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Numerical Behavior of Extended End-Plate Bolted Connection under Monotonic Loading

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Abstract

Extended end-plate connections, which act as joints providing resistance against moments between beams and columns, are commonly categorized as semi-rigid or partial-strength connections. The reason for their extensive application in steel frame constructions lies in their straightforward design, their ability to be reproduced easily, and the convenience they offer in the fabrication process. This research used the ABAQUS FE software to construct a three-dimensional finite element model (FEM) with the main objective of exploring how different geometric parameters impact the behavior of the extended end-plate bolted connection, which functions as a semi-rigid, partial-strength beam-to-column connection. Accurately determining the moment-rotation relationship and connection stiffness is of utmost importance for semi-rigid connections. The developed FEM models incorporate various factors such as geometric and material non-linearities, bolt pretension force, as well as contact and sliding between the connection elements. To establish the credibility of the numerical outcomes, the developed FEM model was meticulously calibrated and verified against experimental data obtained from previous studies available in the literature. Subsequently, using the validated finite element model, a parametric investigation was undertaken to evaluate the influence of distinct geometric parameters, namely the thickness of the end plate and column web stiffeners. This numerical model facilitates a comprehensive analysis of the extended end-plate bolted connection, encompassing critical aspects such as the moment-rotation curve and failure mode. The results demonstrated that the analyzed finite element model aligns well with experimental findings and that the use of column stiffeners is inevitable in the joint, as well as a moderated thickness of the end plate.

Keywords: Beam-to-Column Connection; FEM Model; Validation of FE; Column Stiffeners; End-Plate Stiffeners.

1. Introduction

Extended end-plate bolted connections are commonly used as moment-resistant joints in steel structures, specifically to connect beams with columns. These connections are categorized as semi-rigid, partial-strength joints, offering substantial moment capacity. They are known for their simplicity in installation, as they do not require highly skilled labor, making them suitable for serial productions. These properties contribute to the widespread use of end-plate bolted connections in structural steel frames. Bolted end-plate moment connections are commonly used to connect beams and columns, typically with H or I cross-sections. In these connections, the beam end is welded to the end plate, while the end plate is bolted to the column flange. The classification of these joints is often based on their strength, stiffness, and rotation capacity, as outlined in Eurocode 3 Parts 1–8 [1] and various research studies. These classification criteria provide a framework for assessing the performance and design requirements of bolted end-plate moment connections.

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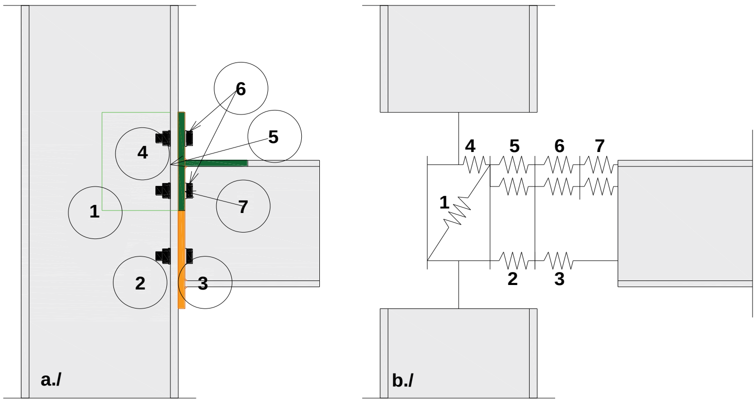
Various analytical analyses and mathematical models have been suggested to analyze the semi-rigid characteristics of extended end-plate beam-to-column joints. Eurocode 3 [1] proposed a method known as the "Component Method," a widely recognized analytical model nowadays for analyzing the mechanical properties of the joint, which can be used for any type of steel, loading, and different types of cross sections. This method, adopted in Eurocode 3 for calculating the behavior of bolted beam-column connections, is primarily based on the research conducted by Zoetemeijer [2]. Zoetemeijer conducted extensive tests on full-scale connections and a T-stub in tension to derive an empirical formula for calculating the effective length of the column flange. Additionally, design methods for T-stubs in tension were developed. Weynand et al. [3] further contributed to the design of bolted beam-column joints by providing design recommendations. The active elements are specified for the joint configuration depicted in Figure 1a. Each element possesses unique tensile, compressive, or shear strength and stiffness, as shown in Figure 1b.



1. Column web in shear
2. Column web in compression
3. Beam flange in compression
4. Column web in tension
5. Column flange in bending
6. Bolt row in tension
7. End-plate in bending

Figure 1. Steel joint with extended end-plate a) Bolted beam-to-column connection, and b) component method representation [4]

In accordance with Eurocode 3 Parts 1–8 [1], design rules are established to determine the design resistance, initial stiffness, and rotation capacity of each component involved in the joint. By combining these properties for each component, the overall behavior of the joint can be assessed, as depicted in Figure 1. The Component Method, as specified in Eurocode 3 Parts 1–8, has been widely utilized in analytical and experimental studies. These studies typically focus on the configuration of end-plate beam-to-column connections with two bolts per horizontal row [5–9]. The Component Method is a valuable framework for analyzing and designing bolted end-plate connections, offering standardized guidelines for assessing their performance.

In the studies conducted by Shi et al. [10, 11], eight end-plate joints with identical configurations were investigated under both monotonic and cyclic loading conditions. The study parameters considered included variations in end-plate thickness, bolt diameter, the presence of column web stiffeners, and end-plate stiffeners. Their research findings indicated that the strength of the connection, rotation capacity, and energy dissipation can be enhanced by incorporating rib stiffeners in the extended section of the end plate. Additionally, the presence of these stiffeners helps to reduce stress concentrations in the welded region between the beam and end plate. Moreover, Shi et al. proposed a novel theoretical model to evaluate the moment-rotation $(M - \varphi)$ relationship for stiffened extended end-plate bolted connections. This model provides a useful tool for predicting and analyzing the behavior of such connections, specifically considering the influence of the introduced stiffeners.

Four experimental tests on external double-extended end-plate bolted joints were carried out by Augusto et al. [12, 13] with particular attention to the force-deformation behavior of the column web components. The experiments included variations in the beams and columns cross-section and the presence of axial force. Experimentally and analytically derived results from eight specimens done by Abidelah et al. [14] for bolted and flush end-plate connections, with or without stiffeners and with two bolts per row, indicated that the absence of column web stiffener could cause the failure of the specimens by the elastoplastic buckling of the column web in compression. They also noted that the stiffening of the end plate increases moment resistance and initial stiffness but decreases the rotation capacity of the connection. Furthermore, the presence of the end-plate stiffeners significantly influences the distribution of forces in the bolts.

Experiments of the end-plate connection under quasi-static loading, carried out by Culache et al. [15], using carbon steel bolts and stainless steel bolts, showed that the connections with carbon steel bolts exhibit brittle failure in the threaded part of the bolt. In contrast, stainless steel bolts have visible ductile necking and absorb the same energy before failure under quasi-static loading compared to carbon steel bolts. Plaitano et al. [16] conducted further research on the simplified modeling of failure in high-strength bolts subjected to combined tension and bending. They identified two distinct failure modes: thread stripping in cases of pure tension and shank fracture in instances of combined tension and bending.

Gao et al. [17] investigated six full-scale beam-to-column joints, three of which were beam-to-interior connections, and three were beam-to-exterior connections, all featuring double extended end-plate configurations. The joints were tested under monotonic loading conditions, and various materials were considered, including carbon steel, stainless steel, and duplex grade. The results of the study revealed interesting findings. Specifically, it was observed that the plastic moment resistances of the stainless-steel joints were significantly underestimated when using codified methods. In contrast, the predictions for the carbon steel joints were found to be relatively accurate. Furthermore, the study highlighted that the stainless-steel joints exhibited higher ductility than the carbon steel joints. In fact, the failure of five out of the six stainless steel specimens was attributed to bolt rupture. On the other hand, the carbon steel joints failed primarily due to cracking at fillet welds.

Using three-dimensional finite element models, Maggi et al. [18], Ismail et al. [19], and Bahaz et al. [20] conducted parametric analyses of bolted end-plate connections. The purpose of these analyses was to assess the accuracy of commonly used design procedures and to gather data to develop new analytical models. By employing finite element models, these studies aimed to investigate various parameters and their influence on the behavior of bolted end-plate connections. The parametric analyses allowed for a comprehensive evaluation of the connection's response under different loading conditions and geometrical configurations.

