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Enhancing Structural Resilience: Exploring the Novel Sleeve Method for Steel T-Stub Connections

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Abstract: A new sleeve device has been introduced with the aim of enhancing the performance of steel structures under extreme loading conditions. Previous research has primarily focused on numerical simulations of this sleeve's application, emphasizing the need for further investigation to validate its effectiveness. This research paper presents a numerical analysis that explores how the sleeve device influences the deformation capacity and strength of a bolt up to the point of failure. The study involved the use of a T-stub connection with multiple sleeves, each featuring different geometric parameters. To assess the impact on strength and deformation capacity, a comparison was drawn between these findings and the behavior of a T-stub bolted connection without using the sleeve. In addition, Finite Element (FE) models were employed for additional parametric studies. The test outcomes demonstrated a substantial increase in the deformability of the bolted connection when utilizing the sleeve device, all the while preserving the strength and initial stiffness of the bolts. This proposed sleeve method in the study significantly enhances the connection's capacity by delaying bolt failure.

Key words: Steel structures, T-stub connection, Steel sleeve, Bolted connection, Ductility.

Yapısal Dayanıklılığın Artırılması: Çelik T-Bağlantılar İçin Yeni Çelik Manşon Yöntemi

Öz: Yeni bir çelik manşon methodu, çelik yapıların aşırı yükleme koşullarında performansını artırmayı amaçlayan bir yöntem olarak tanıtılmıştır. Daha önceki araştırmalar genellikle bu manşon sisteminin uygulanmasıyla ilgili sonlu elemanlar yöntemi odaklı simulasyonlar ile çalışılmış ve etkililiğini doğrulamak için daha fazla araştırmanın gerekliliği vurgulanmıştır. Bu araştırma makalesi, yeni tanıtılan çelik manşon kullanım metodu ile bir civata üzerinde deformasyon kapasitesi ve dayanıklılığın nasıl etkilendiğini amaçlayan nümerik bir analiz sunmaktadır. Çalışma, farklı geometrik parametrelere sahip çelik manşon kullanılan bir T-profil bağlantısının kullanımını içermektedir. Dayanıklılık ve deformasyon kapasitesi üzerindeki etkiyi değerlendirmek için bu bulgular ile çelik manşon kullanılmadan T-profil bir bağlantının davranışı arasında bir karşılaştırma yapılmıştır. Ayrıca, ilave parametrik çalışmalar için Sonlu Eleman modelleri kullanılmıştır. Araştırma sonuçları, çelik manşon kullanımı ile cıvatalı bağlantının deformasyon kapasitesinde belirgin artış gözlemlenmiş ve aynı zamanda civataların kendi dayanıklılığını ve başlangıç sertliğini korudukları görülmüştür. Bu çalışmada önerilen çelik manşon yöntemi, civatalı bağlantıların dayanıklılığını civata hasarını geciktirerek önemli ölçüde artırmaktadır.

Anahtar kelimeler: Çelik yapılar, T-profil bağlantısı, Çelik manşon, Civatalı bağlantı, Süneklik.

1. Introduction

The steel connection between beams and columns plays a critical role in transmitting various forces such as moment, shear force, axial force, and torque in a steel framework. It is crucial to maintain the integrity and flexibility of these connections to safeguard against both disproportionate and gradual structural failure, as emphasized by Khandelwal et al. [1] Connections are also essential for ensuring the stability and safety of steel structures, as highlighted by Kombate et al. [2]. For instance, a significant portion of failures in steel structures can be attributed to problems with connections, while the occurrences of failures in structural members are relatively rare [3]. In the construction of steel assemblies, the use of high-strength bolts in end-plate connections is the favored approach for beam-column joints. This preference stems from their significant ability to withstand deformation. The complexity of bolted connections arises from multiple nonlinear factors, including contact, geometry, and material properties, as well as the presence of numerous components. Consequently, it becomes necessary to employ approximations in the analysis of such connections. One common approximation in the study

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of steel bolted connections involves representing the tension side of the connection as an equivalent T-stub, as specified in the EN 1993-1-8 standard. The behavior of the T-stub model is influenced by various phenomena and factors. T-stubs play a crucial role in these end-plate connections and have a notable impact on the way these connections fail and their flexural performance [4]. Therefore, it is possible to simplify extended end-plate connections by modeling them as T-stubs. A T-stub comprises three key elements: a stem, a flange, and bolts. The stem is welded to the flange, and the T-stub is connected to a structural element using bolts. In this arrangement, the flanges handle bending loads, while the bolts are responsible for bearing the tension loads.

