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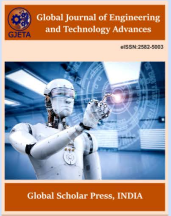

(RESEARCH ARTICLE)

Structural reliability assessment of offshore tubular t-joints under static axial brace loading

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Abstract

This paper presents a comprehensive study on the structural reliability assessment of tubular T-joints under axial brace loading in offshore structures. The investigation combines numerical modeling and experimental analysis to understand the behavior of these joints and assess their structural integrity. Based on Hot sport stresses in the joints. The numerical investigation reveals that the brace region experiences higher stress concentrations compared to the cord region, with maximum stress concentrations observed at the 90-degree position. Experimental results confirm these trends, although slight discrepancies exist between numerical and experimental stress concentration factors (SCFs), with percentage difference of about 12 percent on the average for both Chord and Brace. The likely cause of this discrepancies is due to Fabrication imperfections and limitation in terms of Mesh size on the part of the software. The findings contribute to the knowledge of tubular T-joint behavior and have implications for designing mitigation measures. Further research is needed to analyze additional parameters and refine design guidelines to enhance the performance of tubular T-joints in offshore structures.

Keywords: Tubular T-joints; Structural reliability; Stress concentration factors; Hotspot; Experimental

1. Introduction

Offshore tubular T-joints play a crucial role in the construction of offshore structures, it must withstand harsh environmental conditions and significant loads [1]. These joints serve as critical connections between main structural elements, providing strength, stability, and load transfer. The behavior of tubular T-joints under various loading conditions has been extensively studied in structural engineering due to their widespread use and importance in ensuring the structural integrity and safety of offshore structures [2].

Tubular T-joints are commonly used in the connections between braces and chords, forming an essential part of the bracing systems in offshore platforms. They experience axial brace loading resulting from the interaction between the braces and surrounding structural elements. This axial brace loading poses unique challenges, subjecting the T-joints to high compressive and tensile forces, bending moments, and shear stresses. Understanding the behavior of tubular T-joints under axial brace loading is crucial for accurately predicting their performance and ensuring the reliability and safety of offshore structures [3].

A significant amount of research has been dedicated to investigating tubular T-joints in structural engineering, particularly under axial brace loading. The factors influencing their structural response have been extensively studied. For instance, research has been conducted on joint strength under fatigue loading [4][5][6][7][8], leading to new design recommendations based on thickness effect considerations from tests conducted. Full-scale experiments have also been performed to evaluate the structural capacity and failure modes of tubular T-joints subjected to axial brace loading [9].

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Finite element analysis (FEA) has been used to investigate the stress distribution and failure modes of these joints, emphasizing the importance of accurate material modeling and contact analysis [10].

Furthermore, an effective width method has been proposed for predicting the ultimate strength of tubular T-joints under axial brace loading, demonstrating good agreement with experimental results [11]. Some studies have focused on specific joint configurations and loading conditions, limiting the generalization of findings, and there is a need for more comprehensive investigations encompassing various joint geometries, materials, and loading scenarios [9]. The accuracy of numerical simulations in comparison to experimental results also needs further evaluation, as it impacts their application in design and analysis [11]. Additionally, a deeper understanding of the joint's behavior concerning load-displacement response and stress distribution is required.

Moreover, previous studies have primarily focused on ultimate capacity and failure modes, while this study will delve into the joint's behavior regarding stress distribution and load-displacement response. Additionally, the study by [20] proposed probability distribution models for stress concentration factors (SCFs) in internally ring-stiffened tubular KT-joints under various in-plane bending loads, using finite element stress analysis and validated with experimental data [22]. Furthermore, another study using ANSYS for finite element analysis examined the static strength of an offshore tubular T-joint with circular cross-section tube chord and circular cross-section tube brace, and the results confirmed the safety of existing tubular joint design formulas [22].

This study aims to address these research gaps through a comprehensive investigation involving both numerical simulations and experimental tests of tubular T-joints under axial brace loading. The study intends to provide valuable insights into the joint's response and assess the accuracy of numerical simulations against experimental data. By doing so, the research will contribute to the development of improved design guidelines and assessment methodologies for tubular T-joints in offshore structures.