In their research, Luo et al. [21] constructed a finite element numerical model to investigate the behavior of an extended end-plate bolted connection subjected to cyclic loading from the column's top side. Through a parametric study, they found that the panel zone shear force plays a crucial role and significantly impacts the connection's stiffness. Dessouki et al. [22] introduced a three-dimensional finite element model to investigate the behavior of extended end-plate moment connections, considering both geometrical and material non-linearities. They used ANSYS software to develop a parametric study, focusing on two end-plate configurations: a four-bolt and multiple-bolt rows extended end-plate in the tension zone. The study revealed a significant increase, ranging from 30% to 35%, in both yield and ultimate moment capacities in the case of multiple rows extended end-plate compared to the four-bolt configuration. Various parameters were examined in the parametric study, including bolt diameter, beam depth, end-plate thickness, bolt pitch, inner bolt pitch, bolt gauge, and end-plate stiffener. Additionally, the study explored new yield line patterns for circular and non-circular arrangements. The researchers proposed new design equations based on their finite element analysis results and compared them with the current design code.

Numerous test setups are used to comprehensively understand the behavior of moment-resisting joints under both monotonic and cyclic loading. These setups aim to encompass a wide range of configurations for moment-resisting joints. These tests investigate the influence of various parameters on the behavior of the connections. These parameters include moment resistance, initial stiffness, rotation capacity, and failure modes. By systematically varying these parameters and studying their impact on the joint's performance, valuable insights can be gained regarding the design and analysis of such joints. Additionally, these tests contribute to the development of a comprehensive database. Overall, the use of extensive test setups and the analysis of various parameters in moment-resisting joints aim to enhance our understanding of their behavior, facilitate the development of accurate design models, and provide valuable data for the calibration and validation of these models.

The main goal of this paper was to develop a reliable three-dimensional finite element model (FEM) using ABAQUS FE software [23] to analyze bolted extended end-plate joints. The model incorporates various factors, such as bolt pretension force, material non-linearity, contact, and sliding between different surfaces. The results are compared with experimental data published in previous studies to validate the accuracy of the finite element analysis (FEA). The second objective was to utilize the verified FEM to conduct a parametric study. The main objective of this research was to examine how two crucial factors impact the study: column web stiffeners, which require more in-depth investigation to comprehend their effects on the web panel zone and end-plate thickness. These investigations are carried out under monotonic loading conditions. The column web panel and the joint zone are crucial components of the beam-to-column joints. The study parameters related to the column web panel include variations in transverse compression and tension stiffeners, single- and double-side web plates, as well as unstiffened column web configurations. On the other hand, the effect of end-plate thickness is analyzed within the connection zone. By conducting this parametric study, the paper aimed to provide insights into how column web stiffeners and end-plate thickness impact the critical properties and failure modes of the extended end-plate bolted connection. This research contributes to a better understanding of the behavior and design considerations of such joints under monotonic loading.

2. Research Methodology

The initial step involved reviewing and analyzing existing literature to identify significant findings, methodologies used, and any limitations. Subsequently, a Finite Element Model (FEM) was modeled in Abaqus [23] and then compared and validated with experimental results reported in the literature. Next, a parametric analysis was conducted on a double-stiffened extended end-plate bolted connection. This analysis aimed to study the effects of various factors, including transverse stiffeners in the compression and tension zones, single and double-side web plates, and an unstiffened column web. Additionally, the impact of end-plate thickness was considered. The analysis was performed using the methods described in Eurocode 3 Parts 1–8 [1], and the numerical Finite Element Analysis was conducted using the ABAQUS software [23].

Afterward, the results were meticulously scrutinized and compared with experimental data from previous studies as well as findings in reference literature. Finally, the research conclusions were summarized based on the collective outcomes of these analyses. A flowchart outlining the research methodology can be found in Figure 2.

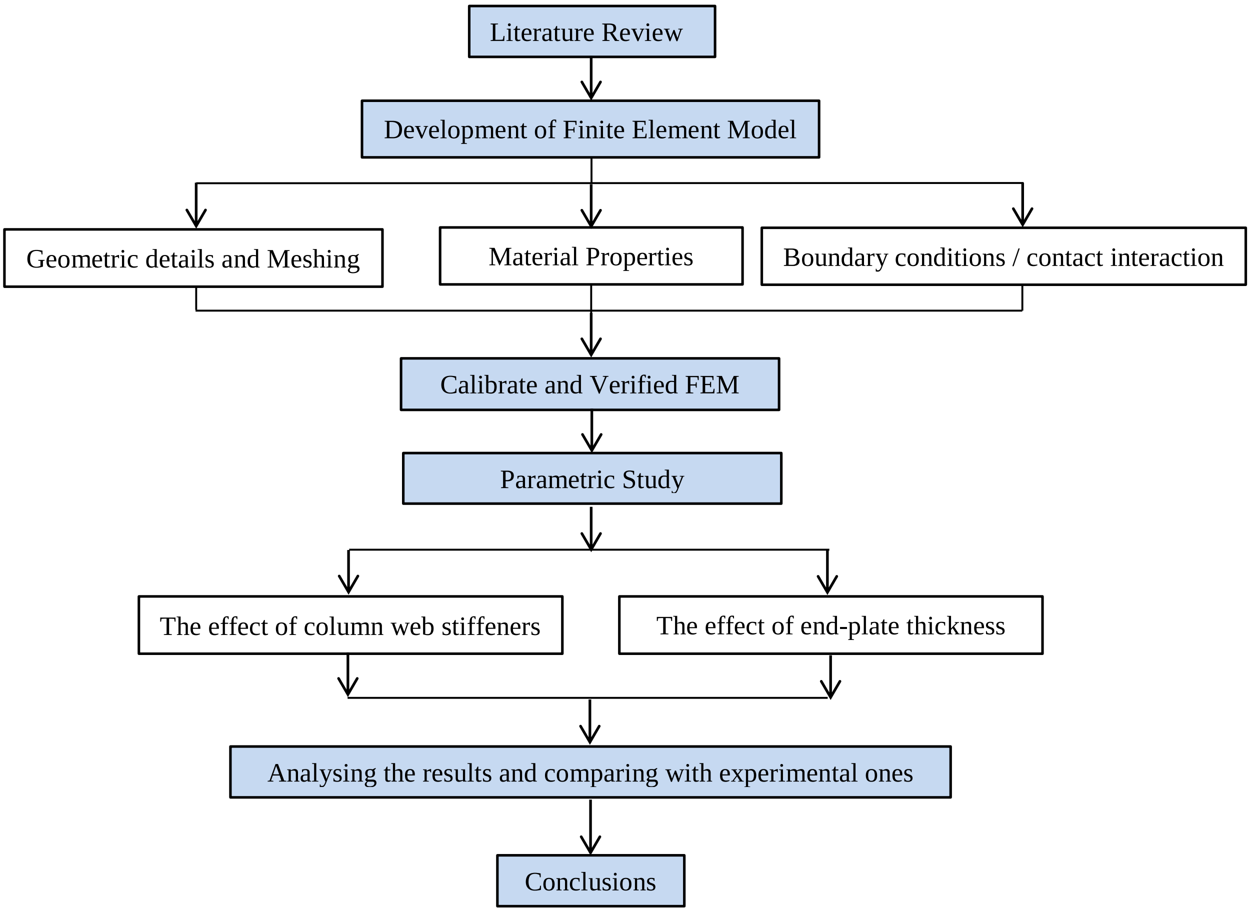


Figure 2. Flowchart of the methodology

3. Finite Element Model

The advantage of utilizing nonlinear finite element modeling lies in its ability to achieve cost and time savings compared to experimental work. Additionally, it helps prevent unpredictable errors during testing procedures and offers valuable insights into the mechanical behavior of joints, which can be difficult to measure through traditional experimental tests. This research aimed to create a 3D finite element model to examine the bolted connection of a double-stiffened extended end plate. The focus was on understanding how the presence of column web stiffeners can contribute to enhancing joint properties, particularly resistance and stiffness growth, by applying those stiffeners in the panel zone, as it is shown below in this paper, and the impact of the end-plate thickness on the properties of the joint.