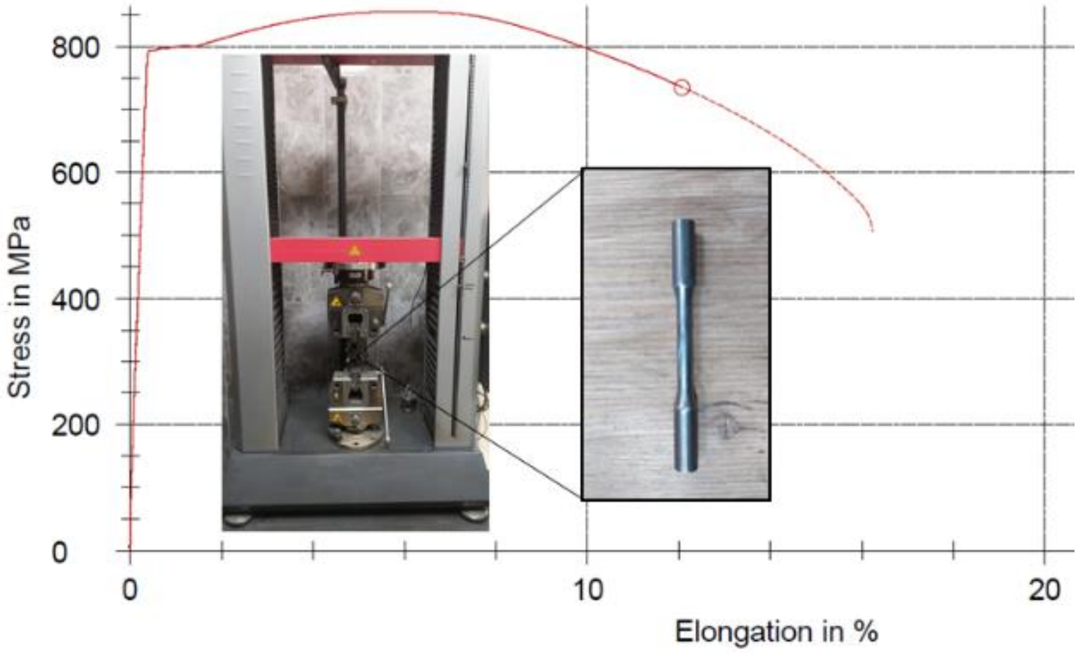
Many researchers have undertaken studies to examine the behavior of T-stub connections. For instance, Piluso and Rizzano [5] conducted experiments on T-stub joints exposed to cyclic loading and devised a theoretical equation that can predict the tensile strength curve when subjected to monotonic loading conditions. Tartaglia et al. conducted a comprehensive investigation, involving both experimental and numerical studies, to evaluate the influence of bolt types and initial imperfections in the presence of significant deformations [6]. In a separate study, Ghazanfar demonstrated that increasing the spacing between the bolt and the stem of a T-stub improves ductility but reduces resistance [7]. [8] Bezerra et al. carried out an experimental study on unstiffened T-stubs to examine the impact of the T-stub flange thickness on the performance of bolts when subjected to monotonic loading conditions. Swanson et al. studied a series of tests and finite element analyses to evaluate various aspects of T-stub connections, including their bearing capacity, initial stiffness, and deformation characteristics [9][10][11]. Swanson et al. [10] proposed a theoretical framework for predicting the rigidity and deformation characteristics of the T-stub model when it reaches a state of failure. Francavilla et al. examined the plastic deformation capability of a single-row bolted T-stub by employing the SAP2000 computer software [12]. Zhang et al. carried out an experiment focused on T-stub connections [13]. This study aimed to investigate their ultimate performance while taking into account the influence of different parameters. Furthermore, a plate-shell theory was used to estimate the tensile capacity and initial stiffness of these connections. Zaharia et al. carried out a full-scale test that included assessments of T-stub connections with single joint configurations [14]. Özkılıç conducted a comprehensive experimental investigation with the objective of analyzing the performance of stiffened T-stubs [15].

Simultaneously with the previously mentioned research on frame systems, there have also been studies focused on the development of different dissipative elements, commonly known as "fuse" elements. The introduction of these elements aimed to enhance the effectiveness of structural fuses and enhance the earthquake resistance of beam-column joints. Moreover, seismic connections often integrate structural "fuse" systems that are specifically designed to display ductile behavior, serving the purpose of dissipating energy and mitigating the destructive effects of earthquakes [16]. These fuse components experience plastic deformation ahead of the primary structural members, effectively containing any damage within the fuses and preserving the integrity of the primary structural elements. Although the idea of incorporating fuses is a common practice in steel beam-column connections, its practical implementation is often constrained [17]. The reason for this limitation is that introducing fuses in connections may require alterations to the columns and beams, which are typically not approved or accepted in standard construction practices [18]. Shaheen et al. have recently introduced a novel method that employs steel sleeves to improve the rotational capacity of end plate connections [19]. This technique is primarily centered on enhancing the effectiveness of bolts, leading to an overall improvement in the performance of the connection. During scenarios involving distinct extreme loading conditions, this system has the capacity to considerably diminish the expenses associated with repairs since any damage would be isolated to the sleeve without impacting the integrity of the steel beam. The innovative sleeve technique has been utilized in various connection situations, encompassing progressive collapse mechanisms [20], connections between end plates and beam columns [21], additionally, connections involving base plate anchor rod attachments [22]. It's important to highlight that the majority of published research in this area has predominantly consisted of numerical analyses, with limited comprehensive experimental testing to substantiate and illustrate the practical viability of the sleeve concept.

