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FINITE ELEMENT 3-D MODELLING OF SEMI RIGID STEEL BEAM-TO-COLUMN CONNECTIONS WITH TOP-AND-SEAT AND DOUBLE WEB ANGLES

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Abstract. Semi rigid beam to column connections are pivotal in shaping the behavior and efficacy of steel structures. Their inherent flexibility significantly impacts load transmission mechanisms, structural responses and internal force redistributions. Widely applied in steel structures enduring substantial loads, especially in towering structures, bridges and industrial complexes. These connections fall into two primary categories: moment-resisting and shear connections. Moment-resisting connections are precisely constructed to convey bending moments between members, enabling controlled rotation. These joints typically join bolts, welds and plates to form a linkage proficient in transferring moments among the interconnected members. Conversely, shear connections are devised to relay shear forces between members while accommodating rotational motion, predominantly relying on bolts or welds for shear force transmission.

Partially restrained steel beam to column connections are engineered to permit rotational movement between the beam and column while upholding a degree of stiffness and strength. Analytical investigations employ nonlinear finite element modeling techniques through software like ABAQUS, encompassing geometric and material nonlinearities. ABAQUS capabilities are harnessed to replicate bolt pretension and precisely simulate interactions among angles, columns, beams and bolts. Validation of finite element model outcomes closely corresponds with experimental and analytical findings.

This study aims to validate the usage of angle cleats instead of extended end plates and analyze the impact of various parameters on the stiffness of semi-rigid connections via moment-rotation curves. It offers recommendations focusing on an exhaustive exploration of semi rigid beam to column steel connections with angles through finite element modeling to comprehend their behavior under diverse loads, considering connection stiffness and geometry.

Keywords: Top and seat angles, Joints, Angle connection, Finite element analysis, Double web angles, Pretension bolts and Semi-rigid connections

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1 Introduction

The utilization of Bolted Top and Seat Angle Connections with Double Web Angles (TSDW) are common in steel and composite structures due to their notable moment capacity and ease of construction, primarily serving to withstand the gravity loads of specific steel beams. TSDW falls under the category of semi-rigid beam-to-column connections, necessitating consideration of moment-rotation (M-θ) behavior in force distribution and structural analysis, highlighting the critical importance of accurately predicting the M-θ behavior of TSDW joints. The M-θ behavioral patterns of steel connections are pivotal aspects of their response, particularly concerning initial stiffness ($S_{j,ini}$), maximum moment capacity (M_n), and maximum rotation (θ_u), with the precise estimation of these characteristics enabling a dependable simulation of actual behavior for optimal structural design outcomes. In the context of a steel building, the accurate prediction of connection behavior is essential for understanding the overall structural response and determining the precise distribution of forces among interconnected steel elements reliant on such connections. When analyzing steel frames, connections are typically categorized as either rigid or pinned. Rigid connections ideally prevent any relative rotations between the connected components, while pinned connections ideally offer no resistance to moments. This distinction gives rise to a third type of connection known as semi-rigid, which permits controlled relative rotations and can resist certain moments based on the stiffness of the connection. The semi-rigidity is influenced by a multitude of parameters including top and seat angles, double web angles, gage length, bolt diameter, number of bolt rows, vertical and horizontal bolt spacing, bolt grade, pretension force in the bolts, beam and column dimensions, steel yield strength and the friction coefficient between contacting surfaces, among others. Due to the complexity and numerous variables involved, thoroughly studying the behavior of these connections was historically challenging and often required costly physical experiments. However, with the advancement of computer programs, finite element modeling (FEM) has emerged as a valuable tool providing accurate insights into such connection types. Eurocode 3 [1] offers a mathematical approach, known as the component method, to characterize the behavior of semi-rigid connections based on the moment-rotation (M-θ) characteristics of the joint aiding in a more understanding of their structural response and behavior.

