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SLEEVE FUSE SYSTEM FOR IMPROVED STEEL CONNECTION PERFORMANCE

Muhammed ATAR¹

¹ *Fırat University, Department of Civil Engineering, Elazığ, Türkiye, matar@firat.edu.tr*

ABSTRACT

This study introduces an approach to improving the connection performance of steel structures by utilizing a sleeve fuse mechanism. The system introduced suggest a steel sleeve which is positioned between the end plate and the nut to modify the load path for improving the system's ductility. To validate the proposed method, experimental models from existing studies were employed, ensuring that the numerical simulations provided accurate results. A range of sleeve designs were analysed utilising a numerical FE model, confirming the system's efficacy in improving connection behaviour. The sleeve system showed notably better performance than conventional end-plate connections. The results indicate that the system increases the connection's rotational capacity by 85%, functioning as a structural fuse under monotonic loading and enhancing both ductility and energy absorption by 90%. Additionally, the increased elongation of the bolts further contributes to the rotational capacity, providing greater stability to the frame structure. Overall, this sleeve-based system offers a promising advancement over conventional designs by boosting energy absorption and ductility, making it a robust alternative for improving connection performance.

Keywords: Monotonic loading, Steel structures, Bolted connections, Fuse system, Ductility.

1 INTRODUCTION

The behaviour of steel structures under destructive loading conditions, such as blasts and earthquakes, has attracted increasing popularity in recent decades [1], [2], [3], [4]. Previous research has emphasized the importance of connection layouts and related parameters in enhancing structural performance during extreme loads and in mitigating progressive collapse. Since the connection area is the most critical zone for energy dissipation, it is essential that the

connection can withstand high strain energy without failing. For instance, the General Services Administration (GSA) [5] specifies 0.2 radians (approximately 11 degrees) of rotational capacity to allow beams to engage in catenary action, which helps prevent progressive collapse during extreme loading events. Because of the restricted ductility of connection components, earlier research has mainly aimed to redirect inelastic deformation away from the connection area.

Seismic connections often incorporate energy-dissipating elements, known as 'fuses,' which rely on ductile behaviour to reduce the destructive effects of earthquakes. These fuses undergo plastic deformation prior to the main structural elements, limiting damage to the fuse and maintaining the stability of the primary structure. In the replaceable fuse type, energy dissipation occurs by confining damage to the fuse elements. These elements may be removed after catastrophe. However, incorporating fuses requires additional fabrication and extends installation time, as they are used alongside existing connections [6]. In a self-centering connection, the top and seat angles elements are used to absorb more energy by experiencing plastic deformation [7]. Moreover, incorporating shape memory alloy (SMA) angles can help avoid the need to replace steel angles after a major earthquake [8]. However, the higher cost of SMA compared to conventional steel materials restricts its widespread application in construction. Other method for dissipating earthquake energy is to ensure the failure mechanism is located in specific position in beam section where the connection area is not effected. This can be done by either reinforcing the connection to prevent plastic deformation in its components [9], or by reducing the beam's strength, such as through flange cuts (RBS) [10] or modifications to the beam web (RWS) [11]. As a result, the beam undergoes substantial inelastic deformation and will need to be substituted after a major seismic event.

The typical approaches to improving ductility focus on modifying the rigidity of the beam or the end plate. However, in certain connection configurations, the deformation capacity of the joint zone can also be influenced by the bolts, which may undergo significant elongation [12], [13]. In Eurocode-based design (EN 1993-1-8), end plate connections are commonly assessed using a T-stub representation [14], where the bolts define the boundary conditions, whereas AISC 358 specifies end plate thickness based on yield line theory derived from plastic mechanism analysis. As the bolts elongate more, the rotational capacity that can be achieved increases [15]. Bolts often employed in structural applications are typically constructed from steel with high tensile strength, such as 8.8 and 10.9 grades [16], which reach their peak strength at around 0.05 strain and then fracture suddenly [17]. In comparison, mild steel can endure strains up to 0.2 before failure occurs [5]. The bolt's short length typically has a minimal impact

on the rotational capacity through elongation, especially when compared to the influence of the end plate. In the earthquake-resistant design of steel frames, the design is often controlled more by drift limitations specified in codes than by strength limitations. Member sizes chosen to meet drift requirements are generally larger than those necessary to fulfill strength requirements. In such scenarios, the RBS and RWS approaches are effective, given the beam is intentionally over-designed. In such cases, it is essential to thoroughly evaluate the beam's bending strength to ensure that removing steel elements does not substantially reduce its capacity. Additionally, cuts in the steel plates can form crack tips, potentially leading to failure as a result of fatigue crack propagation [15]. Flange cuts made in the RBS method may reduce the beam's stability, increasing the risk of it twisting or buckling under load. On the other hand, the sleeve method helps retain the strength of the steel component, offering greater flexibility and applicability to different frame design needs.

