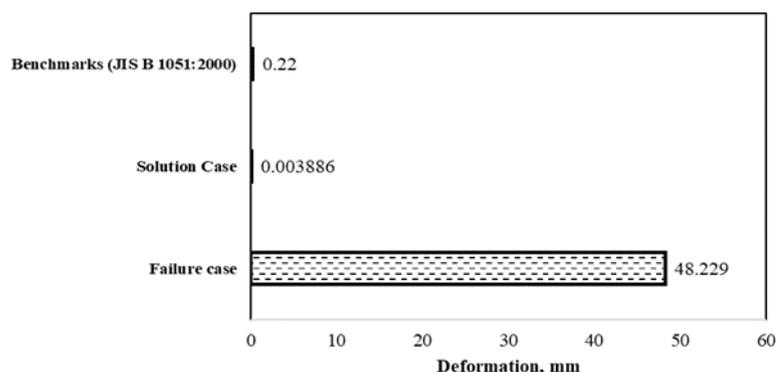


Fig. 12 Deformation Comparison

Conversely, the solution case managed to maintain values well within the permissible range, which affirms the effectiveness of the corrective measures implemented in the design. This substantiates the reliability of the ANSYS simulation results, which corresponded with the practical outcomes, thereby validating the simulation's predictive capability in assessing and preventing bolt failure.

However, it is important to note that the Factor of Safety (FOS) is predicated on the assumption that no additional dynamic or impact loads affect the bolt's performance. For a comprehensive safety assurance, it would be necessary to consider all potential operational loads, and the FOS should be evaluated within the context of the specific application and environmental conditions. The stress and strain/elongation benchmarks in the failure specimen were exceeded, but the simulated values for the solution case were within the benchmarks (Fig. 13).

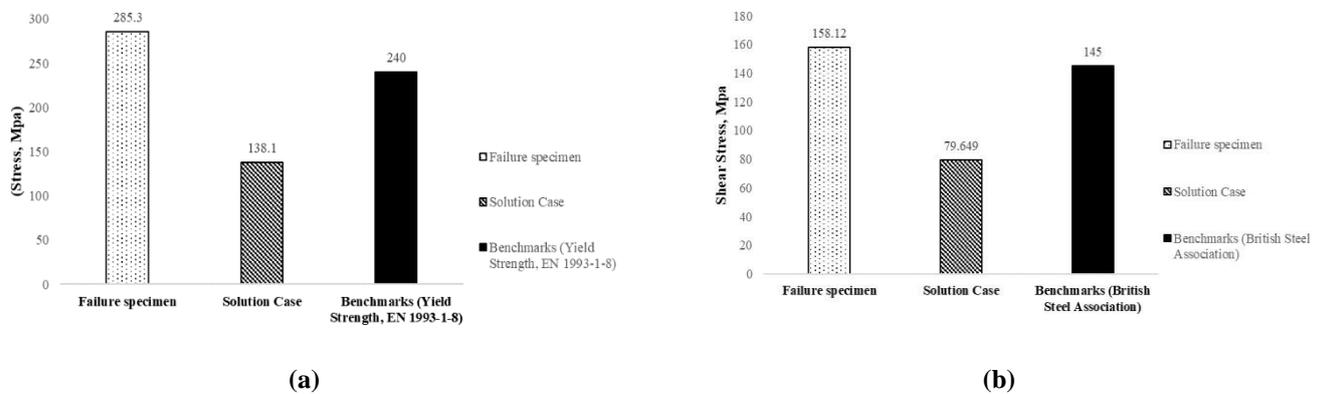


Fig. 13 Stress comparison (a); (b) Shear Stress comparison

The investigation into the industrial bolted connection failures revealed a 'jack out' failure mechanism in the initial design, attributed to an oversized gap at the centre of the mating parts, which reduced the clamping force. This critical finding was a driving force behind the simulation and subsequent redesign efforts to enhance the connection's integrity and prevent similar failures in the future.

7. Conclusion

The outcomes of the ANSYS simulation offer significant insights into the performance of bolted connections across various torsional loads. The implications of these results for the design and structural integrity of bolted joints are substantial. To begin with, it is apparent that the failed bolt has ruptured as a result of surpassing the yield strength threshold for steel bolts. This underscores the utmost significance of choosing bolt materials and dimensions that are suitable to endure applied loads.

For the optimized design, the findings suggest that the stresses experienced in the bolted joint remain significantly below the yield strengths of the materials utilised in the case of a successful solution. This highlights the importance of competent design and engineering in bolted connections to guarantee their durability and dependability.

Additionally, our analysis underscores a critical element in attaining prosperous bolted joints: the maintenance of intimate proximity between the mating plates across their entire surface area. The failure specimen illustrates how the existence of gaps between the mating plates can result in substantially increased stresses. This phenomenon arises due to the concentrated application of force on a relatively small contact area, which ultimately causes the rupture of the bolt. Based on these results, we strongly advise designers and engineers to prioritise maximising the contact area between the mating plates and to eliminate any gaps between them when constructing bolt joints. This approach can substantially improve the safety and dependability of bolted connections in a wide range of engineering applications.

Conflict of Interest

There was no conflict of interest regarding the publication of the paper.

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