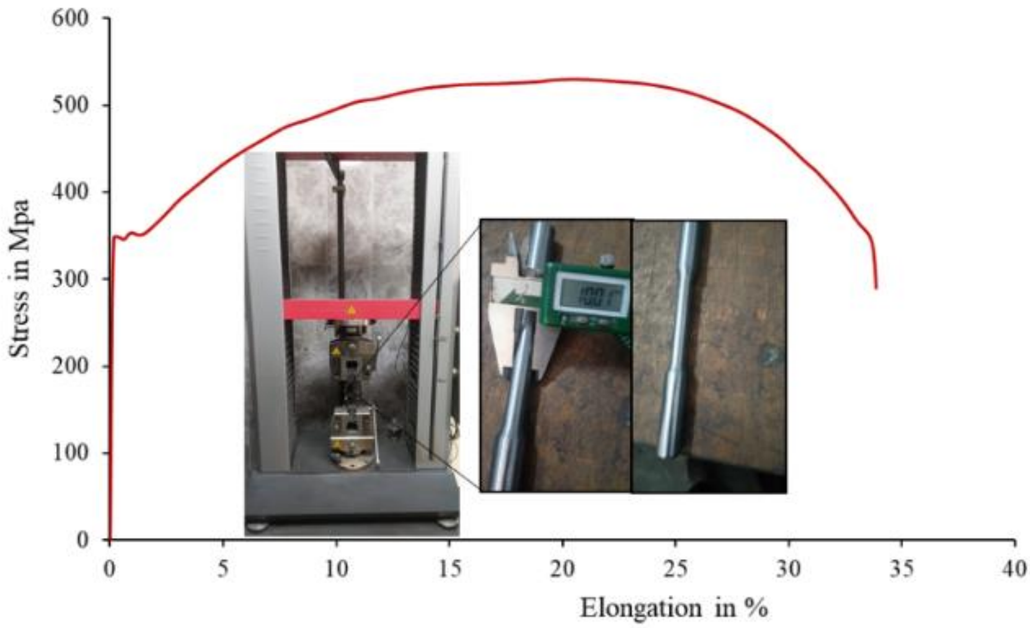
The current study introduces an innovative sleeve system aimed at enhancing the deformation capacity of T-stub connections. In this system, the suggested sleeve element is positioned between the plate and the bolt washer. This unique design enables the sleeves to serve as structural fuses in situations of severe loading, containing any damage within the sleeves and preventing the plastic deformation of other structural elements. After a damaging event, these sleeves can be readily replaced. This inventive sleeve system can also serve as a practical and economically efficient retrofitting solution to improve the performance of pre-existing steel structure connections. The current study is particularly centered on T-stub connections featuring thick plates, where the integrity of bolts is pivotal in determining failure. To assess its behavior, the research utilizes a finite element (FE) model, enabling a comprehensive parametric analysis.

2. System Description and Material Testing

The experimental study employed two different testing setups. In the initial round of experiments, the primary aim was to assess the capacity of bolts under tension. To achieve this goal, a coupon test was conducted to gather data on the material properties of the bolt component, specifically using M20, 8.8 grade bolts for this investigation. In the subsequent series of experiments, the material of the sleeve rod underwent a standard tensile test. The data and material properties obtained were specifically collected for their application in Finite Element Analysis (FEA) study. The standard tensile tests were conducted on two 15 mm diameter specimens made from both sleeve and bolt materials, and the stress-strain curves from these tests are detailed in Figure 1.



(a) Bolt coupon tensile test



(b)Sleeve coupon tensile test

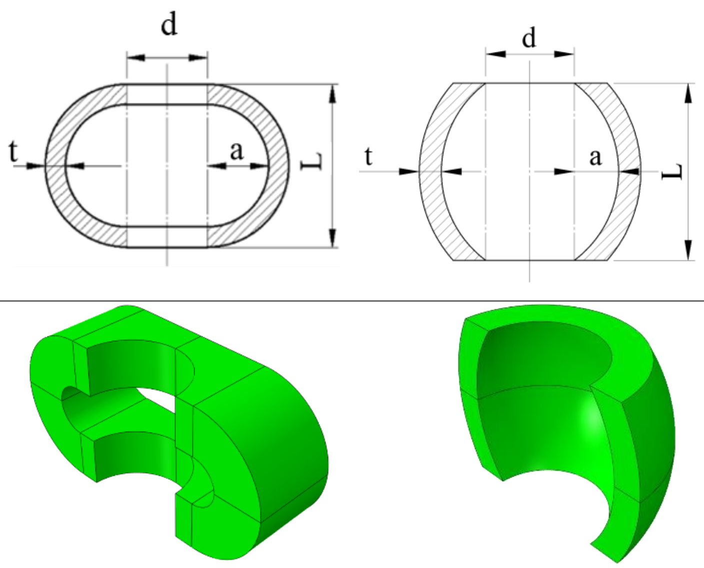
Figure 1. A presentation of the standart tensile test result of bolt and sleeve coupon

It's worth noting that this study involves two different types of sleeves, referred to as circular waveform (CW) and U-shape (US) waveform sleeves. In Table 1, the detail of geometric specifications for the proposed sleeve samples is given, and Figure 2 provides a comprehensive overview of the sleeved models. The specimen labels provide valuable information about the unique features of each individual sample. The parameters describing the geometric features of the sleeve can be ascertained through the formulas outlined by Shaheen et al. [21]. To enhance the ductility of the connection, it is crucial for bending deformation to occur in the sleeve before any connection components fail. This goal can be achieved by ensuring that the sleeve's capacity is lower than the force in the bolt at the point of failure [21]. Consequently, the initial design of the connection should follow conventional methods for calculating the bolt force at failure. Subsequently, the dimensions of the sleeve are determined based on this calculated bolt force. For example, if bolt necking is identified as the predominant failure mode, the sleeve must be designed with an ultimate capacity lower than that of the bolt, allowing the sleeve to undergo plastic deformation before the bolt fails.

The wave form of sleeve – L x t x a
CW: Circular waveform – The sleeve length x The sleeve thickness x The amplitude value
US: U – shape waveform – The sleeve length x The sleeve thickness x The amplitude value

Figure 2. Specimen identification

Table 1. Geometric characteristic of tested specimens



U-shape waveform **Circular waveform**

Specimen	a (mm)	L (mm)	d (mm)	t (mm)	Bolt grade
CW-30x5x5	5	30	21	5	8.8
CW-30x5x7	7	30	21	5	8.8
CW-30x6x8	8	30	21	6	8.8
CW-30x6x10	10	30	21	6	8.8
US-28x9x5	5	28	21	9	8.8
US-30x10x5	5	30	21	10	8.8
US-30x9x6	6	30	21	9	8.8
US-32x10x6	6	32	21	10	8.8
US-34x11x6	6	34	21	11	8.8

The proposed and sleeve system designed for the T-stub connection is illustrated in Figure 4. This sleeve is positioned between the T-stub and the bolt's washer and can be characterized by its geometric attributes, such as its length, thickness, and the curvature of its walls. The sleeve takes on a shape resembling a barrel, engineered to withstand applied loads by distributing stress through a combination of membrane and bending forces. To prevent immediate buckling of the sleeve's walls and promote bending failure, the walls are intentionally curved. The extent and shape of this curvature are determined by the amplitude and waveform of the sleeve. While theoretically, any waveform configuration could be applied to the sleeve design, the ideal waveform should offer the best structural performance at the lowest manufacturing cost.