A diagram illustrating the proposed system is shown in Figure 1, where a steel sleeve, characterized by its length, wall curvature, and thickness, is positioned between the bolt nut and the end plate. The sleeve functions as a curved shell, where the applied load is resisted by both membrane forces and bending stresses [18]. The wall of the sleeve is curved to encourage bending failure instead of sudden buckling. The curvature determined by an amplitude at the middle of sleeve. Several studies have examined methods to enhance the performance of steel end-plate beam–column connections. Shaheen et al. [19] introduced a device to improve the robustness of end-plate connections, while Shaheen [23] proposed modifications aimed at enhancing cyclic behaviour. Shaheen et al. [24] conducted experimental tests on a bolt sleeve device, demonstrating increased ductility in end-plate connections, and Shaheen et al. [25] presented a numerical investigation that validated the benefits of sleeve systems in improving connection ductility. Atar and Çete [26] explored the sleeve method for steel T-stub connections, highlighting its potential to enhance structural resilience. More recently, Atar [27] compared sleeve fuse systems with the reduced beam section (RBS) method, showing that sleeves can effectively concentrate plastic deformation within replaceable components.

In contrast to previous studies, this work focuses on the monotonic behaviour of bolted end-plate connections with a replaceable sleeve fuse. Combining experimental validation with FE modelling, it examines the effect of sleeve design on rotational capacity, bolt elongation, and overall connection performance. The results demonstrate that sleeve devices act as structural fuses, enhancing ductility and energy absorption while maintaining frame stability. Moreover, the sleeve's length and diameter can be adjusted to achieve different rotational capacities without altering connection strength or design.

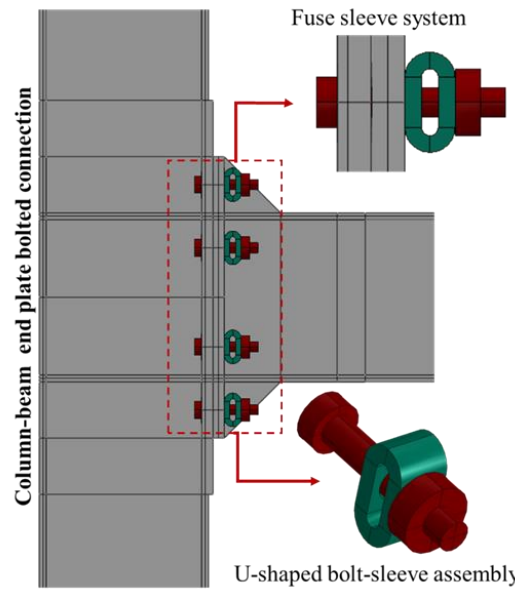


Figure 1. Fuse connection system with sleeve

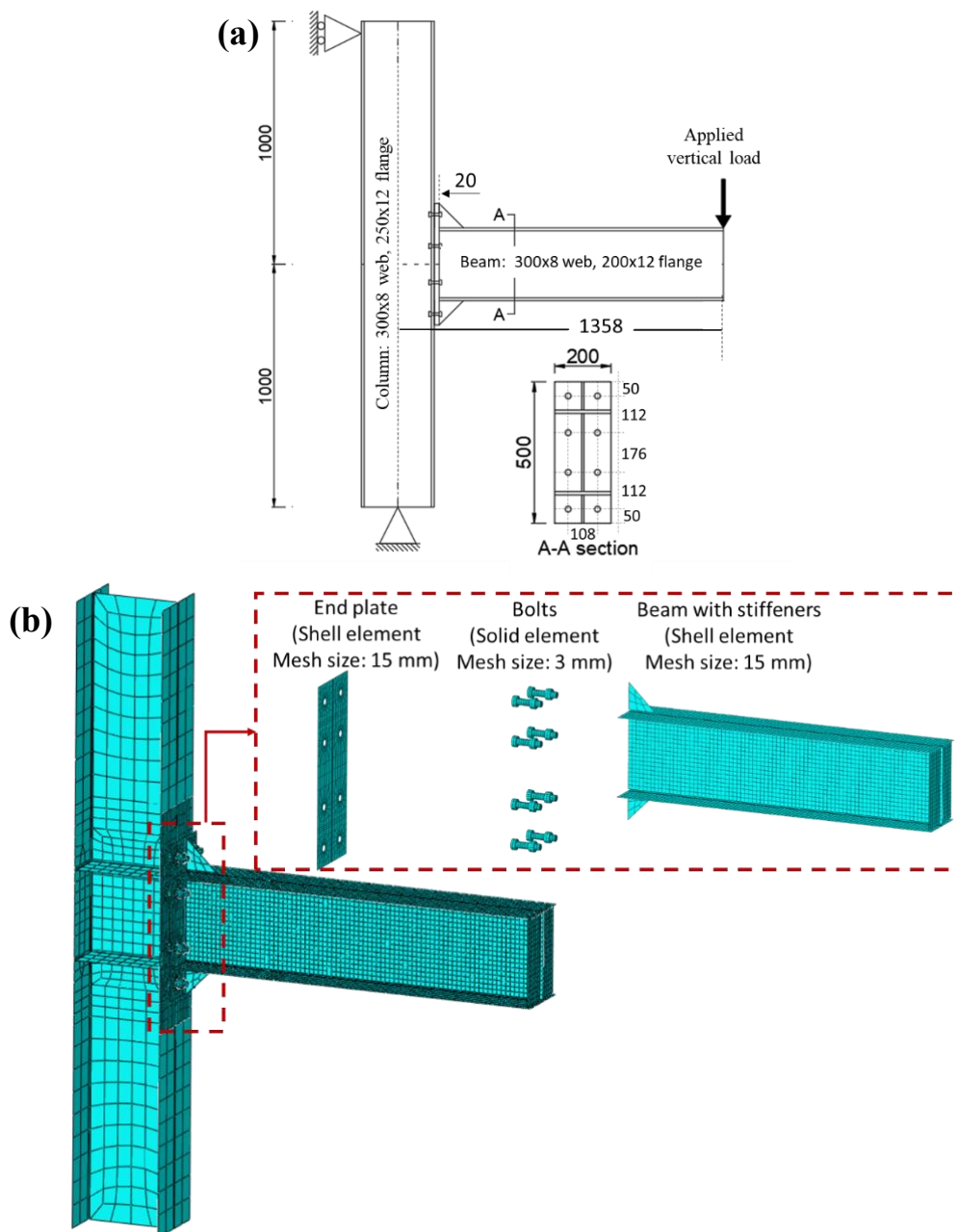
This study primarily focuses on evaluating the global performance of the sleeved end-plate connection system, with emphasis on its rotational capacity and energy dissipation. Within this framework, the influence of the sleeve mechanism on the ductility of the end plate region is also examined, while ensuring that the initial stiffness and strength of the connection are preserved. A previously validated experimental model [20] was used for precise FE analysis, which were performed to assess the behaviour of the sleeved connection. The results of the sleeved connection were then compared with those of the standard (no-sleeve) connection to demonstrate the effectiveness of the proposed method in improving load-bearing and deformation capacity.