2 Literature Review

An extensive review of the existing literature is conducted to analyze the previous studies on semi-rigid connections in steel structures. The review encompasses the various approaches, analytical models, experimental investigations, and numerical simulations employed in studying such connections. The findings from the literature review provide the foundation for the development of the research methodology. Ghindea et al. [2] (2016) presented analytical methods for beam-to-column joints with angle cleats and bolts, they compared the analytical results against calibrated numerical data and conducting sensitivity analyses. Highlighting the semi-rigid behavior of bolted connections with angle cleats and suggesting future research directions to expand the analysis to other joint configurations and utilized the components method based on SR EN 1993 1-8. Van et al. [3] (2019) presented a study on optimizing steel frame structures with semi-rigid beam-column connections using the Genetic Algorithm method implemented through Matlab demonstrating. They considered the existent behavior of semi-rigid connections results in lighter and more economical structures due to improved internal force redistribution. Živković et al. [4] (2020) introduced an innovative extension to the classic deformation method for globally analyzing steel structures with semi-rigid connections, focusing on the rotational rigidity of connections to evaluate tension and deformation fields within structures, they provided a straightforward and general calculation method suitable for both computational and manual applications, with potential cost-saving implications in steel frame design. Faridmehr et al. [5] (2021) studied the ultimate moment capacity and the initial stiffness of top and seat angle connections with double web angles (DWA), using various mechanical models. They introduced an optimized artificial neural network (ANN) model which is based on the artificial bee colony (ABC) algorithm, that outperformed Eurocode 3, shedding light on the challenges of accurately modeling plastic responses and interactions in bolted connections, emphasizing the importance of relationships among constitutive components and the limitations of traditional modeling methods in capturing essential behaviors. El-Abidi et al. [6] (2013) investigated semi-rigid beam-to-column connections with fasteners by testing 6 specimens under monotonic loading: 4 with double web angles and 2 with top-seat angles, revealing distinct failure modes and differing material strengths affecting stiffness and moment capacity as shown in Figure 1.

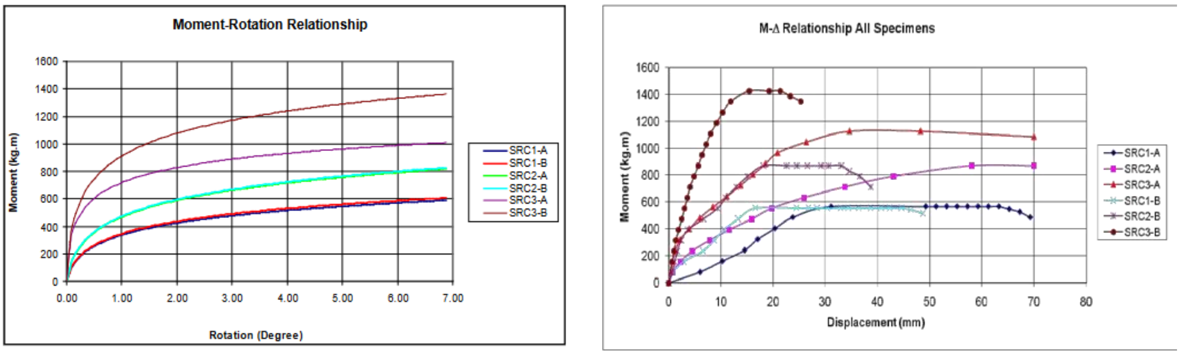


Fig. 1. M-θ relationship from analytical solution and M–Δ relationship from test result (El-Abidi et al. [6])

Ghindea et al. [7] (2015) experimentally tested four different configurations of bolted angle connections in steel beam-to-column joints to assess their elastic and inelastic behavior under bending loads, highlighting the varying nonlinear moment-rotation responses of the connections as shown in Figure 2. The effectiveness of stiffened top and seat angle cleats over web angles and the specific advantages of the TS-10 configuration for stiffness and moment resistance gains.