The material chosen for the fixed base and T-stub plate matches the S355 steel grade used for the sleeve material. Given that the objective of the study is to investigate bolt failure and evaluate the impact of the proposed sleeve method, a T-stub with a thick plate and a fixed base stub, as described in Liu et al. [23], has been selected. Figures 3 and 4 provide three-dimensional representations of the modeled T-stub and present essential geometric properties of the connection assembly.

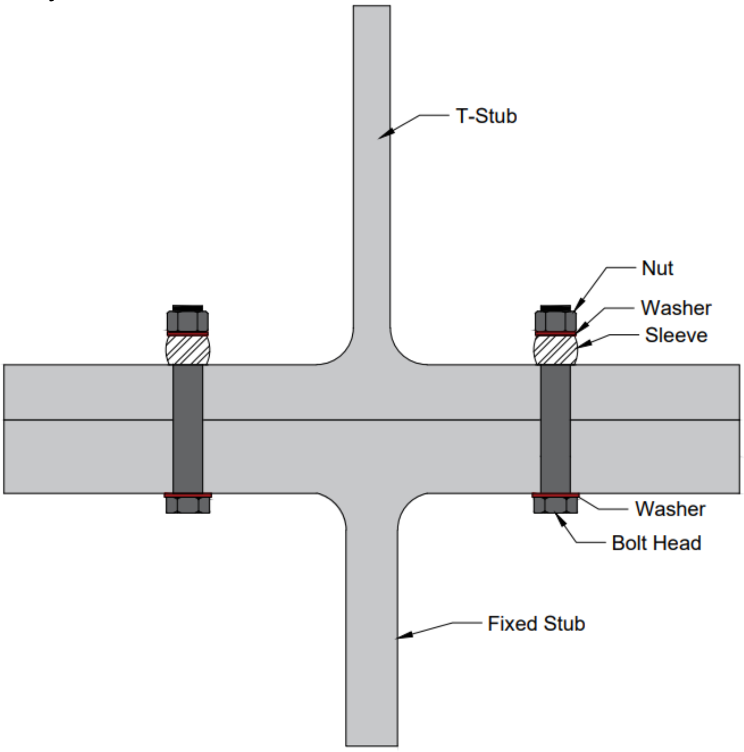


Figure 3. T-stub,bolt and sleeve assembly

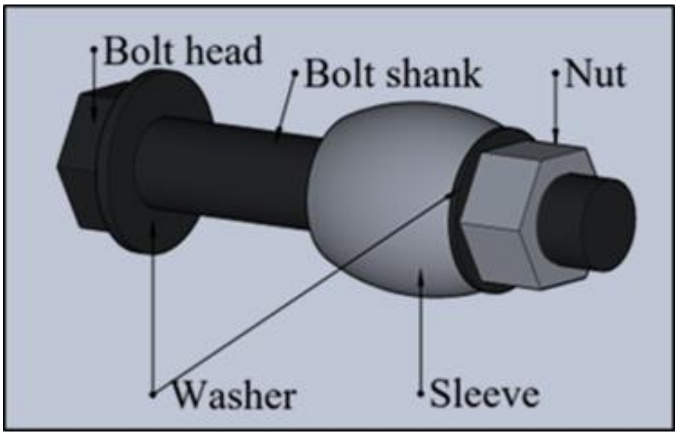


Figure 4. A presentation of the proposed bolt and sleeve assembly

3. Numerical Model Development

A 3D finite element analysis (FEA) model of the T-stub connection was generated using ABAQUS/CAE, as depicted in Figure 6. Initially, the bolt model was created in finite element modeling, and the results of the bolt exposed to tension force were compared to the experimental coupon test of the bolt material. The results detailed in Figure 5 demonstrate a close match between the results. After that, the FEA model was designed to represent one-quarter of the T-stub connection, taking advantage of the symmetry in both the specimen's shape and boundary conditions (see Figure 6). Symmetrical boundary conditions were applied at the central point of the model. The T-stub model was subjected to displacement until the bolt element failed, while restricting movement of the base stub in all directions. Solid elements (C3D8R) were used to discretize all components of the system. The Abaqus implicit solver was employed to analyze a nonlinear model that considered both geometric and material nonlinearity. Additionaly, parts prone to experiencing high stress concentrations, such as sleeves, were allocated a fine mesh of 2 mm, while parts located away from critical zones, like the bolts, T-stem and flange (5 mm), were assigned a coarse mesh. A mesh convergence study was performed to determine the suitable mesh size.