2 MODEL DESCRIPTION

This research evaluates the behaviour of the proposed sleeved end-plate connection in comparison to the conventional (no-sleeve) beam-to-column connections in moment-resisting frames (MRFs). For validation and parametric analysis, the experimental test conducted by Shi et al. [20] was adopted, specifically specimen EPC-1, which had an end-plate thickness of 20 mm and bolt diameter of 20 mm. The connection properties are illustrated in Figure 2. The boundary conditions and applied load scenario follow those of the original experiment. Monotonic loading was applied at the end of the beam, and the material properties of all connection components are provided in Table 1 [20].

Table 1. Material characteristics used in the numerical analysis [20].

	Steel (thickness ≤ 16.0 mm)	Steel (thickness > 16.0 mm)	Bolts	Sleeve
Young's modulus (MPa)	195452	188671	210000	210000
Yield strength (MPa)	409	373	995	355
Ultimate tensile strength (MPa)	537	537	1160	510

**Figure 2. (a) Geometrical specifications of the test specimen as outlined by [20], (b) Mesh resolution.**

3 FE MODEL VALIDATION

A numerical FE model was used to replicate real structural connections. ABAQUS/Standard was utilised for the simulation and parametric analysis, with simplifications made to reduce computational time without sacrificing accuracy.

The extended end-plate connection (Figure 2) was modelled using S4R shell elements for the beam, column, and end plate to efficiently capture bending and membrane behaviour with fewer degrees of freedom, while the bolts, and nuts were represented by C3D8R solid elements to accurately simulate three-dimensional stress states, contact, and potential local plasticity. This approach balances computational efficiency with modeling accuracy. A refined mesh captured high-stress zones [23], and surface interactions were defined using a small-sliding formulation. A surface-to-surface contact with friction coefficients of 0.44 and 0.2 were applied for the endplate-column flange and bolt-plate interfaces, respectively. The material behaviour was modeled using a bilinear stress–strain curve based on [21], with elastic–plastic behaviour and isotropic hardening. The von Mises yield criterion was employed, and ultimate strain values were taken from [20].

Figure 3 presents the comparison between experimental and FE results: (a) illustrates the deformation of the connection components, and (b) shows the moment–rotation response. The FE models closely match the experimental results reported by Shi et al. [20], capturing both the initial stiffness and post-elastic behaviour, although a slight overestimation occurs in the inelastic range due to idealized boundary conditions and material simplifications. Bolt rupture was observed as the primary mode of failure in the experiments [20]. In the FE analyses, the model is terminated when the bolt reaches a PEEQ value of 0.075, indicating the onset of fracture. At this stage, the column web and stiffeners exhibit some plastic deformation, but the main and critical deformation occurs in the bolts, as shown in Figure 3(a).