In conclusion, the research on offshore tubular T-joints under axial brace loading is essential, and this study aims to contribute significantly by addressing existing research gaps through a comprehensive numerical and experimental investigation. The findings will lead to enhanced design guidelines and assessment methodologies for these critical joints in offshore structures.

2. Material and method

Numerical simulations, utilizing advanced computational techniques, have become indispensable tools for studying the behavior of complex structures such as tubular T-joints under axial brace loading. In this section, the numerical simulation techniques employed in this study, along with the associated modeling assumptions and considerations, material properties, boundary conditions, and meshing strategies, will be discussed. The commercial software ANSYS will be used for the numerical modeling.

Finite Element Analysis (FEA) is the primary numerical simulation technique used in this study to model the behavior of tubular T-joints. FEA is a powerful and widely adopted numerical method that discretizes the structure into finite elements, enabling the analysis of complex geometries and nonlinear behavior. The software package ANSYS provides a comprehensive set of tools and capabilities for performing FEA simulations.

In developing the numerical model, certain assumptions and considerations are made to balance accuracy and computational efficiency. Some common modeling assumptions include considering the material behavior as linear elastic or elastic-plastic, neglecting geometric imperfections, and assuming small deformations. The choice of these assumptions depends on the objectives of the study and the level of accuracy required.

Accurate representation of material properties is crucial for capturing the behavior of tubular T-joints. The material properties, such as Young's modulus, Poisson's ratio, and yield strength, are essential inputs for the numerical model. These properties can be obtained from experimental tests or from published material data. It is important to note that the material behavior of tubular T-joints can exhibit nonlinear characteristics, especially in the plastic range, and appropriate material models, such as the Von Mises yield criterion, may be employed.

The selection of appropriate boundary conditions is crucial for realistic simulation results. The boundary conditions should accurately represent the actual loading and support conditions of the tubular T-joint. In the case of axial brace loading, appropriate boundary conditions would include restraining the ends of the brace and applying the prescribed axial force. Additionally, boundary conditions related to other components of the structure, such as the chord and other braces, should also be considered to capture the overall structural behavior accurately.

Meshing is the process of discretizing the geometry into small finite elements. The quality and refinement of the mesh significantly affect the accuracy and computational efficiency of the numerical simulation. For tubular T-joints, a suitable meshing strategy should consider the complexities of the joint geometry, such as the weld regions and the transition areas between the brace and the chord. A fine mesh near these critical regions and a coarser mesh in less critical regions can be employed to balance accuracy and computational cost. [22] Simulation results matched well with experiments in the elastic range but showed early inelastic behavior, resulting in a 4% difference in maximum load capacity

2.1. ANSYS Software

In this study, the commercial software ANSYS will be utilized for the numerical modeling of tubular T-joints. ANSYS offers a wide range of capabilities, including pre-processing, finite element analysis, and post-processing, allowing for a comprehensive and accurate simulation of the joint's behavior under axial brace loading. It provides a user-friendly interface, extensive material models, and solvers capable of handling the nonlinear behavior of the joints.

By employing ANSYS and carefully considering the modeling assumptions, material properties, boundary conditions, and meshing strategies, the numerical model can accurately represent the behavior of tubular T-joints under axial brace loading. This facilitates the analysis and understanding of the joint response and provides a valuable tool for further investigations and design optimizations.

2.2. Experimental Analysis

The Fabrication of three T joint specimens is conducted for the purpose of investigating their response solely under axial load. The geometric parameters of the test specimens are carefully selected to fall within the acceptable range by API. The geometric configuration of the investigated joints is illustrated in Table 1. Welding of the joints adheres to the API recommendations and undergoes testing with a pressure tester to identify any defects. The applied loads are supported by utilizing an existing loading frame depicted in Figure 2 as a reaction wall.