3.1. Geometric Details of the Joints

The behavior of extended end-plate bolted connections under monotonic loading was predicted using a three-dimensional finite element model (FEM) developed with ABAQUS FE software [23]. To validate the proposed FEM, an experimental test was conducted on a specific beam-to-exterior column joint configuration with a double extended end-plate, as performed by Gao et al. in 2020 [17]. In this validation process, one connection out of the six studied by them was modeled. The geometric characteristics of the selected joint specimen can be found in Table 1 and Figure 3. All specimen dimensions, including those of the column, beam, end-plate, rib stiffeners, and column stiffeners, were kept consistent and are presented in Table 2.

Table 1. Configuration details of joint specimens analyze for beam-to-exterior column joint [17]

Specimen	Material grade	Bolt grade	Bolt pretension force Fpre (kN)	Column axial force Fc (kN)	End-plate rib stiffener
S30408-ES-r	EN 14301	A4-80	124	290	Yes

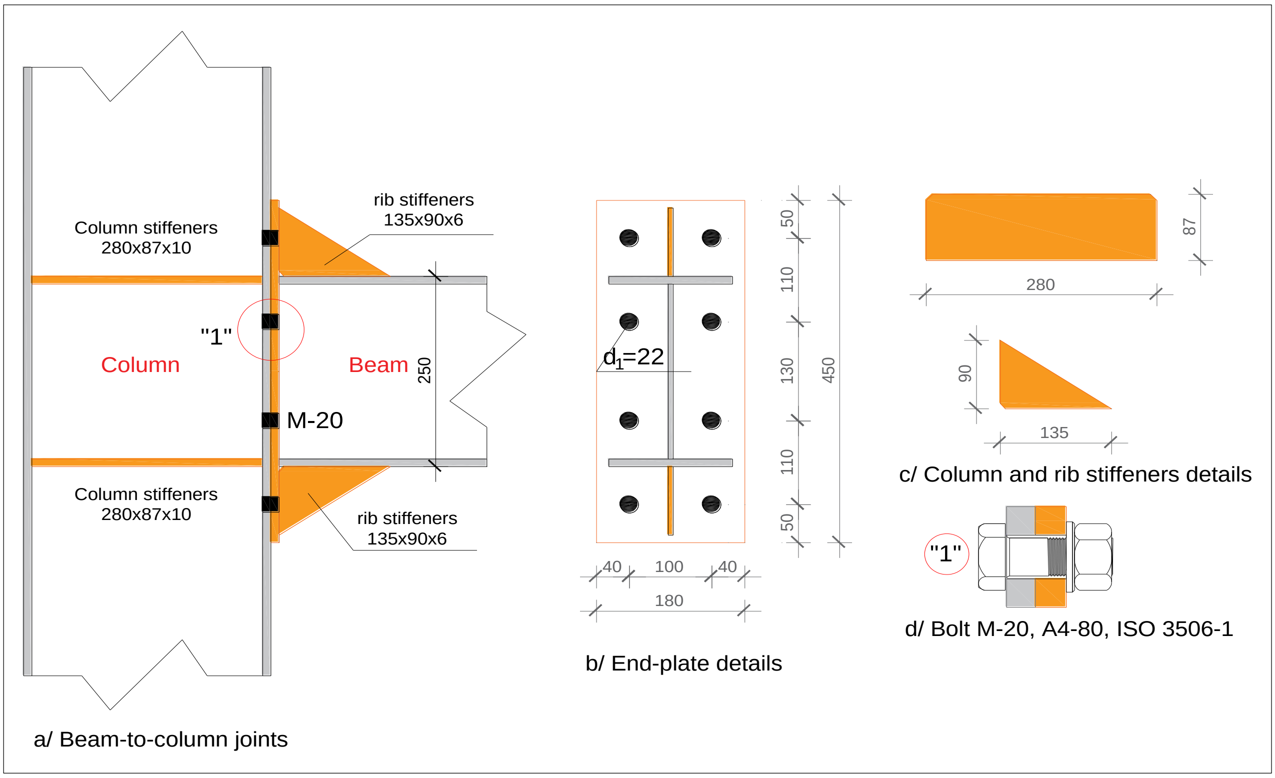


Figure 3. Geometric details of the joint specimens (all dimensions in mm), Gao et.al (2020) [17]

Table 2. Geometrical dimensions of the tested specimens [17]

Specimens	h (mm)	b (mm)	t_f or t_p(mm)	$t_w$or t_s (mm)
Column	300	180	10	6
Beam	250	150	10	6
End-plate	450	180	10	-
Column Stiffener	280	87	-	10
Rib stiffener	135	90	-	6

3.2. Development of Finite Element Model

The performance of beam-to-column joints with a double extended end-plate connection was simulated using the ABAQUS FE software [23]. In the presented model, Figure 4, all components involved in the connection were modeled using the deformable solid element C3D8I (incompatible mode eight-node first-order brick element). This element was chosen to effectively prevent the shear-locking phenomenon. The modeling process involved representing various components, such as the column, beam, end-plate, column stiffeners, and rib stiffeners, in a 3D modeling space. These components were treated as deformable objects using a solid shape with an extrusion-type approach. The bolts were modeled using the revolution-type method, considering the bolt head, nut, and bolt shank as a single entity. The hexagonal shape of the bolt head and nut was simplified to a cylinder shape. The extended length of the bolt and the threaded part of the bolt shank were not included in the model.

The accuracy of Finite Element (FE) analysis heavily depends on precise element meshing, as the quality of the results is directly influenced by it. Using a coarse mesh size leads to inaccurate predictions that do not align with experimental data. To address this issue, specific measures were taken, setting the overall mesh sizes for the column and beam to 20mm and 25mm, respectively. This finer meshing aims to improve the reliability and accuracy of the FE analysis, ensuring better agreement with experimental results. A mesh size of 10mm was used for the column stiffeners and rib stiffeners, while a much finer mesh was employed in the region of the connection, end-plate, column flange, and bolts with hexagonal element shape and sweep technique. This approach ensures reliable results while minimizing computational time.

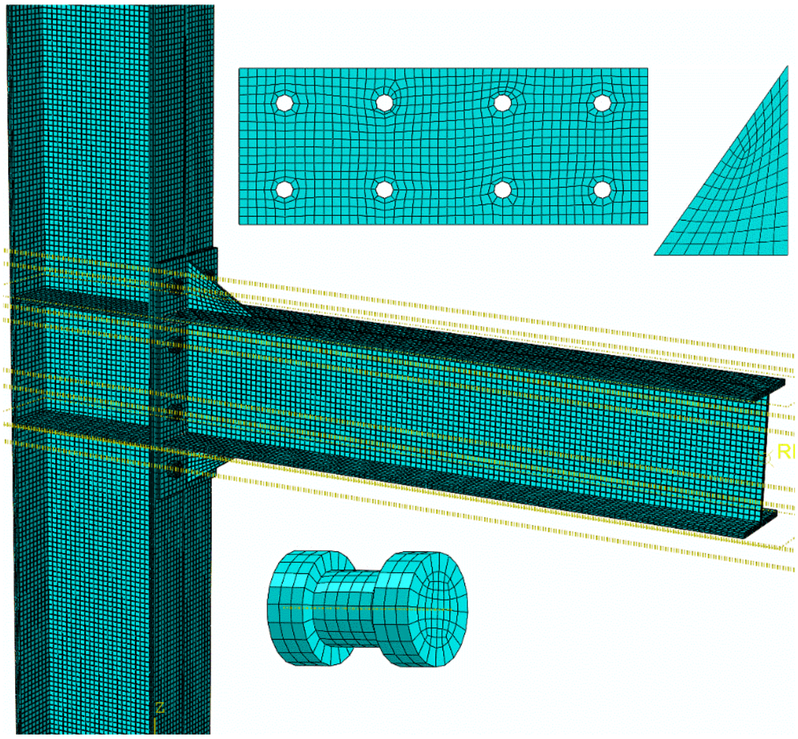


Figure 4. Finite element mesh for beam-to-column joints

3.3. Material Properties

The material behavior of the presented joint utilizes a nonlinear stress-strain curve. Simple elastoplastic isotropic hardening models with the Von Mises yield criterion were implemented in Abaqus. The material properties for the steel plates and bolts used in the joint specimens were obtained from test results conducted by Gao et al. in 2020 [17]. These properties, listed in Table 3, include the initial Young's modulus (E_0), nominal yield strength ($\sigma_{0.2}$), yield strength of steel (σ_y), ultimate tensile stress (σ_u), strain at the yield strength ($\varepsilon_{0.2}$ or ε_y), strain at the ultimate tensile stress (ε_u), and an assumed Poisson's ratio of 0.3. These material property values were derived from tensile coupon tests performed on structural steel specimens. The stress-strain curve ($\sigma - \varepsilon$) for the plate material is considered and illustrated in Figure 5.