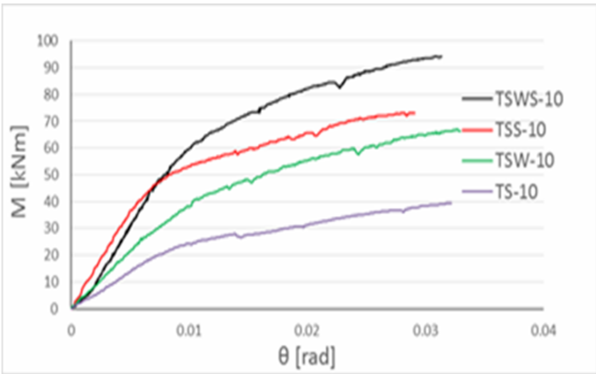


Fig. 2. Comparison of moment-rotation behavior for different connections (Ghindea et. al [7])

Tusnina et al. [8] (2017) explored the behavior of semi-rigid joints in girder-column connections through experimental and theoretical investigations, utilizing the ABAQUS 6.13 computational tool, to determine the stiffness and actual behavior of a beam-to-column connection, featuring paired vertical angles bolted to the beam web and column flange, with an emphasis on the significance of angle's deformation in the joint's overall deformability and the transition to the elastic-plastic stage in the column flange connection angles. Prabha et al. [9] (2015) proposed an enhanced polynomial model for angle connections, considering the air-gap distance as a supplementary parameter to address limitations of the Frye-Morris model, demonstrating improved accuracy in predicting moment-rotation behavior by incorporating this important factor often overlooked in connection stiffness estimations. The moment-rotation curves derived from Finite Element Analysis (FEA) are contrasted with the experimental findings in Figure 3.

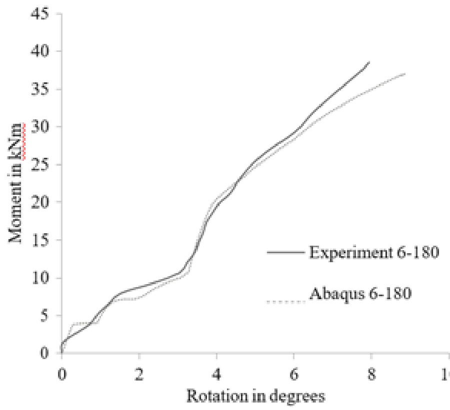


Fig. 3. Comparison of moment-rotation curves (Prabha et al.[9])

Ahmed and Hasan [10] (2015) demonstrated that plastic hinges in steel connections occur at various locations, including the top angle's heel, bolt shank and bolt hole regions, challenging the assumptions of Kishi and Chen's 1990 power model. Their findings highlighted the significance of top angle thickness and gage distance on prying action emphasizing the impact of distributed prying force on connection failure. The study proposed a mathematical formulation to determine the prying force action point, confirming the finite element analysis model's validity and providing insights into plastic hinge locations and prying force effects, with key conclusions emphasizing deviations from previous assumptions: the movement of prying force with increasing connection moment and the importance of accurate prying force location determination for design considerations. Kong and Kim [11] (2015) investigated the moment-rotation behavior of single angle connections bolted to the beam web and column flange. proposing simpler hyperbolic function models that exhibit improved accuracy over existing models like the Power model of Kishi and Chen and the Log model of Lee and Moon within a wider range of behavior, demonstrating the practical utility of their findings. Varsha and Senthil [12] (2017) investigated the semi-rigid behavior of single web angle connections in steel structures, employing adjustments to the stiffness matrix and partial moment release factors in Staad Pro to simulate semi-rigidity, with findings suggesting the feasibility of utilizing a partial moment release factor of 0.74 to replicate the behavior of single web angle connections accurately.

While experimental works have become increasingly limited in recent years, the results derived from experiments remain the most reliable. Jabłońska-Krysiewicz and Gołowczyc [13] (2018) analyzed moment-rotation curves for beam-to-column joints with flange cleats using numerical elastic-plastic 3-dimensional finite element models to evaluate connection deformation. The results indicated that while the finite element (FE) models slightly underestimated experimental outcomes, adjustments accounting for dimensional variations in sections, bolt prestressing forces, and bolt positions could improve alignment between experimental and numerical results as shown in Figure 4.