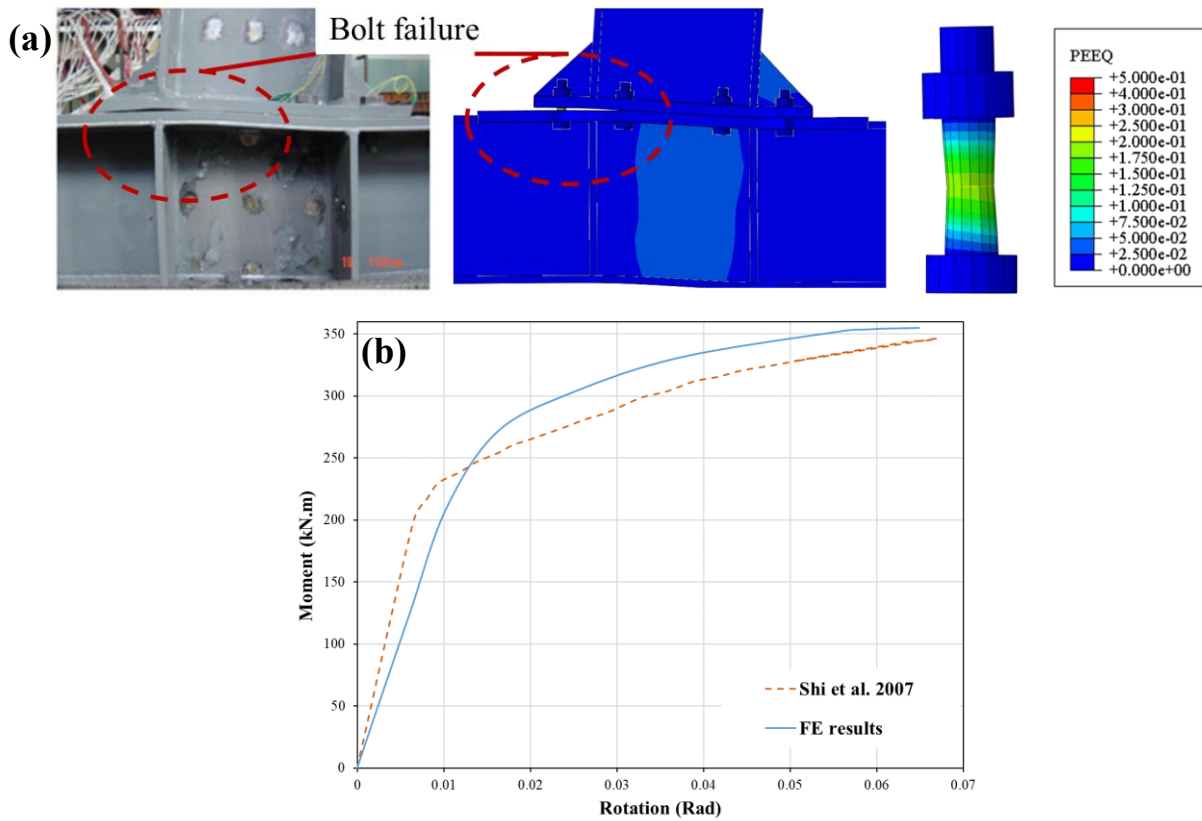


Figure 3. Validation results of the experimental connection model: (a) comparison of experimental and FE deformation, (b) comparison of moment-rotation response.

4 PROPOSED SLEEVE SYSTEM DESCRIPTION

This research aims to improve the behaviour of connection frameworks by enhancing the ductile capacity of the end plate, while maintaining their initial stiffness and strength [23]–[25]. The sleeve fuse is characterized by three key parameters: length (L), thickness (t), and amplitude (a) (see Figure 4). In this analysis, only one type of sleeve—the U-shaped wave (US)—is considered. The sleeve identification follows the format US–sleeve length (L) $\times$ amplitude (a) $\times$ thickness (t).

For improved ductility, it is essential that the sleeve deforms before any other component of the connection fails. Therefore, the maximum load-bearing capacity of the sleeve should be lower than that of the bolt. The sleeve's behaviour is influenced by its amplitude: a small amplitude limits deformation, causing the bolt to fail before the sleeve; a moderate amplitude allows some plastic deformation prior to bolt failure; and a large amplitude, referred to as PA (plastic amplitude), enables significant deformation, allowing the sleeve to yield before the bolt fails. The sleeve thus acts as a structural fuse, absorbing localized damage and protecting other connection components.

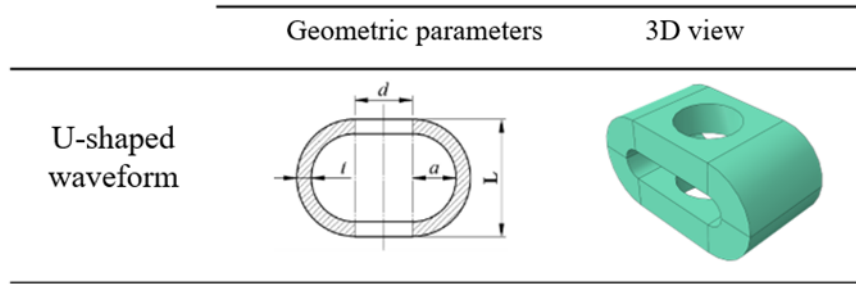


Figure 4. Sleeve geometry and identification considered in this study

5 RESPONSE OF THE U-SHAPED (US) SLEEVE SYSTEM TO MONOTONIC LOADING

The verified numerical model was employed to analyse the performance of beam-column end plate connections featuring different sleeve designs under monotonic loading. The results demonstrate that the US-type connections substantially improve the rotational capacity in comparison to standard connections. The moment-rotation behaviour of the US sleeves are illustrated in Figure 5. Additionally, Table 2 presents the normalized characteristic values of the sleeved connection compared to the experimental test connection.