Table 3. Material properties of steel plates and bolts [17]

Material		t (mm)	E_0 (MPa)	$\sigma_{0.2}$ (σ_y) (MPa)	$\varepsilon_{0.2}$ (ε_y) (%)	σ_u (MPa)	ε_u (%)
EN 14301 column	tw	5.81	-	287.59	0.378	751.66	56.3
	tf	9.94	179400	275.94	0.382	757.41	53.6
EN 14462 column	tw	5.89	185500	538.37	0.476	743.86	24.6
	tf	9.82	177800	555.45	0.501	762.11	23.3
EN 14301 beam	tw	5.78	183700	282.88	0.355	755.15	60.5
	tf	9.78	204200	296.31	0.346	707.33	62.6
EN 14462 Beam	tw	5.91	196700	563.79	0487	748.76	26.7
	tf	9.99	200500	547.55	0473	739.83	26.2
A4-80 bolt		20	177900	574.12	0.526	746.89	14

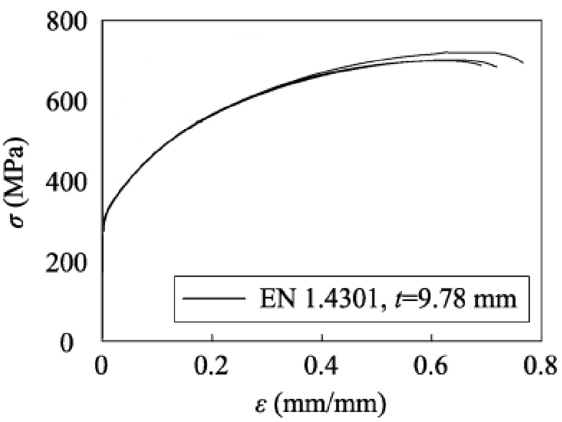


Figure 5. True plastic stress-strain curves of plate material [17]

3.4. Boundary Conditions and Contact Interaction

One of the most challenging aspects of modeling the Finite Element (FE) model was defining the boundary conditions. These conditions had to accurately replicate the support conditions used in the experimental setup conducted by Gao et al. [17]. Ensuring the proper representation of the support conditions in the FE model was crucial to achieving meaningful and comparable results with the experimental data (see Figure 6). The accuracy of the boundary conditions directly influenced the reliability and validity of the FE analysis.

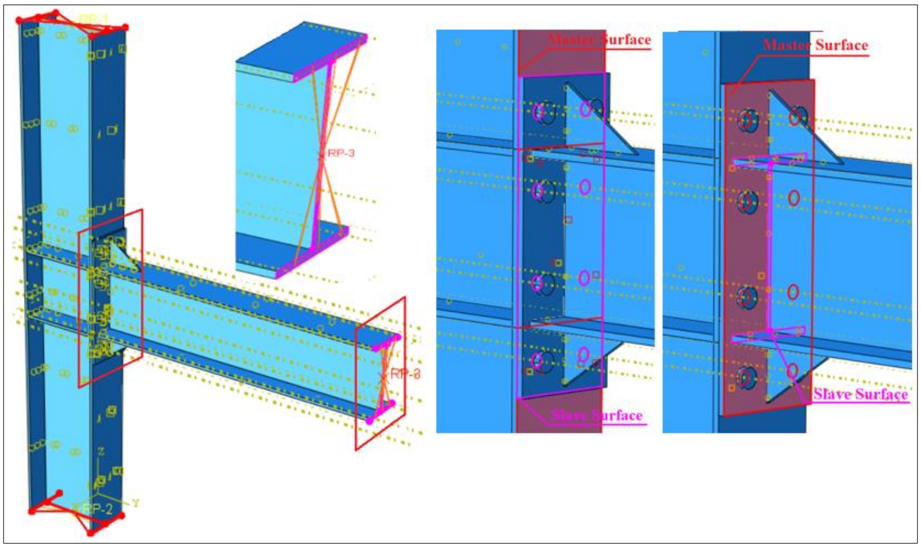


Figure 6. Boundary conditions and contacts in end plate connection

In the finite element model, all degrees of freedom at each end of the column were fixed except for rotation about the strong axis of the column cross-section. Additionally, the longitudinal translation at the bottom end of the column was allowed to move freely to introduce the axial load (CF3). Two reference points, RP1 and RP2, were employed to implement the restraints at the column ends. RP1 represented the top-end cross-section of the column, while RP2 represented the bottom-end cross-section. The kinematic coupling type was used to ensure the appropriate restraints (constrained degrees of freedom).

Similarly, an additional reference point, RP3, was used to control the degrees of freedom for the beam ends. This facilitated the application of loading in the form of a prescribed vertical displacement (U3). Furthermore, the bolt pretension forces were defined using the "bolt load" command in the FE model. The magnitude of the pretension forces was determined based on the values prescribed in Table 1 [17], which were calculated according to Equation 1.

$$F_{pre} = \frac{0.7 \cdot f_{ub} \cdot A_s}{\gamma_{M7}} \tag{1}$$

Equation (1) is utilized to calculate the pretension forces of the bolts. In this equation, f_{ub} represents the ultimate tensile strength of the bolts, A_s represents the tensile stress area of the bolts, and γ_{M7} (with a value of 1.1) is the partial safety factor.

Another significant challenge in finite element modeling (FE) was the interaction between different components of the joint. This interaction played a crucial role in the modeling process and required careful consideration to accurately depict the behavior of the entire joint system. The contact between these components was represented using finite-sliding and surface-to-surface contact as the discretization method. In this approach, one surface was designated the master surface, while the other was considered the slave surface. Four different contact pairs were generally considered:

- The End-Plate and Column Flange;
- The Bolt Head and Column Flange;
- The Bolt Nut and End Plate;
- The Bolt Shank and the Corresponding Bolt Hole.

The default hard contact model was employed to simulate the normal behavior of the contact surface, representing bearing. The tangential behavior was defined using a frictional coefficient of 0.2 value, employing a penalty stiffness formulation as per Gao et al. [17]. Regarding the welds between the beam and end-plate, rib stiffeners between the beam flange and end-plate, and the column web stiffeners and column web, a "Tie" constraint was applied to define their connection in the finite element model.

4. Validation of the Proposed FE Model

To validate the presented finite element model, a comparison was made with the monotonic experimental results conducted by Gao et al. [17]. The comparisons focused on the load-displacement (F-Δ) characteristics and failure modes of the connections. The finite element models were executed using a general static analysis, which involved two steps. In the first step, a ramp-like incrementally increasing pretension load was applied to the eight bolts connecting the end plate and column flange until the applied pretension force was reached. Simultaneously, a concentrated axial force was applied at the reference point (RP-2). The magnitude of these loads was determined based on the values specified in Table 1.

Moving on to the second step, a displacement- or rotation-controlled load was applied to the beam ends at the reference point (RP-3). In Figure 7, a comparison is depicted between the force and displacement values obtained from the experimental test and those derived from the finite element analysis. The graph shows remarkable similarity, indicating a close agreement between the FEM model and the published test results. The error percentage in estimating the maximum force is very small, both in the elastic region and the plastic region. This small margin of error further validates the precision and reliability of the FEM model.