Figure 1 Experimental Set Up

In order determining the hot-spot stresses, deflection measurements are taken using rosette strain gauges (0–45–90°). The deformation data is acquired through the utilization of the Adriano software code specifically designed for strain gauges. Figure 3, shows the arrangement of the sample with the strain rosettes. Ansys software is employed to predetermine the maximum hot-spot location, providing guidance on the gauge placement within the model. The gauges are positioned at 0 degrees, 45 degrees, and 90 degrees to capture deflection in multiple degrees of freedom. The Arduino code incorporates the following formula. The deflection is used to compute the Hotspot stresses. The Stress Concentration Factor, SCF, is calculated by taking the ratio of the Hotspot stress and the nominal stress, as presented in equation 4, the nominal stress is the ratio of the applied load on Brace to the area of the Brace, as presented in equation 3. The dimensions of the 3 specimen is presented in table 1.

Table 1 Specimen Dimension

S. No	Specimen No	Chord L×D×T (mm)	Brace L×D×T (mm)
1	T – 1	750 × 84 × 3.2	170 × 57 × 2.7
2	T -2	750 × 84 × 3.2	170 × 57 × 2.7
3	T -3	750 × 84 × 3.2	170 × 57 × 2.7

Figure 2 Strain Gauge Arrangement

2.3. Strain Gauge Calculations

Strain gauges play a vital role in mechanical testing, enabling precise measurements of material deformation and stress under various conditions. In this journal paper, we present an innovative formula to calculate strain gauge values (σ_1 and σ_2) that accurately determine principal stresses in materials subjected to mechanical forces. This formula incorporates axial, shear, and circumferential strains (ε_a, ε_β, and ε_c), along with Young's modulus (E) and Poisson's ratio (ν), accommodating complex strain distributions and different material properties

$$\sigma_1 = E\left[\frac{(\varepsilon_a + \varepsilon_c)}{2(1-v)} + \frac{\sqrt{(\varepsilon_a + \varepsilon_c)^2 + (2\varepsilon_b - \varepsilon_a - \varepsilon_c)^2}}{2(1-v)}\right] \quad \text{..........}(1)$$

$$\sigma_2 = E\left[\frac{(\varepsilon_a + \varepsilon_c)}{2(1-v)} - \frac{\sqrt{(\varepsilon_a + \varepsilon_c)^2 + (2\varepsilon_b - \varepsilon_a - \varepsilon_c)^2}}{2(1-v)}\right] \quad \text{.......}(2)$$

2.4. Stress Concentration Factor Calculation

To find the SCF experimentally, strain values measured are converted to appropriate stress values to compute the applied stress, which is given by

$$\text{Applied stress (nominal stress)} = \frac{\text{Applied Load on Brace}}{\text{Area of brace}} \text{............}(3)$$

$$SCF = \frac{\text{Hot Sport stress}}{\text{Norminal stress}} \quad \text{............}(4)$$

2.5. Static Analysis Equation

After using a discretization scheme to model the continuum, we have obtained an expression for the total potential energy in the body as

$$\pi = ½\, Q^T KQ - Q^T F \text{............}(5)$$

Where K is the structural stiffness matrix, F is the global load vector, and Q is the global displacement vector

2.6. Von Mises Stress

Von Mises stress is used as a criterion in determining the onset of failure in ductile materials. The failure criterion states that the Von Mises stress σ_{VM} should be less than the yield stress, σ_Y of the material. In the inequality form, the criterion may be put as

$$\sigma_{VM} \leq \sigma_Y \ldots\ldots\ldots\ldots(6)$$

The Von Mises stress σ_{VM} is given by

Where I_1 and I_2 are the first two invariants of the stress tensor. For the general state of stress I_1 and I_2 are given by

$$I_1 = \sigma_x + \sigma_y + \sigma_z \quad \ldots\ldots\ldots\ldots(7)$$

$$I_2 = \sigma_x \sigma_y + \sigma_y \sigma_x + \sigma_z \sigma_x - \tau^2{}_{yz} - \tau^2{}_{xz} - \tau^2{}_{xy} \quad \ldots\ldots\ldots\ldots\ldots\ldots(8)$$

In terms of the principal stress σ_1, σ_2, and σ_3, the two invariants can be written as

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \quad \ldots\ldots\ldots(9)$$

$$I_2 = \sigma_1 \sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots(10)$$

Von Mises stress can be expressed in the form

$$\tau_{VM} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_{31})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