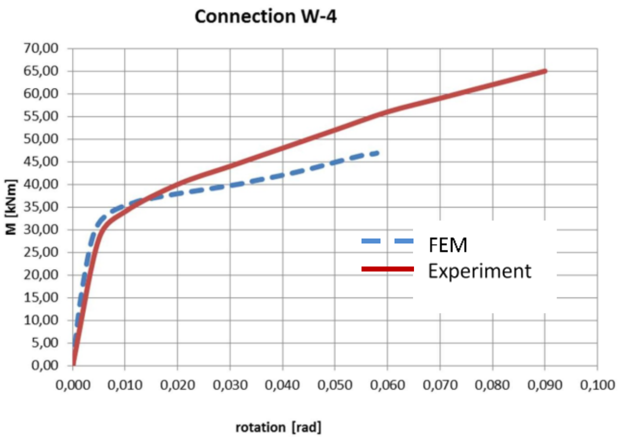
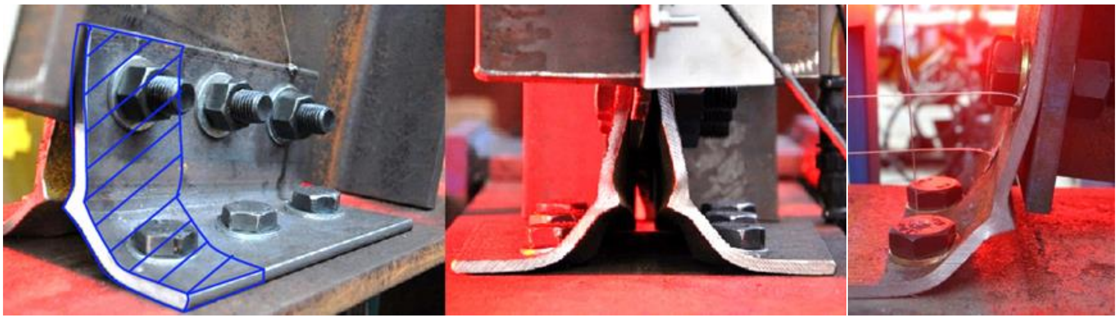


Fig. 4. Moment-rotation curves comparison between FEM analysis and experimental research (Jabłońska-Krysiewicz and Gołowczyc [13])

Yan et al. [14] (2020) explored the flexural behavior of DWA connections through experimental tests and an advanced mechanical model based on the Component Method. As indicated by the comparison illustrated in Figure 5, an angle segment exhibits a deformation pattern similar to that of a tensile flange cleat utilized in top and seat angle connections, demonstrating good agreement between model predictions and experimental results, providing insights into complex load transfer mechanisms and connection behavior from initial stages to complete failure.



(a) Deformation of web angle (b) Flange angle deformation

Fig. 5. Analogy between web angle and top flange angle (Yan et al. [14])

Al Fakih et al. [15] (2018) investigated the behavior of DWA in steel connections using ABAQUS, focusing on finite element analysis to simulate DWA connections with material and geometric nonlinearities, achieving strong agreement between numerical predictions and experimental results for moment-rotation relationships and deformations, demonstrating the reliability of the numerical model for analyzing DWA steel beam-column connections. Reinosa et al. [16] (2015) developed reliable 3D finite element models of stiffened angle connections using ABAQUS software, aiming to understand 3D deformational responses. The presence of angle stiffeners significantly increased initial connection stiffness and stress in the column panel zone, potentially altering the behavior of angle connections, indicating their potential as a robust option in European steel construction. In the second part of the paper by Ghindea et al. [17] (2016), advanced numerical simulations using ABAQUS software were conducted to develop accurate finite element models of bolted beam-to-column connections, aiming to faithfully reproduce experimental results and provide deeper insights into joint behavior with good agreement observed in terms of stiffness and bearing capacity for bending moments. Al-Fakih et al. [18] (2019) investigated the behavior of top and seat angle with double web angle bolted steel beam-to-column connections under various loads using numerical finite element analysis, highlighting the impact of factors like bolt strength and quantity on load-bearing and rotation capacities, with the numerical model effectively capturing the overall behavior observed in experimental tests. Ghodajkar and Sawant [19] (2018) aimed to analyze moment-rotation responses of semi-rigid connections for design purposes using Finite Element Method (FEM) models, noting that under different loads with accelerations, the top and seat angle connection displayed lower stress levels compared to double web angle and extended end plate connections, suggesting a preference for the former due to their consistent performance across various load scenarios. Gomes et al. [20] (2018) assessed semi-rigid connections through a numerical model validated against experimental data, two analyses were conducted on the experimental model. One involved a full nonlinear static analysis without considering rupture criteria, while the other incorporated the progression of damage in an explicit dynamic analysis. Both sets of results exhibited strong agreement with the experimental data, as depicted in Figure 6. Conducting a parametric study on flush endplate connections by varying bolt diameters and endplate thicknesses to explore their ultimate capacity, revealing that larger bolt diameters increased rotation capacity and thicker endplates enhanced bending moment capacity, emphasizing the importance of these factors for structural resilience and ductility in extreme events.