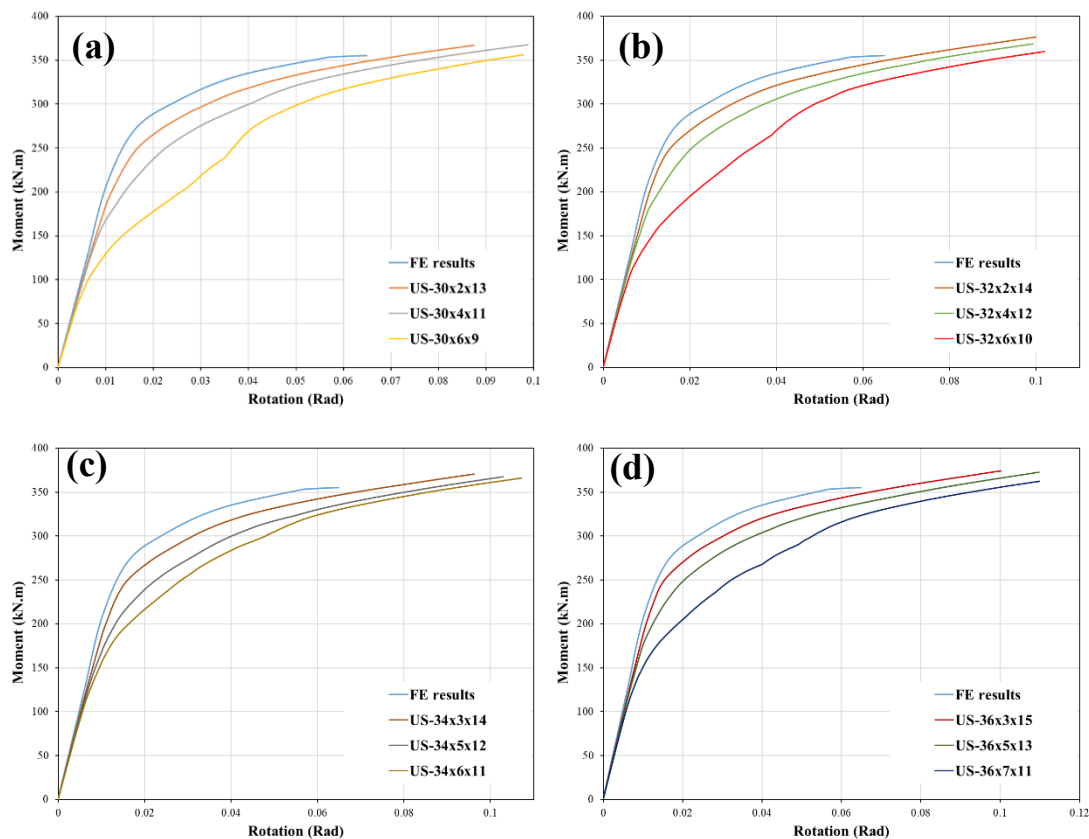


Figure 5. Moment-rotation curves of the U-shaped sleeve bolted connection for different sleeve lengths: (a) 30 mm, (b) 32 mm, (c) 34 mm, (d) 36 mm, (e) 38 mm, and (f) 40 mm

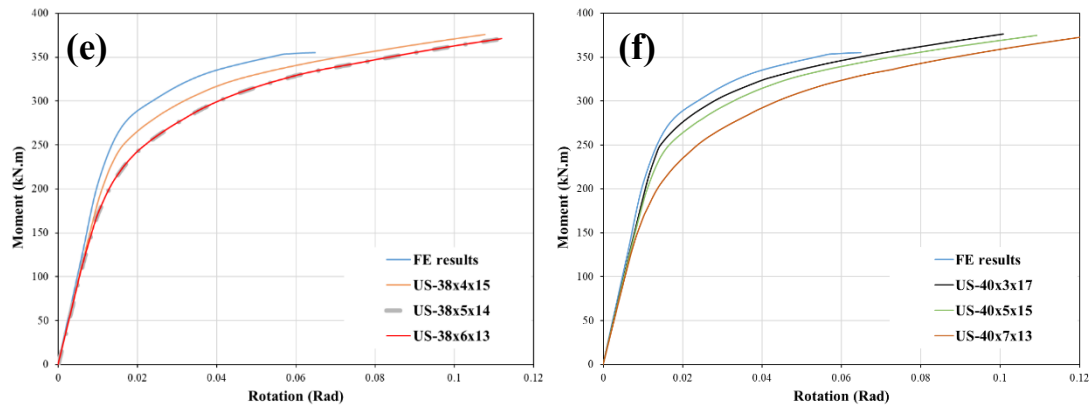


Figure 6 (continued). *Moment-rotation curves of the U-shaped sleeve bolted connection for different sleeve lengths: (a) 30 mm, (b) 32 mm, (c) 34 mm, (d) 36 mm, (e) 38 mm, and (f) 40 mm.*