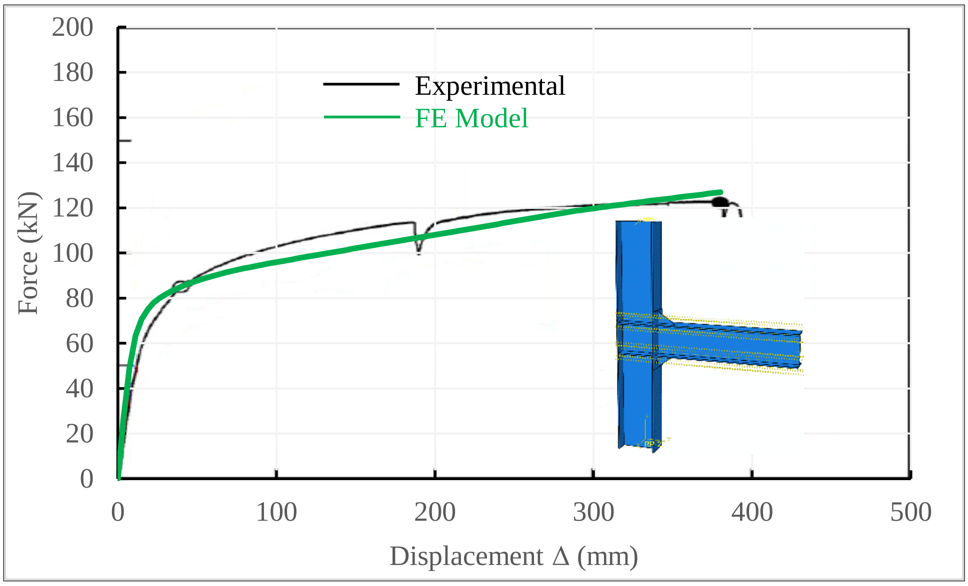


Figure 7. Comparison of numerical and experimental F-Δ curves of joints

Table 4 provides a comparison of the moment resistance, rotation capacities, and initial stiffness of the connection. The moment resistance of the joint is calculated by multiplying the applied load with a lever arm of 1.1m. The ratio of the stiffness values ($S_{i.ini.Exp}/S_{i.ini.FE}$) is 0.975. The average ratios of ($M_{Rd.Exp}/M_{Rd.FE}$) and ($M_{U.Exp}/M_{U.FE}$) are calculated to be 1.05 and 1.03, respectively.

Table 4. Comparison between experimental and FE result

Test configuration	F_{Rd} (kN)	F_u (kN)	Δu (mm)	$S_{j,ini}$ (kNm/rad)	M_{Rd} (kNm)	M_u (kNm)
Experimental	85.43	123.58	378.8	10974.24	93.97	135.94
FE model	87.52	120.55	380	11254.52	89.18	132.61
		Ratio Exp / FE		0.975	1.05	1.03

The total joint rotation is defined as the combined effect of the shearing rotation in the column panel zone and the gap rotation resulting from the relative deformation between the column flange and the end-plate [10].

Figure 8 depicts the comparison of the moment-rotation ($M - \varphi$) curves obtained from the finite element (FE) model and the experimental results of the extended double-stiffened end-plate bolted connection. The ($M - \varphi$)curves from the FE model demonstrate a strong correlation with the experimental results, indicating that the FE model accurately captures the behavior of the connection in terms of moment and rotation.

Figure 9 illustrates a comparison of the failure modes between those observed in tests and those obtained from the numerical simulation. The applied displacement at reference point 3 (RP-3) is Δ=380 mm, as described in Table 4. It is evident that as the displacement increases, the gap between the end plate and column flange in the tension zone also increases. In the compression zone, the rib stiffener experiences local buckling, and the shear deformation of the column web is noticeable. Plastic deformation, bending deformation of the end plate and column flange, buckling of rib stiffeners, and panel zone deformation are all accurately simulated. These comparisons clearly demonstrate that the finite element model effectively captures the behavior and failure modes of extended end-plate bolted connections with acceptable accuracy.

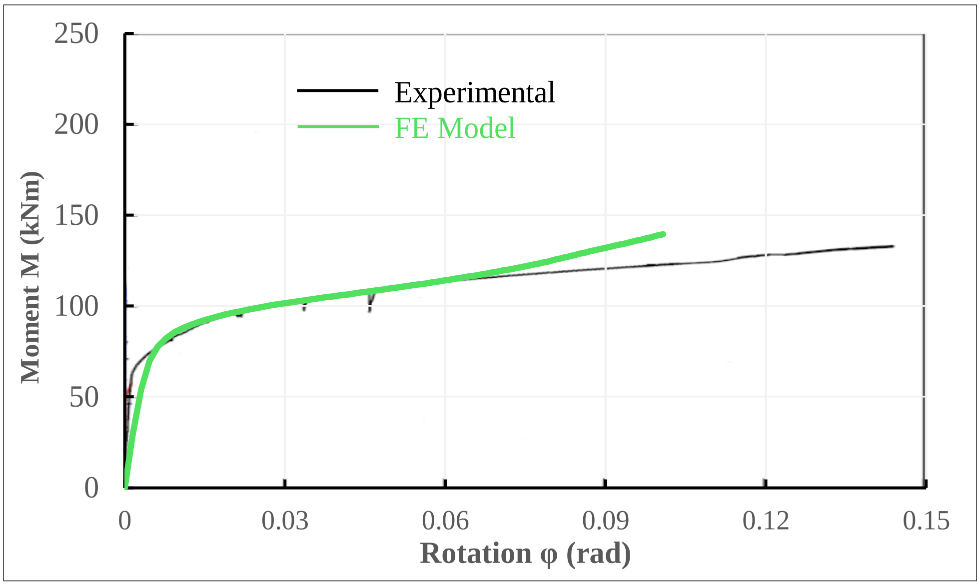


Figure 8. Comparison of moment-rotation curves of joints

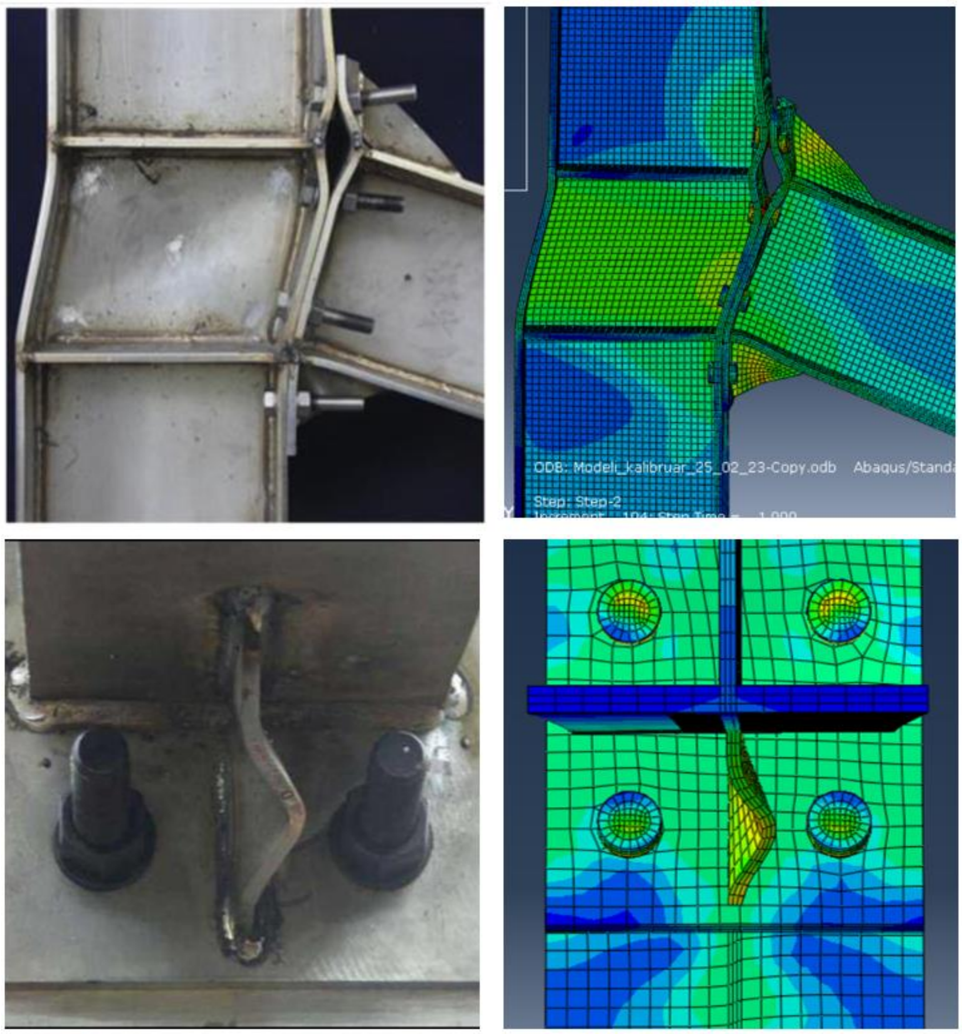


Figure 9. Comparison of failure modes of the joint specimen from FE model and experiment