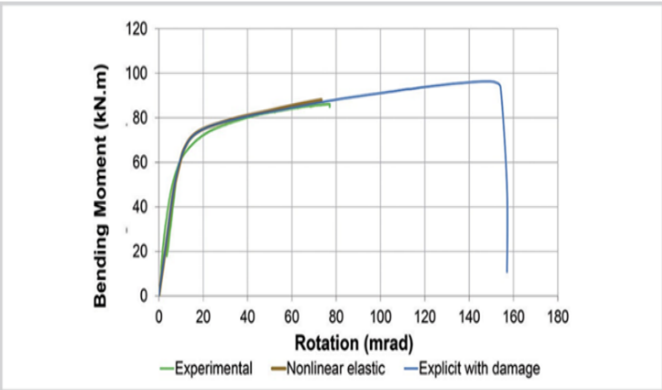


Fig. 6. Comparison between static and explicit analysis with connection damage. (Gomes et al. [20])

Aydin et al. [21] (2021), analyzed the behavior of 6 steel bolted T-connection models and 4 steel bolted beam-to-column connection models with top and seat angles, showing a 2–29% decrease in energy dissipation for bolted T connections and 2–13% for top and seat angle connections across five hysteretic loadings, focusing on comparing energy dissipation levels using moment-rotation hysteresis curves and exploring key factors affecting the connections' performance.

3 Verification

The software ABAQUS is utilized to model the behavior of bolted angle connections under monotonic loading conditions. The advanced features of ABAQUS 2018 enable accurate simulation and analysis of the mechanical characteristics of bolted top and seat connections with double web angles. These capabilities facilitate the simulation of the selected angles and the generation of moment-rotation curves, which are needed for capturing the intricate interactions within the connection elements. Parameters such as geometric and material nonlinearities, bolt pretension forces, responses to stress distributions, contact mechanics between bolts and angle components, compressive interface stresses, and friction are considered in this study. However, factors like bolt clearance-induced slip, imperfections (e.g., residual stresses), and environmental influences (e.g., temperature) are not accounted for in the FE modeling.

The following 2 verification models are used to confirm the accuracy of the proposed 3-D model:

3.1 Gang Shi Experimental Model

Moment-rotation curves derived from the analytical model data were plotted and subsequently compared with the moment rotation curves generated from the ongoing finite element modeling. Table 1 displays the loading capacities derived from analytical model outcomes. Figure 7 illustrates the comparisons between the moment-rotation curves from the present study, the experimental tests, and prior finite element analyses.

To verify the non-linear proposed model, the numerical simulation results are compared with those previously obtained by Yongjiu Shi et al. [22] and Fattouh M.F. Shaker et. al. [23] specifically concerning moment-rotation curves. The test specimen EEP1 was specifically selected for validation purposes. The moment-rotation curves from both numerical models simulation and the experimental data are aligned with identical definitions, as used in the experimental tests, and are depicted in Figure 7. The key findings are shown in Table 1.

Table 1. Loading capacities derived from analytical model outcomes.