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3. Results and discussion

The finite element model of the T-joint, created using ANSYS pre-processor is shown in Figure 4, it represents the displacement distribution of the chord and the brace throughout the length of the loading condition. The meshed model of the T-joint, when subjected to axial compressive load, revealed that the portion of the chord directly under the brace is subjected to high stresses. Von Mises equivalent stress is taken to define yield point and hence calculate the stress concentration factor. As expected the displacements are greatest at the intersection of the branch and chord

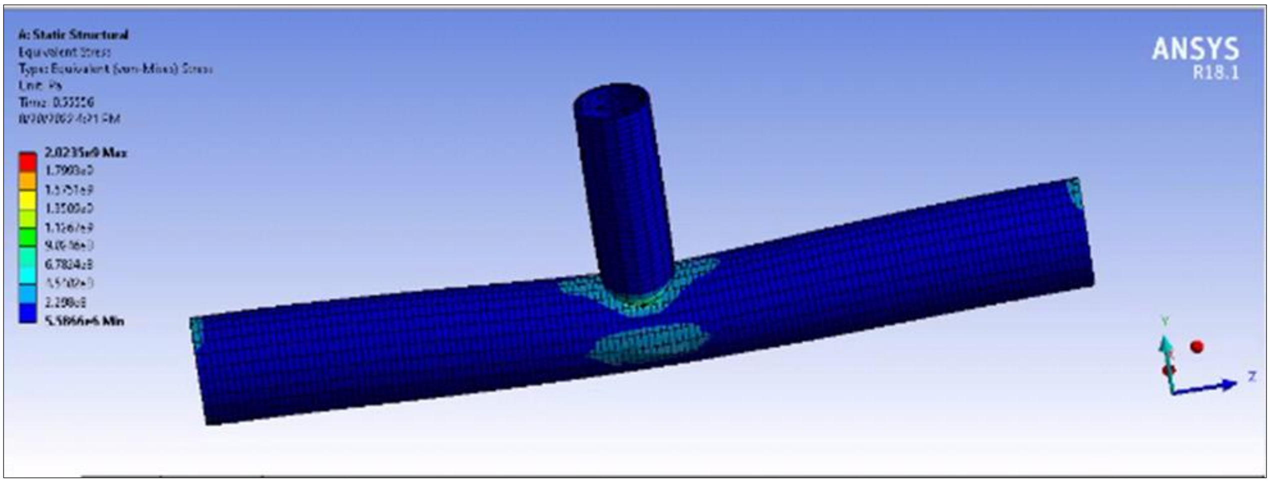

Figure 3 Displacement Distribution of the Cord and Brace

Static load was applied fixed at the other two end the, high displacement was also noticed at the side 45 degrees to the applied load, this was also notice in the experiment, the highest displacement at 90 degree on the position and at the point of intersection between the cord and the brace.

3.1. Comparing the Numerical Investigation Results

The results obtained from both the numerical investigation and the experimental study provide valuable insights into the behavior of the tubular T-joint under axial brace loading. The stress concentration factors (SCFs) at different positions starting from the crown of the joint are compared for the brace and cord regions. The result is presented in figure 4 and 5.

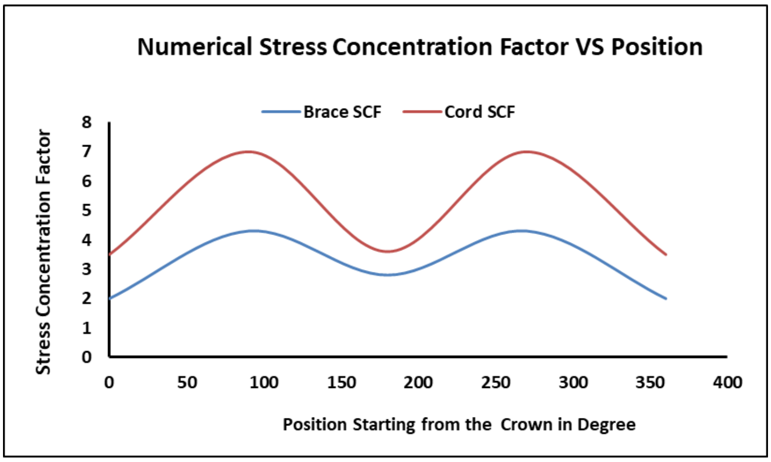

Figure 4 Numerical SCF for Cord and Brace

In the numerical investigation, the SCFs for the brace region range from 2 to 4.3, while for the cord region, they vary from 3.5 to 7. These values indicate that the brace region experiences higher stress concentrations compared to the cord region. This is because the brace have a smaller area and hence, the load is not shared. The maximum SCF is observed at the 90-degree position, where the brace SCF reaches 4.3 and the cord SCF reaches 7.The percentage difference between the Chord and the brace is 38.57 %