5. Parametric Study

Using the validated model, a 3D solid model of extended end-plate bolted connections (as depicted in Figure 3) was created to examine the behavior of the connection in detail. Through the finite element model, a parametric study was conducted to investigate the effects of two key factors: the column web stiffeners and the thickness of the end plate. These parameters were carefully selected due to the lack of comprehensive analysis in the existing literature, particularly concerning the application of different column web stiffeners. Based on a calibrated model, including stiffeners in the panel zone is essential in connections to prevent buckling of the column web. Properly selecting the appropriate column web stiffener can enhance the joint's performance and lead to cost and time savings in the connection process [24, 25]. By investigating these parameters, this research aimed to address the knowledge gap and provide valuable insights for optimizing the design and performance of such connections.

5.1. Effect of Column Web Stiffeners

Based on the numerical analysis, the column web is considered one of the weakest components of the joints, as it is subjected to compression, tension, and shear forces. The presence of stiffeners in the panel zone significantly affects three key properties of the extended end-plate bolted connection: moment capacity ($M_{i,Rd}$), initial rotational stiffness ($S_{i,ini}$), and rotation capacity (φ_{cd}). The study parameters focused on variations in transverse stiffeners (compression and tension stiffeners), double-web and single-web stiffeners, as well as the absence of column web stiffeners. These parameters were investigated to understand their impact on the overall performance of the connection.

Figure 10 displays the moment-rotation curves, highlighting the impact of different stiffeners on the extended end-plate bolted connections and using one of those in the column panel zone as mandatory. Including compression and tension stiffeners (a) significantly enhances the design moment resistance and rotation capacity while slightly increasing the initial stiffness of the joints. Interestingly, the effect of a double-sided web plate (c) on moment capacity and rotational stiffness is similar to that of transverse stiffeners (a) until a critical point (1) is reached. At this point, there is a sharp decrease in moment resistance due to premature failure of the joint, as illustrated in Figure 9. Furthermore, calculations indicate that joints with transverse stiffeners exhibit ideal rigidity. The calculation of the initial rotational stiffness for such joints considers only three components: column web panel in shear, column web in transverse compression, and transverse tension.

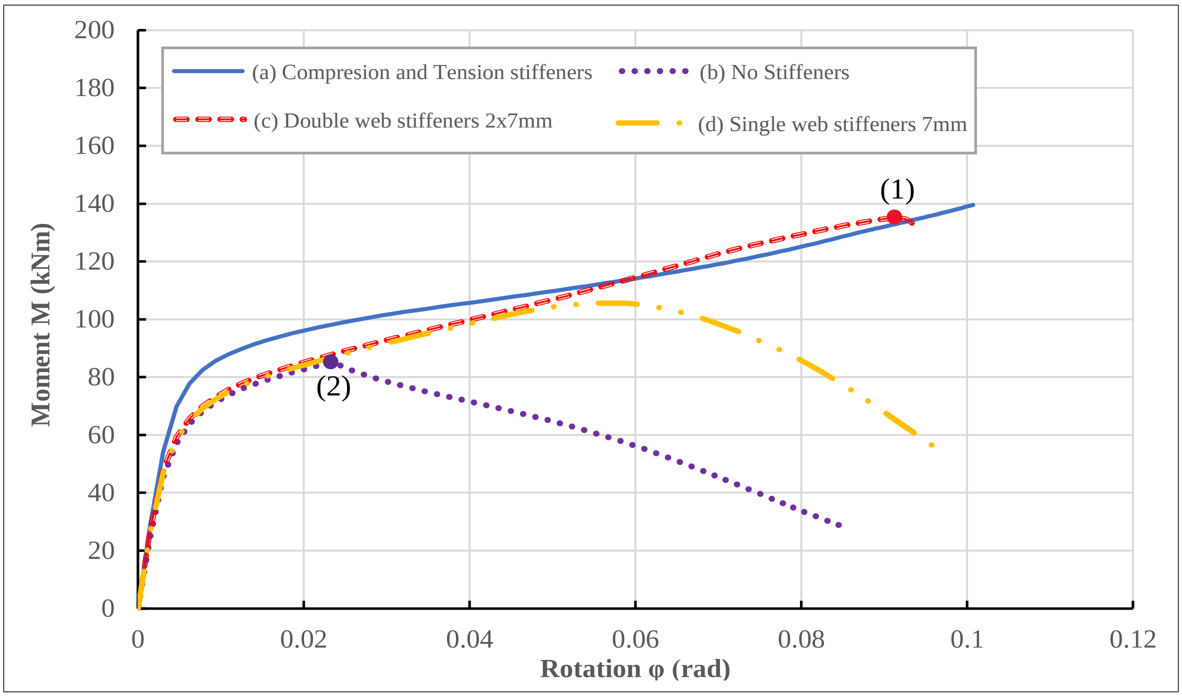
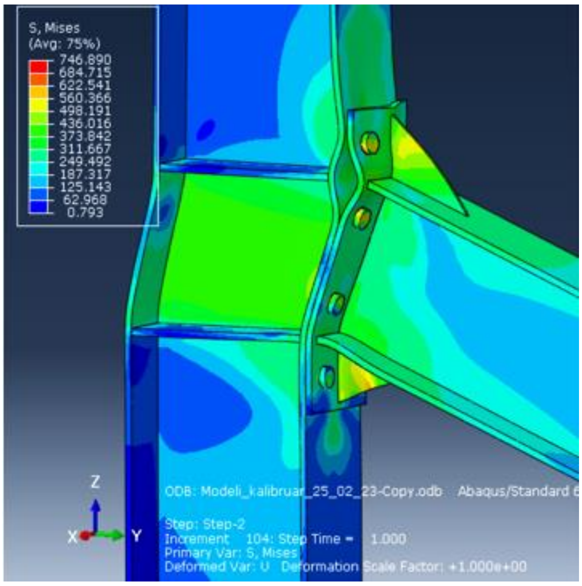


Figure 10. Monotonic results of M-φ curves for different column web stiffeners

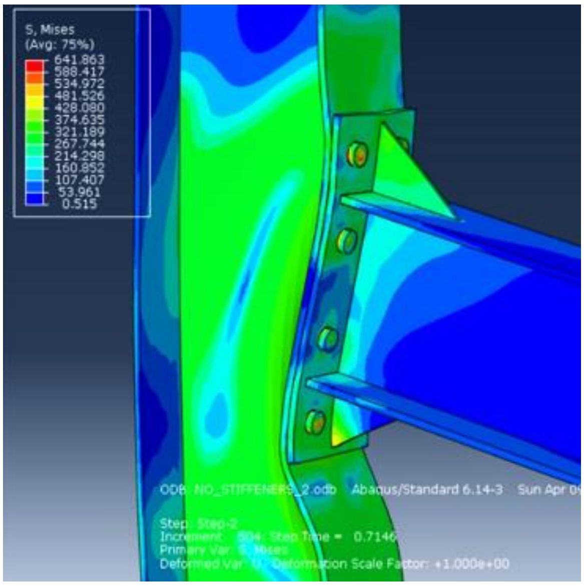
In contrast, for joints with a one-sided web plate (d), adding a 7mm thick web stiffener increases the cross-section area in shear. Although this has a minimal effect on the moment capacity compared to transverse stiffeners (a), it still leads to a noticeable improvement compared to the unstiffened joint (b). However, the column web panel in compression remains the weakest component of the joint. For the unstiffened joint (b), it was observed that the column web in compression is the weakest component. As the joint rotation reaches approximately 0.025 radians, it becomes evident that all the components within the joint experience buckling. This phenomenon is also reflected in the joint's ultimate moment, which starts to decline after point (2). The reduction in ultimate moment indicates the joint's decreasing capacity to withstand further loading due to the buckling of its components.