Figure 5 illustrates that all U-shaped (US) sleeve configurations exhibit greater ductility than the standard connection. While the moment capacity remains unchanged, no significant variations are observed in the elastic behaviour of the connection. Among the tested configurations, the US-40x7x13 sleeve demonstrates the highest ductility, showing an increase of approximately 80%. It is essential to note that the analysis concludes when the bolt reaches its failure capacity. Sleeves with greater thickness provide limited ductility, as bolt failure occurs before the sleeve undergoes complete crushing, making this configuration less effective for the intended connection approach. In particular, US-40x3x17 and US-38x4x15 experience bolt failure prior to sleeve crushing (see Figure 6). Conversely, all other US sleeve configurations in this study exhibit complete sleeve crushing before bolt failure, which is the preferred failure mode under all loading conditions.

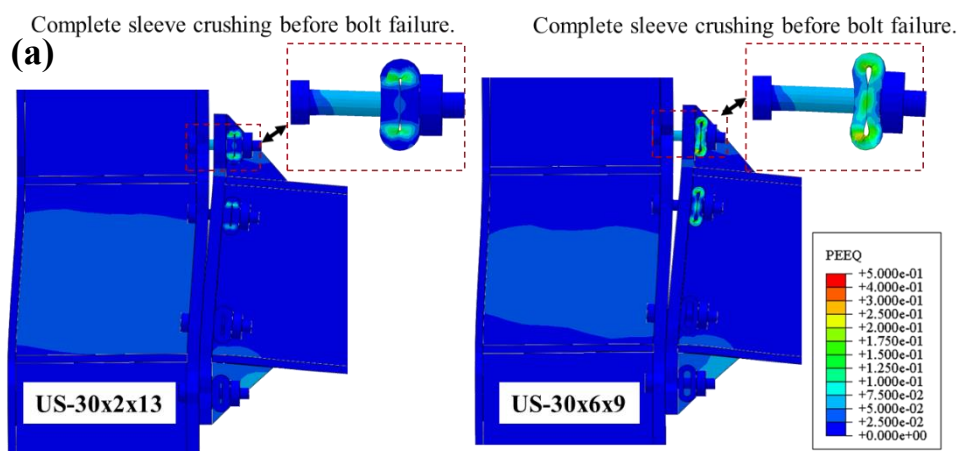


Figure 6. *Failure modes of the US sleeves at bolt rupture under the given conditions for (a) 30 mm, (b) 38 mm, and (c) 40 mm, with varying amplitude and thickness values.*