3.2. Comparing the Experimental Investigation Results:

In the experimental investigation, the SCFs for the brace region range from 2 to 5.1, while for the cord region, they vary from 4.2 to 9.3. Similar to the numerical results, the brace region shows higher stress concentrations compared to the cord region. The maximum SCF is observed at the 90-degree position, where the brace SCF reaches 5.1, and the cord SCF reaches 9.3, a percentage difference of about 45.16% was observed. This is 6.6 % more than that of the experiment, this could be due to the accuracy of the software and variation in the strain gauge due to temperature.

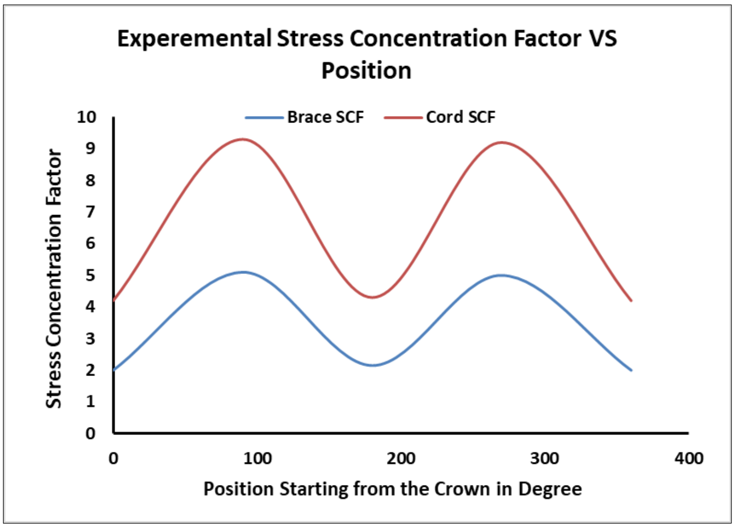

Figure 5 Experimental SCF for Cord and Brace

3.3. Comparing Numerical and Experimental Results for the Brace:

The stress concentration factors (SCFs) for the brace in the tubular T-joint were compared between numerical and experimental methods at different positions from 0 to 360 degrees, measured from the crown. The results show that there are variations between the two methods, with percentage differences ranging from approximately 7% to 29%. These discrepancies could have implications for the structural reliability of offshore structures, as accurate determination of stress concentration factors is crucial for assessing the joint's performance and ensuring its safety under various loading conditions. The differences observed highlight the importance of validating numerical simulations with experimental data to improve the accuracy of design and analysis methodologies for offshore tubular T-joints.