Introducing tension stiffeners effectively reduces deformation in the panel zone of the connection and significantly improves the moment and rotation capacities compared to an unstiffened extended end-plate bolted connection. In extended end-plate bolted connections, rotation primarily occurs due to shearing deformation in the column panel zone and the gap rotation between the column flange and end plate. Hence, the results indicate that deformation in the panel zone plays a more crucial role in rotation for unstiffened column webs compared to stiffened ones.

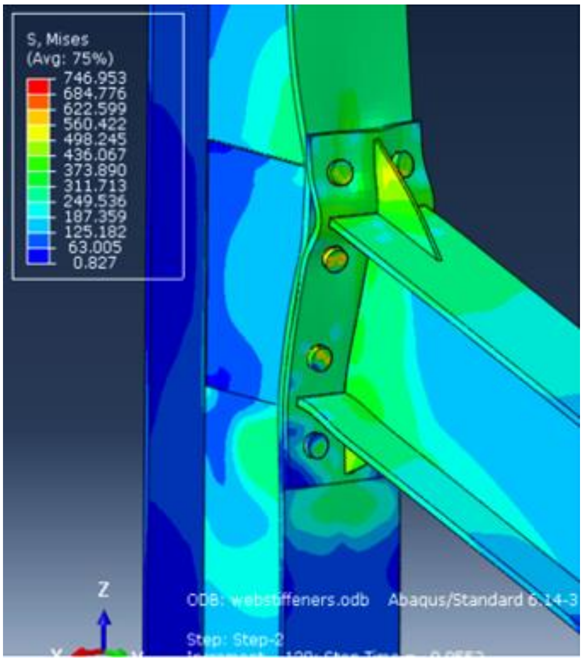
Furthermore, the absence of column web stiffeners in the design of extended end-plate bolted connections can lead to column web buckling, resulting in premature joint failure, as demonstrated in Figure 11.



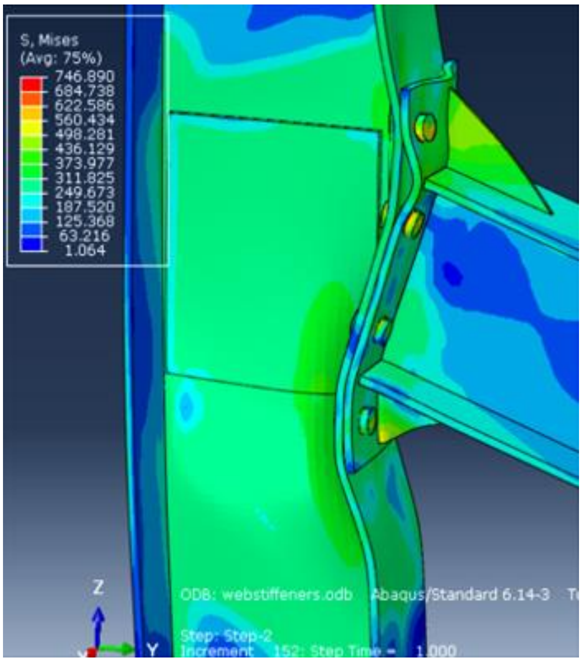
(a) Compresion and Tension stiffeners



(b) No column web stffeners



(c) Double web stiffeners 2×7 mm



(d) Single web stiffeners 7 mm

Figure 11. Von Mises stress representation and ultimate failure modes.

The findings displayed in Figure 11 reveal that failure in the joint without stiffeners (b) is primarily governed by the failure of the column web panel in shear and the column web in transverse compression. On the other hand, joints equipped with transverse stiffeners in both the tension and compression zones (a) demonstrate an elastic response. In this case, the failure mode occurs due to significant bending deformation of the end plate. As the end plate's deformation increases and reaches the ultimate stress, it leads to the yield and rupture of the bolts, resulting in joint failure.

In the case of double-column web stiffeners (c), failure occurs as a result of bolt fracture and end-plate buckling. For joints with a one-sided web plate (d), failure is predominantly influenced by the failure of the column web in compression and the column web panel in shear. Also, it is noted that the presence of the end-plate rib stiffeners on both sides reduces stress concentration in the weld between the beam flange and the end plate, especially on the upper side. Furthermore, it can contribute to a reduction in rotation capacity.

5.2. Thickness Effect of End Plate

Figure 12 illustrates the influence of different end-plate thicknesses (10mm, 15mm, 20mm, and 25mm) on the moment and rotation capacities of the analyzed connections. The results indicate that as the end-plate thickness increases, the moment resistance also increases. However, a corresponding decrease in rotation capacity occurs with the higher end-plate thickness, resulting in a non-ductile connection. Generally, it is observed that reducing the end-plate thickness results in a lower moment capacity. The thickness of the end plate plays a significant role in determining the connection's ultimate moment and rotational capacity.

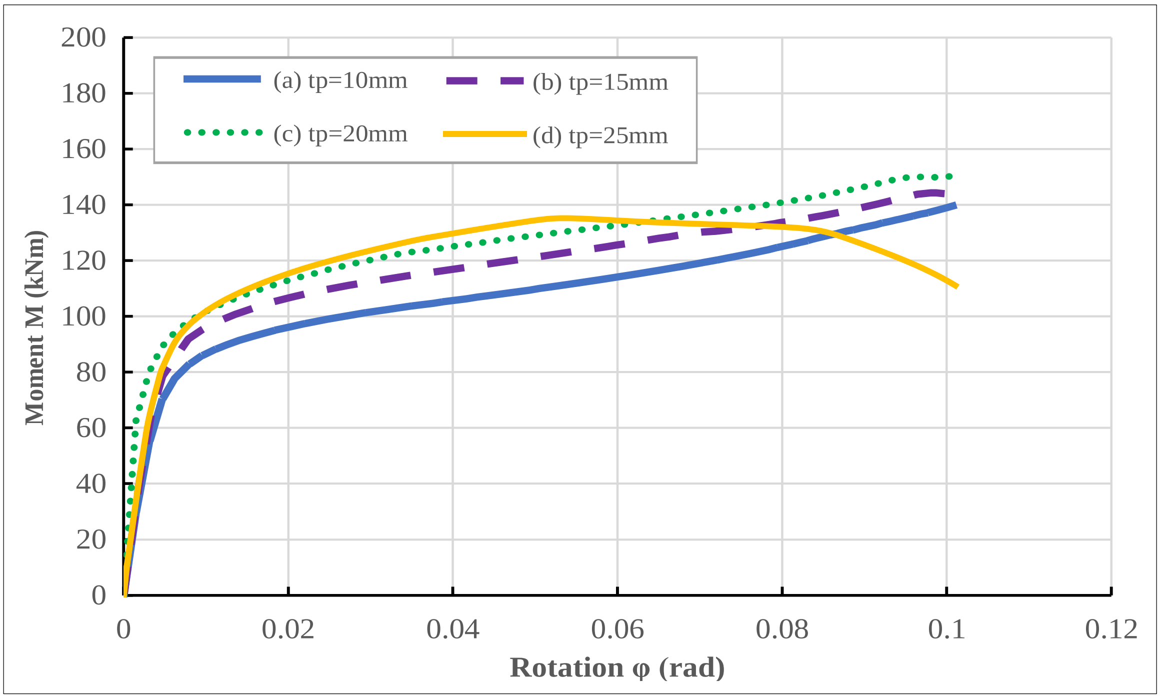
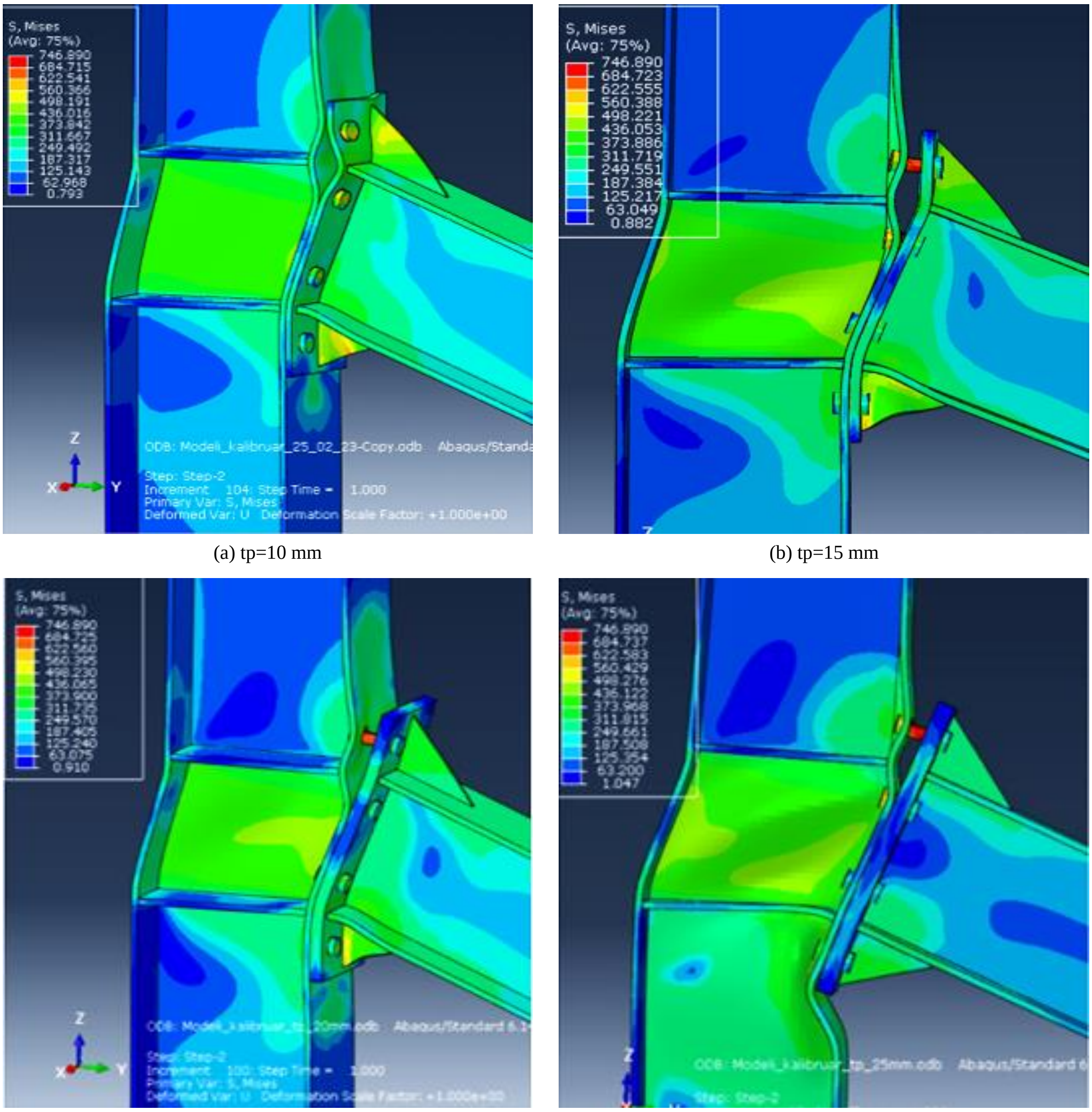