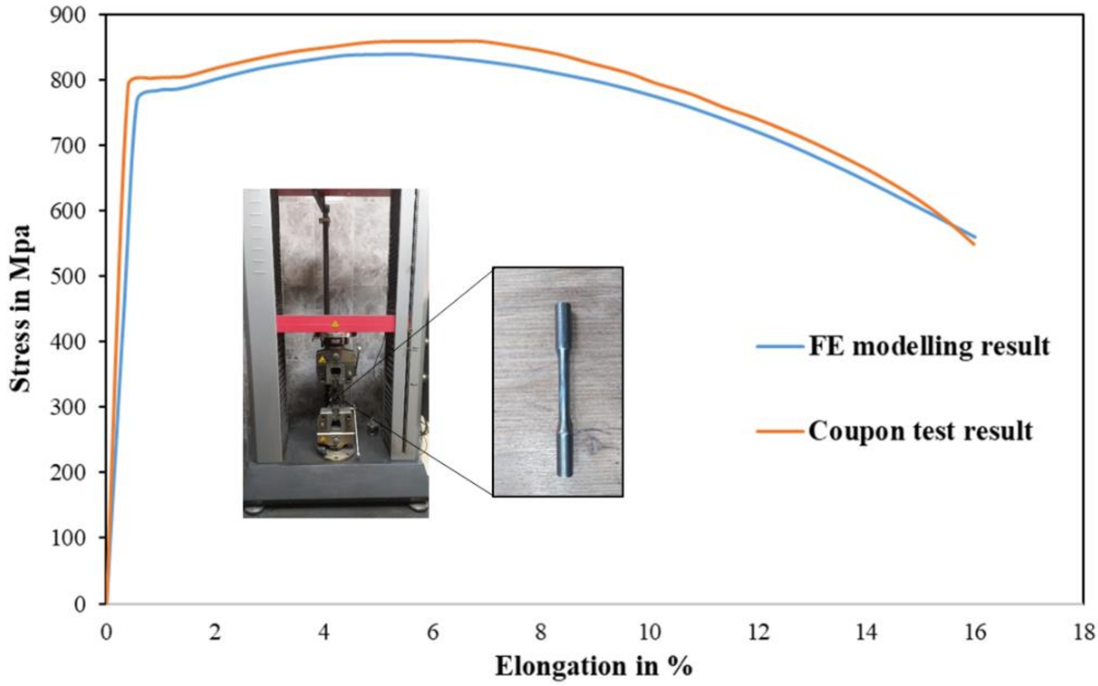
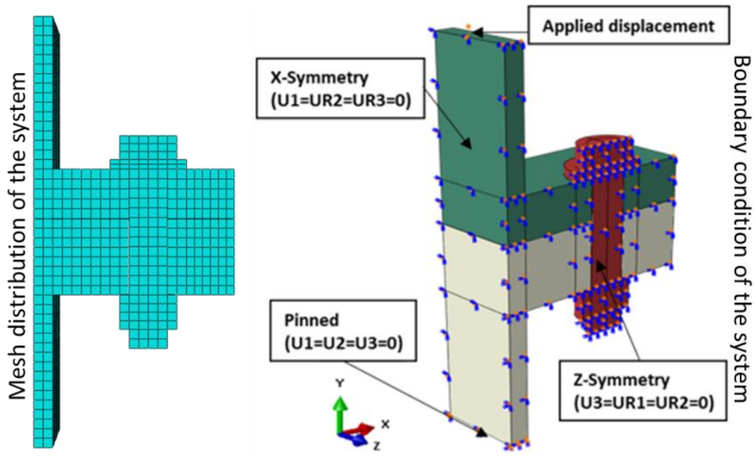
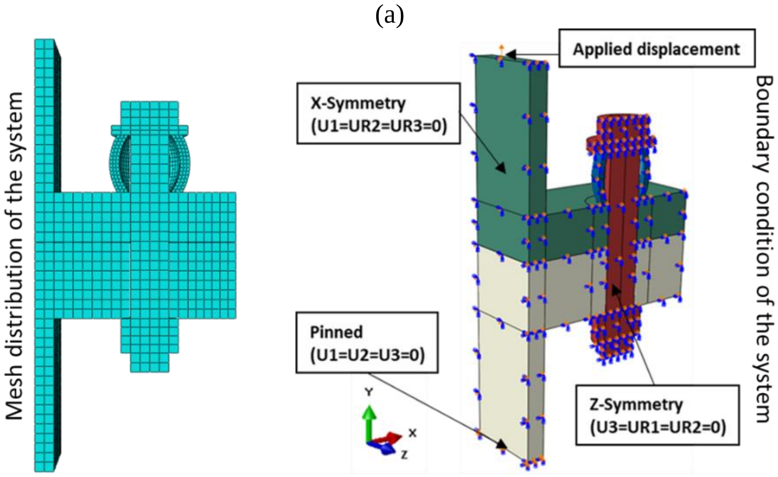


Figure 5. FE model and and coupon test results comparison

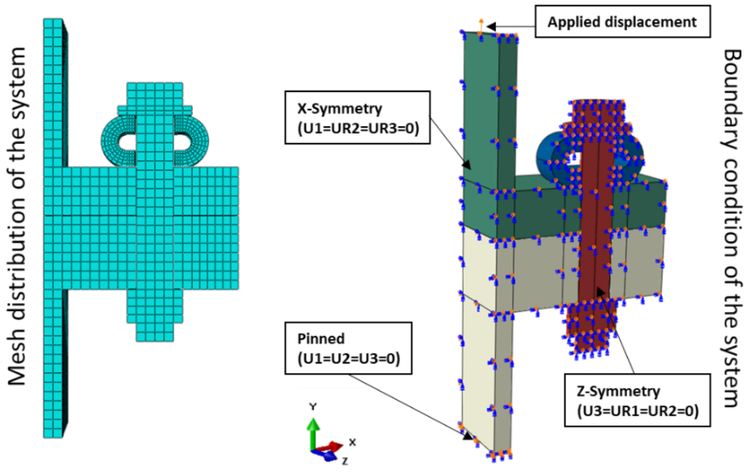
A surface-to-surface interaction was applied for all the necessary components in the model, employing a friction coefficient of 0.2 [24]. More specifically, the connections between the bolt and nut, as well as between the nut and washer, as monolithic surfaces, ensuring that they remained intact throughout the analysis. Similarly, since there were no instances of crack deformations in the welds during testing, the junction between the T-stub and the plate was likewise considered as a continuous connection. The material's mechanical response was described using a bilinear von Mises yield criterion with isotropic hardening. In addition, the ABAQUS/Standard incorporated ductile damage models to address material damage and fracture specifically in the bolts. However, T-stub and fixed-stub were excluded from the material damage criteria, as they showed no signs of damage in the conducted tests.