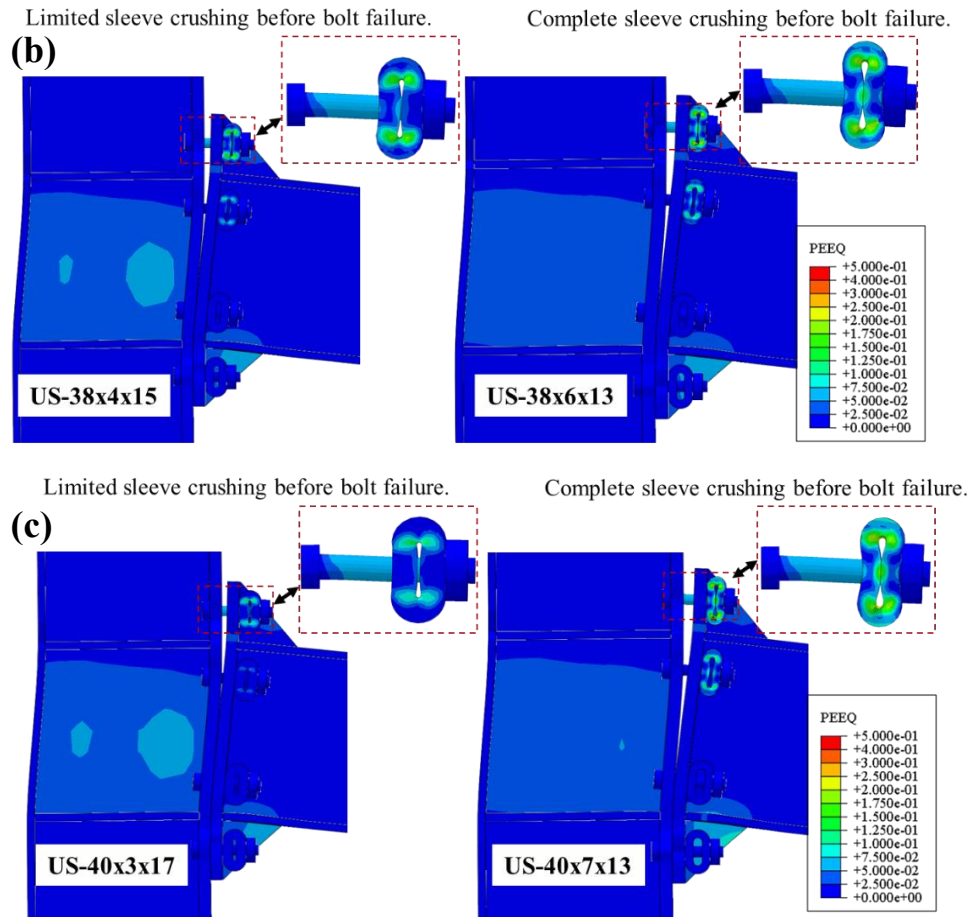


Figure 7 (continued). Failure modes of the US sleeves at bolt rupture under the given conditions for (a) 30 mm, (b) 38 mm, and (c) 40 mm, with varying amplitude and thickness values.

Furthermore, sleeves with shorter lengths exhibit the lowest rotational capacity due to their reduced strength and thinner walls (see Figure 5(a)). The moment capacity of the sleeved connection remains comparable to experimental standard connection test, with the highest moment capacity recorded for US-40x3x17. The findings also suggest that reducing sleeve thickness while increasing amplitude values enhances the likelihood of sleeve crushing before bolt failure, depending on the bolt's load-bearing capacity.

Table 2. Normalized values of the sleeve fuse connection relative to the standard connection.

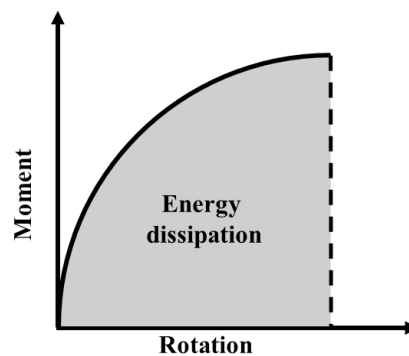
Model	Max Rotation (Rad)	ϕ_{US}/ϕ_{FE}	Max Moment (kN.m)	M_{US}/M_{FE}
FE results	0.065	1.000	355.038	1.000
US-30x2x13	0.088	1.349	367.170	1.034
US-30x4x11	0.099	1.522	367.658	1.036
US-30x6x9	0.098	1.509	356.106	1.003
US-32x2x14	0.100	1.540	376.119	1.059

Table 2 (continued). Normalized values of the sleeve fuse connection relative to the standard connection.

Model	Max Rotation (Rad)	ϕ_{US}/ϕ_{FE}	Max Moment (kN.m)	M_{US}/M_{FE}
US-32x4x12	0.099	1.529	368.863	1.039
US-32x6x10	0.102	1.570	360.080	1.014
US-34x3x14	0.096	1.482	370.699	1.044
US-34x5x12	0.103	1.586	367.711	1.036
US-34x6x11	0.107	1.653	365.962	1.031
US-36x3x15	0.100	1.543	374.163	1.054
US-36x5x13	0.110	1.692	372.784	1.050
US-36x7x11	0.110	1.694	362.573	1.021
US-38x4x15	0.108	1.659	367.170	1.034
US-38x5x14	0.112	1.725	370.962	1.045
US-38x6x13	0.112	1.725	370.962	1.045
US-40x3x17	0.101	1.553	376.493	1.060
US-40x5x15	0.109	1.684	374.903	1.056
US-40x7x13	0.120	1.852	372.650	1.050

6 ENERGY DISSIPATION

The ductile behaviour of a connection is linked to the energy absorbed during applied loads. Figure 8 shows the cumulative energy dissipation at the bolt failure point, as predicted by FE simulations. The energy dissipation is quantified as the area beneath the monotonic moment–rotation curve, determined by projecting vertically from each point on the curve to the rotation axis, up to the maximum rotation. This definition aligns with conventional energy absorption concepts, in which the absorbed energy corresponds to the area under the load–deflection curve [28]. A schematic of the moment–rotation curve has also been included (see Figure 7) to illustrate the evaluated area.

**Figure 7. Schematic illustration of energy dissipation calculation under monotonic loading.**

Connections incorporating sleeves demonstrated significantly higher ultimate capacities, leading to improved energy dissipation, particularly at higher rotational levels, when compared to conventional connections. The US-40x7x13 configuration, featuring 7 mm amplitude sleeves, exhibited the greatest energy dissipation. Other U-shaped sleeve configurations, such as US-38x5x14, US-36x5x13, US-34x6x11, US-32x2x14, and US-30x4x11, also showed superior energy dissipation within their respective sleeve length categories compared to the standard connection. Additionally, sleeves with amplitudes exceeding the anticipated plastic deformation threshold further enhanced energy dissipation, as shown in Figure 8. Energy dissipation was not assessed after the bolt failure point. It should be noted that this study focuses on monotonic loading; cyclic loading, which would provide further insights into hysteretic behaviour, residual rotations, and energy dissipation, will be addressed in a subsequent study.