Figure 12. Monotonic results of M-φ for different end-plate thickness tp

When the end-plate thickness is increased, the strength of the bolts becomes a more significant contributing factor, leading to higher tensile forces in the bolts and subsequently increasing the moment capacity. However, it should be noted that as the end plate thickness reaches 20mm and 25mm, as shown in Figures 13c and 13d, the bolt tends to fail in a brittle manner, resulting in a reduced rotation capacity for the connection. In these cases, most areas of the end plates remain within the elastic range, while the bolts experience brittle failure.

The failure modes observed in the connections vary with the increase in end-plate thickness, as shown in Figure 13. With a thin end-plate thickness of 10mm (a), failure predominantly occurs due to the complete yielding of the end plate and column flange. This outcome is because the thin end plate's thinness restricts the connection from exhibiting its full joint performance, leading to premature failure. As the end-plate thickness increases to 15mm (b), failure is characterized by the yielding of the flange and bolt fracture, and for this thickness, the joint has the most significant rotation capability. For the 20mm end plate (c), the main cause of failure is bolt fracture, and there is no bending deformation in the end plate. This is because the thickness of the column flange is 50% smaller than that of the end plate, which leads to the failure mechanism primarily focusing on bolt-related issues rather than end-plate deformation. Finally, with a 25mm end-plate thickness (d), failure occurs through a combination of bolt fracture and compression of the column in the panel zone.

Given the conclusions drawn from this parametric study, it is advisable to restrict the thickness of the end plate, especially in bending applications. This precautionary measure aims to prevent the risk of brittle bolt failure. Moreover, it is essential to consider the thickness of other components involved in the joints, such as the column flange thickness, to ensure a well-balanced and reliable connection. By selecting an appropriate end-plate thickness, the desired moment and rotation capacities can be achieved while maintaining the integrity and reliability of the bolted connection.



(a) tp=10 mm (b) tp=15 mm

(c) tp=20 mm (d) tp=25 mm

Figure 13. Von Mises stress representation and ultimate failure modes

6. Conclusions

This paper presents the development of a finite element model for extended end-plate bolted connections under static loading. The numerical outcomes were contrasted with the experimental findings, and after verifying the model, the parametric study was carried out. The performance of an unstiffened end-plate connection was compared to three types of stiffened connections. Additionally, this study involved comparing joint behavior regarding four different end-plate thicknesses. Based on the analysis, the following key findings are summarized:

- The developed finite element model demonstrates excellent accuracy in simulating the behavior of extended end-plate bolted connections. It provides valuable insights into the mechanical behavior of joints that are challenging to measure through experimental tests.
- The finite element method allows for parametric analysis of the connection, enabling comprehensive results that could be used to propose an analytical design procedure consistent with Eurocode's component method design approach.
- Incorporating web stiffeners in the panel zone offers a straightforward approach to enhancing both joint and panel zone strength and stiffness. These stiffeners effectively reduce shear deformation within the panel zone, making their inclusion in the connection essential.
- Column web stiffeners significantly enhance moment resistance and rotation capacity. Failure due to column web buckling can be avoided by incorporating these stiffeners into the design.

- End-plate rib stiffeners on both sides reduce the stress concentration in welding between the beam flange and the end plate, especially on the upper side.
- In unstiffened joints, the weakest component is the column web panel under compression, shear, or tension. By adding stiffeners, the design resistance of these components increases, resulting in higher moment resistance. Transverse stiffeners (compression and tension) increase the design moment resistance by 60%. Double web stiffeners provide a moment capacity increase of approximately 50% but with limited rotation capacity. Single web stiffeners offer a moment resistance increase of around 22% with a modest rotation capacity.
- The end plate's thickness significantly impacts the behavior of extended end-plate bolted connections, particularly in terms of moment and rotation capacity. Thicker end plates (10mm and 15mm) yield an approximate 20% increase in the ultimate moment. However, with end-plate thicknesses of 20mm and 25mm, the increase in moment and rotation capacity is minimal. A 25 mm thickness may result in brittle bolt failure and reduced rotation capacity. Therefore, it is recommended to maintain a suitable ratio t_f/t_p between the column flange thickness and end-plate thickness, preferably between 1 and 1.5, to avoid collapse.

These findings presented in this study provide valuable insights for the design and analysis of extended end-plate bolted connections. This information enables engineers to make informed decisions regarding column web stiffeners and end-plate thickness to enhance the overall performance and reliability of such connections.

7. Declarations

7.1. Author Contributions

Conceptualization, A.G., F.S., P.C., and A.M.; methodology, A.G., F.S., P.C., and A.M.; software, A.G. and F.S.; validation, A.G. and F.S.; formal analysis, A.G., F.S., P.C., and A.M.; investigation, A.G., F.S., and P.C.; resources, A.G., F.S. and P.C.; data curation, A.G. and F.S.; writing—original draft preparation, A.G. and P.C., writing—review and editing, A.G., F.S., P.C., and A.M.; visualization, A.G. and F.S.; supervision, P.C. and A.M.; project administration, A.G. and F.S.; funding acquisition, A.G., F.S., P.C., and A.M. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Institutional Review Board Statement

Not applicable.

7.5. Informed Consent Statement

Not applicable.

7.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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