(a)



(b)



(c)

Figure 6. FE model and boundary condition of the T-stub connection (a) without sleeve (b) with CW sleeve and (c) with U-shape sleeve

4. Results and Discussion

This section examines the performance of T-stub connections, comparing those with and without the suggested sleeve system. Table 1 offers comprehensive information regarding the dimensions and characteristics of these sleeves. As mentioned earlier, two types of sleeves were introduced to improve the connection's ability to bear loads. Figure 7 displays the force-displacement behavior of the standard T-stub connection, highlighting different stages of bolt failure. It's apparent that the bolt fails entirely at around 25 mm of displacement. The primary objective in the design of both the T-stub and base stub was to prevent any occurrence of plastic deformation, with a primary emphasis on monitoring potential damage to the bolt. Figure 8 and 9 provides a visual representation of the force-displacement characteristics of T-stub connections when subjected to tensile loading, offering a comparison between the CW-sleeved and conventional configurations. It is noteworthy that a substantial enhancement in load-bearing capacity is apparent for both the CW-sleeved systems with 5 mm and 7 mm amplitudes with thickness of 5 mm. The initial rigidity of the proposed sleeve system closely aligns with that of the standard configuration across all amplitude values. The capacity for displacement is notably influenced by the selected amplitude, where the utilization of 5 mm amplitudes results in an approximate 40% increase in the displacement ratio when compared to the standard connection. In the instance of the CW-30x5x7 sleeved configuration, it is observed that the sleeves experience complete deformation before the bolt itself fails, typically occurring at a displacement of approximately 33 mm which increase the deformation capacity more than 100%. This observation indicates that the plastic amplitude (PA), which signifies that the sleeve has reached its maximum load-bearing capacity, has been observed, and the initiation of bolt failure has commenced. Further investigations were conducted with a sleeve thickness of 6 mm, where none of the configurations experienced a complete crush of the sleeve, as depicted in Figure 9. The results suggest that the optimum sleeve thickness for the proposed T-stub tests may be 5 mm for CW sleeve type.

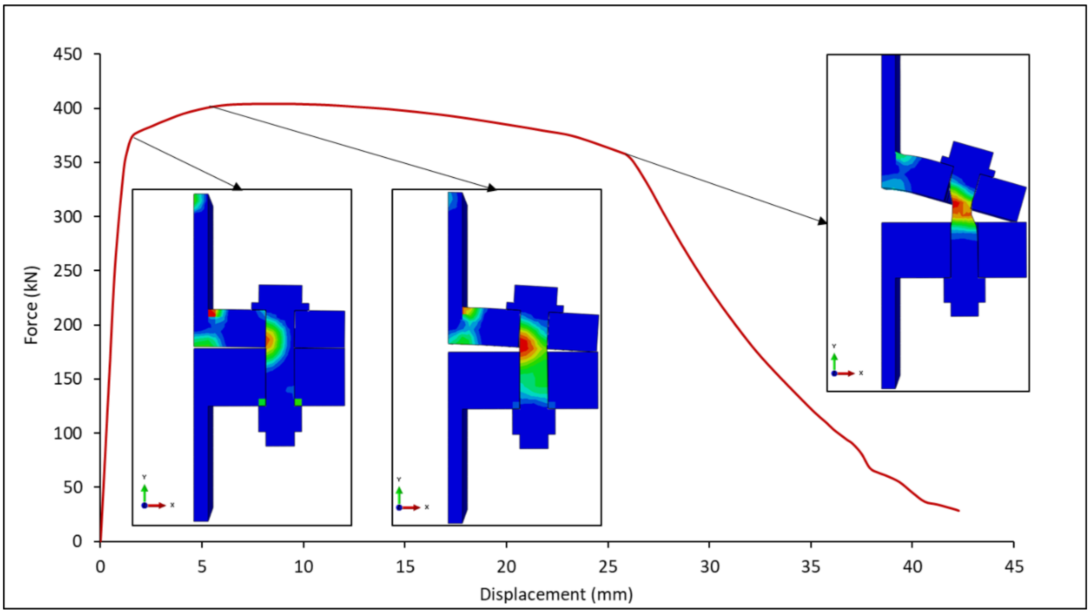


Figure 7. Force-displacement response of the standart T-stub connection and failure of the bolt