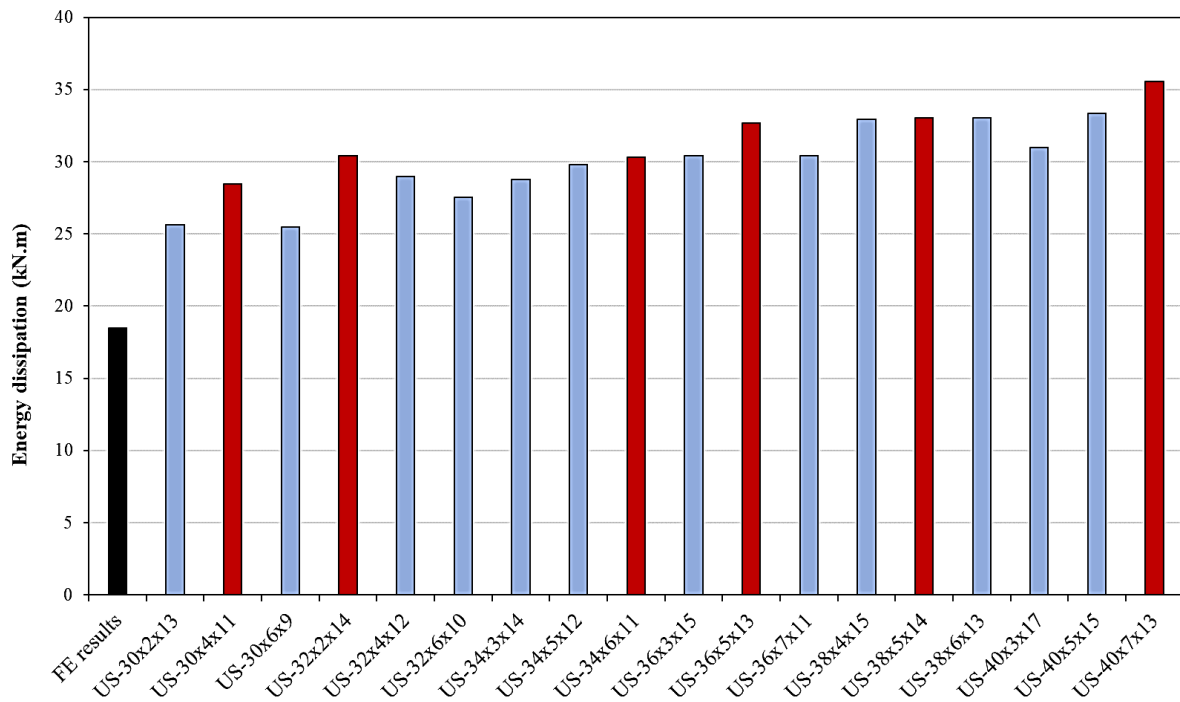


Figure 8. Comparison of energy dissipation.

7 CONCLUSION

This study examines the effectiveness of a steel sleeve fuse system in bolted end plate connections under monotonic loading conditions. A verified FE model was used, and a parametric study was conducted on U-shaped sleeves with varying lengths, thicknesses, and amplitudes. The study compared these configurations with standard connections, focusing on evaluating rotational performance and energy absorption.

The findings demonstrate that the sleeve fuse system significantly enhances both the rotational performance and energy dissipation of the connection, allowing for ductile behaviour. This makes the sleeve fuse system a promising, cost-effective solution for retrofitting steel structures, improving their performance while maintaining the integrity of existing components.

Key conclusions drawn from this study include:

- The parametric study confirmed the feasibility and effectiveness of the sleeve approach for various connection geometries, establishing its potential for practical applications.
- Although US waveform sleeves exhibited a slight decrease in initial stiffness, they significantly improved rotational capacity and enhanced energy dissipation.
- Increasing the amplitude of the US sleeves led to substantial improvements in rotational capacity.
- The energy dissipation of the US fuse system was substantially higher than that of standard connections, with amplitude playing a critical role in this improvement (around 90%).
- The sleeve design extended the failure point, allowing for higher rotations before failure, though failure still occurred within the connection itself (approximately 85%).
- The study also revealed that reducing sleeve thickness while increasing amplitude enhances the likelihood of sleeve crushing before bolt failure, depending on the bolt's load-bearing capacity.

In conclusion, the sleeve fuse system proves to be an effective method for enhancing energy dissipation and rotational capacity in steel end plate connections. This approach not only improves the seismic performance of steel structures but also presents a cost-efficient solution for retrofitting existing connections. Future research should focus on further refining sleeve designs and conducting experimental tests to evaluate their performance under more complex loading conditions, thereby broadening their applicability across a wider range of structural scenarios.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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