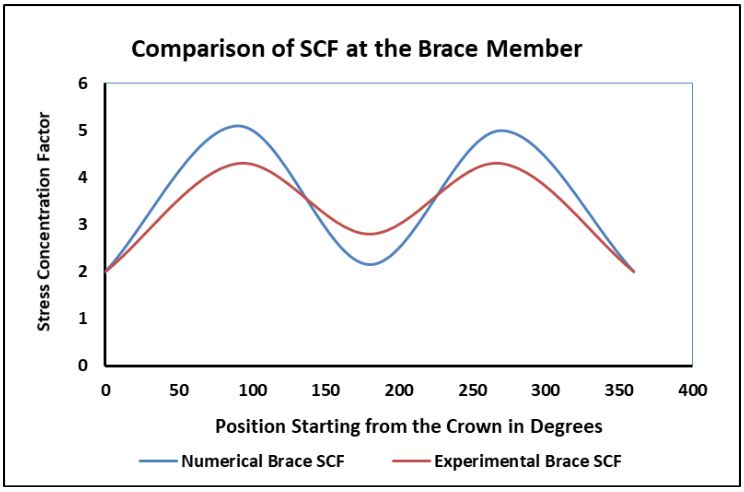

Figure 6 Comparing Numerical and Experimental SCF Brace

3.4. Comparing Numerical and Experimental Results for the Chord:

The stress concentration factors (SCFs) for the chord in the tubular T-joint were compared between numerical and experimental methods at various positions from 0 to 360 degrees, measured from the crown. The results indicate differences between the two methods, with percentage variations ranging from approximately 16% to 26%. These disparities could have significant implications for the structural reliability of offshore structures, as precise determination of stress concentration factors is crucial for evaluating the joint's performance and ensuring its safety under different loading conditions. The observed differences underscore the necessity of validating numerical simulations with experimental data to improve the accuracy of design and analysis methodologies for offshore tubular T-joints.

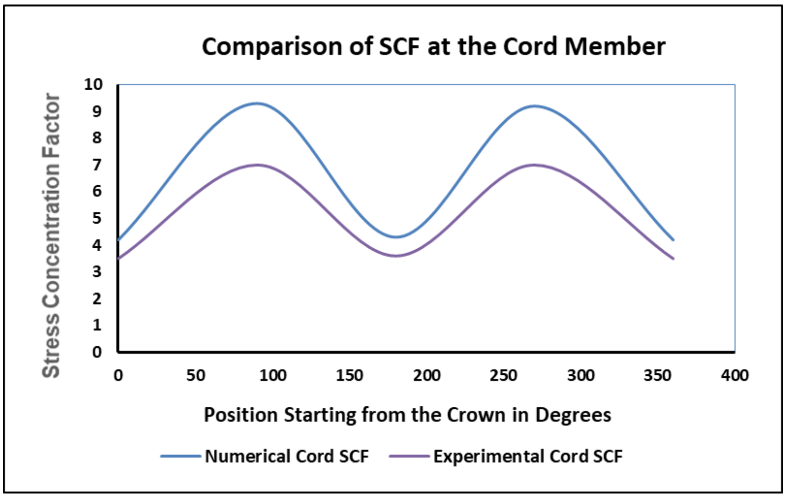

Figure 7 Comparing Numerical and Experimental SCF Chord

In the cord region, the experimental SCFs are consistently higher than the corresponding numerical SCFs. This difference could be due to the experimental specimens exhibiting local imperfections, such as surface roughness, weld defects, or residual stresses, which are difficult to accurately capture in the numerical model.

Despite these discrepancies, the overall agreement between the numerical and experimental results provides confidence in the numerical model's ability to predict the behavior of the tubular T-joint under axial brace loading. The comparison of the SCFs helps identify critical areas of stress concentration, which can be valuable for assessing the structural integrity and designing appropriate mitigation measures, such as reinforcement or local strengthening.

4. Conclusion

In conclusion, this study conducted a comprehensive investigation on the behavior and reliability of tubular T-joints under axial brace loading in offshore engineering applications. Through numerical modeling and experimental analysis, the study provided valuable insights into the stress concentration factors and critical areas of stress distribution in the joints. By examining the hot spot stress at the crown and saddle of the joints the research findings indicate that the brace region of the tubular T-joint experiences higher stress concentrations compared to the cord region. This understanding is valuable for assessing the structural integrity of T-joints and designing appropriate mitigation measures. By identifying critical areas of stress concentration, such as the 90-degree position, engineers can focus on reinforcing or locally strengthening these regions to enhance the joint's performance and durability.

The comparison between the numerical and experimental results provides confidence in the predictive capabilities of the numerical model. Although some discrepancies exist, the overall agreement between the two approaches validates the numerical model's ability to capture the behavior of the tubular T-joint under axial brace loading. This contributes to the understanding of joint performance by providing a reliable tool for analyzing and optimizing T-joint designs.

Furthermore, the research highlights the importance of considering factors such as fabrication imperfections, material behavior, and local imperfections in experimental specimens. These factors can significantly influence the stress concentration levels and must be accounted for in both numerical modeling and practical applications. By acknowledging these discrepancies, engineers can make informed decisions and develop more accurate design guidelines to ensure the structural integrity of tubular T-joints in various load scenarios.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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