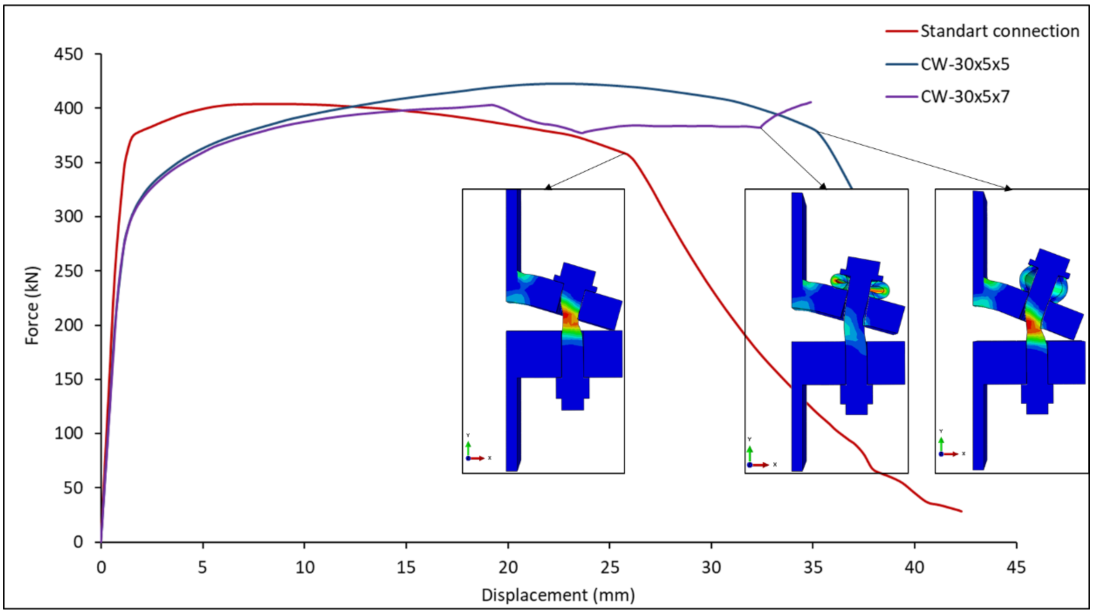


Figure 8. Force-Displacement response of the base plate with circular waveform sleeves of length 30 mm and various amplitudes.

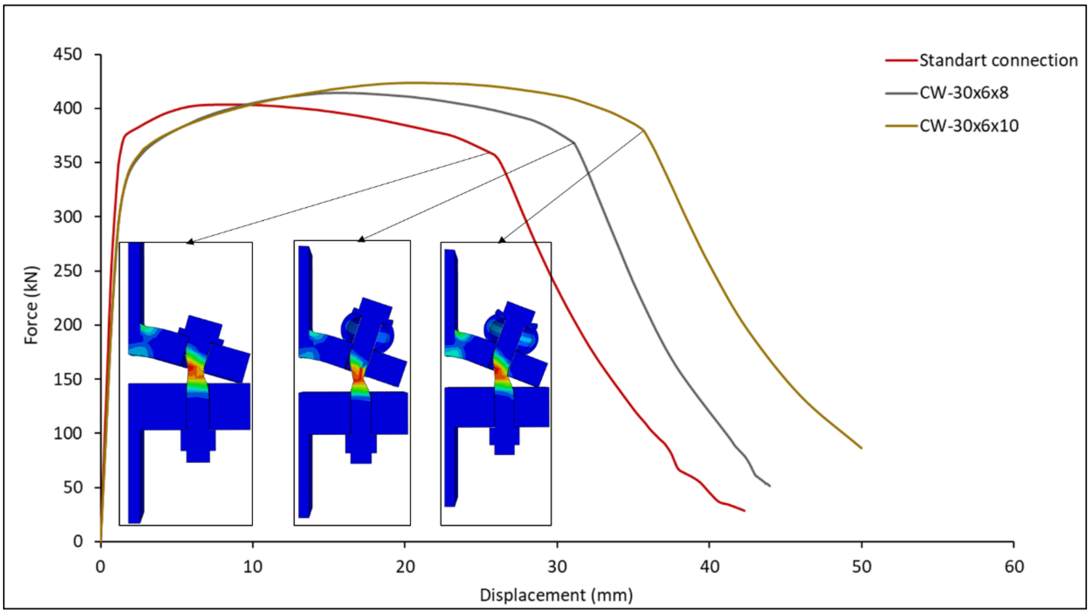


Figure 9. Force-Displacement response of the base plate with circular waveform sleeves of length 30 mm, thickness 6 mm and various amplitudes.

A further comparative analysis was conducted to evaluate the performance of load-bearing capacity between the US-sleeved and standard configurations when subjected to tensile loading (as depicted in Figure 10 and 11). Although the initial rigidity of the proposed sleeve system is not entirely similar with that of the standard configuration for various thickness values, a substantial enhancement in displacement capacity of approximately 80% is observed. In the case of utilizing sleeve configurations with thicknesses of 9 mm, 10 mm and 11 mm, all featuring a 6 mm amplitude, it is noteworthy that the enhancement in displacement capacity follows a similar pattern. However, it is important to note that only the US-30x9x6 sleeve model attains its maximum capacity prior to any plastic deformation occurring in the bolt. This occurrence signifies the observation of the plastic amplitude (PA) and the subsequent initiation of bolt failure, which begins after the sleeve experiences complete deformation. Conversely, the US-30x10x6 and US-30x11x6 sleeve configurations witness bolt failure before the sleeve reaches a state of complete deformation, suggesting that the sleeve's total load-bearing capacity was not fully achieved. In addition, the US-28x9x5 sleeved bolted model increased the deformation capacity almost 80% compared to the standart connection. However, it should also be noted that the US-28x9x5 and US-30x10x5 sleeve configurations were analyzed, and the PA observation was not observed, as premature failure of the bolt occurred before the complete crushing of the sleeve models. This phenomenon suggests that the optimum sleeve design should be more specifically investigated.

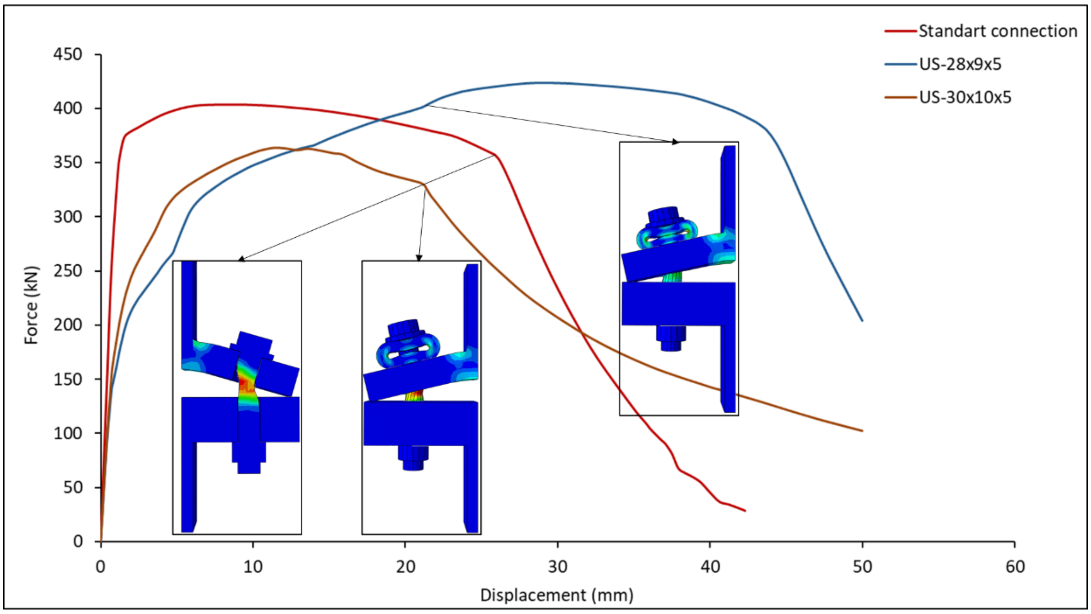


Figure 10. Force-Displacement response of the base plate with u-shape waveform sleeves of 5 mm amplitude and various thicknesses.

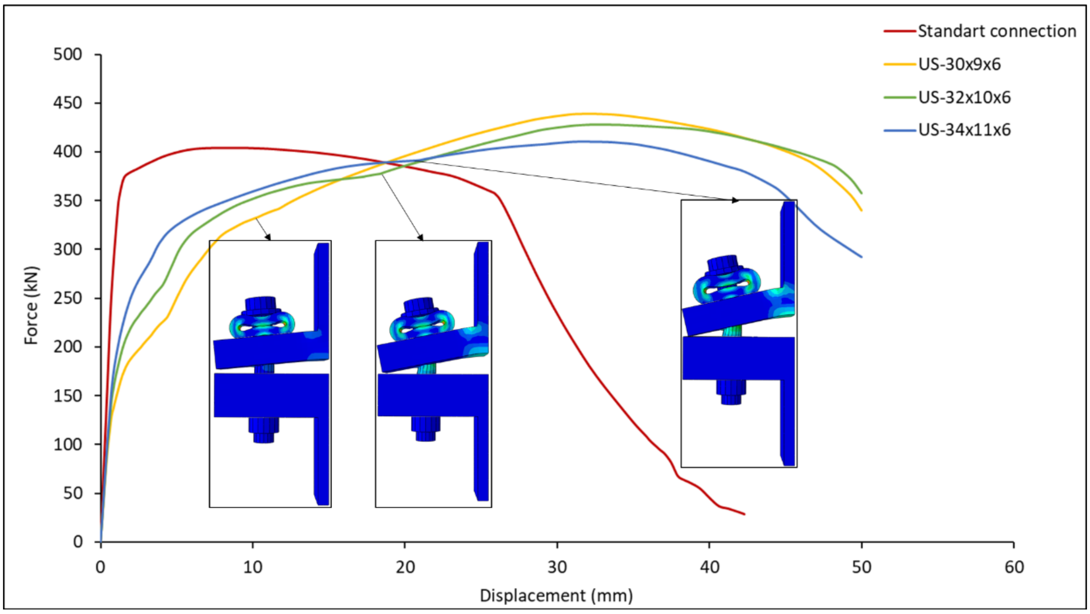


Figure 11. Force-Displacement response of the base plate with u-shape waveform sleeves of 6 mm amplitude and various thicknesses.

5. Conclusion

The primary aim of this research is to assess the performance of a recently developed sleeve system specifically designed for steel T-stub connections subjected to tensile loading conditions. The study encompasses both modeling and a comprehensive parametric analysis, involving two distinct sleeve geometries: circular (CW) and U-shaped (US) waveforms. The investigation explores a range of geometric parameters, encompassing aspects such as length, thickness, and amplitude. The objective of the study was to compare the findings with those obtained from a standard connection, with a focus on evaluating the displacement capacity of the proposed system. The research results suggest that the proposed system effectively improves the load-bearing capacity of T-stub connections in comparison to the standard connection. To summarize, the study's ultimate conclusion is that the proposed sleeve system is effective for both circular (CW) and U-shaped (US) geometries, leading to enhanced connection performance. The research presented in this paper yields the following key conclusions:

- The effectiveness of an innovative sleeve system, featuring various geometries, has been substantiated through numerical parametric investigations applied to a practical case study.
- For connections utilizing circular waveform sleeves, a significant resemblance in linear elastic behavior to that of standard connections was observed. Furthermore, connections with these sleeves demonstrated an enhanced displacement capacity with increasing amplitude. Notably, it was found that at a specific amplitude value, sleeve deformation could happen before the failure of the bolt.
- In the comparison of US waveform sleeves to the standard connection, a distinct difference was evident in their elastic behavior. Initial stiffness degradation, particularly on the negative side, was notable. Nevertheless, with an increase in amplitude, a substantial enhancement in displacement capacity became apparent.
- By adjusting the parameters of the sleeves, it is possible to attain varying ductile responses without the necessity of modifying the connection's strength or configuration. The proposed system provides a straightforward and cost-effective method to improve the resilience of current structures when subjected to a range of loads.

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