Specimen type	M (kNm) Experimental test [22]	M (kNm) Previous FEA [23]	M (kNm) Proposed FEA	Proposed FEA / Experimental test [22]	Proposed FEA / Previous FEA [23]
EEP1	256.90	242.68	249.17	0.97	1.026

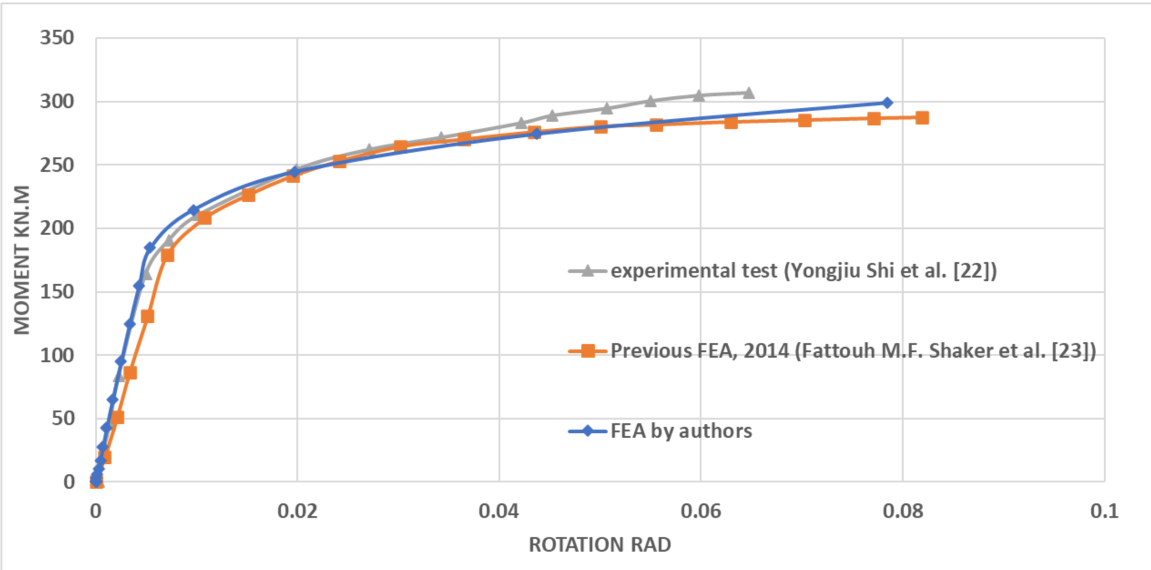


Fig. 7. Moment-rotation curves comparison between the experimental test (Yongjiu Shi et al. [22]), Previous FEA, 2014 (Fattouh M.F. Shaker et al. [23]) and proposed FEA.

3.2 Azizinamini Experimental Model

Azizinamini et al. [24] experimental data on steel bolted angle connections with double web angles under monotonic loading are employed to validate the results of computer analyses. The test specimen 14S1 was specifically selected for validation purposes due to its contrasting beam depth and beam flange angle, as detailed in Figure 8.

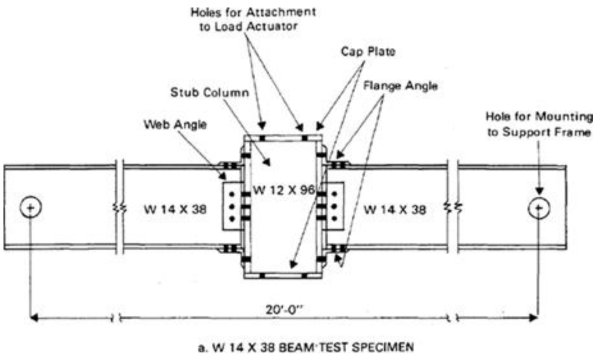


Fig. 8. General configurations of the test specimen (Azizinamini et al. [24])

To confirm the proposed model, the numerical results are compared with the experimental data conducted by Azizinamini (1989) [24] and the numerical result from Previous FEA, 2019 (Fahmy et al. [25]), regarding load-displacement characteristics, moment-rotation behaviors, and failure modes of the connections. The connection loading capacity is determined by identifying the peak force at the loading point.

The Finite Element model demonstrates a strong correlation with the experimental data, particularly evident in the M-θ curves illustrated in Figure 9. Notably, the alignment between the experimental and Finite Element results is more pronounced in the initial stages compared to the later stages. In the non-linear response range, the results from the FEA closely resemble those of the experimental data, particularly mirroring the behavior of specimen 14S1.

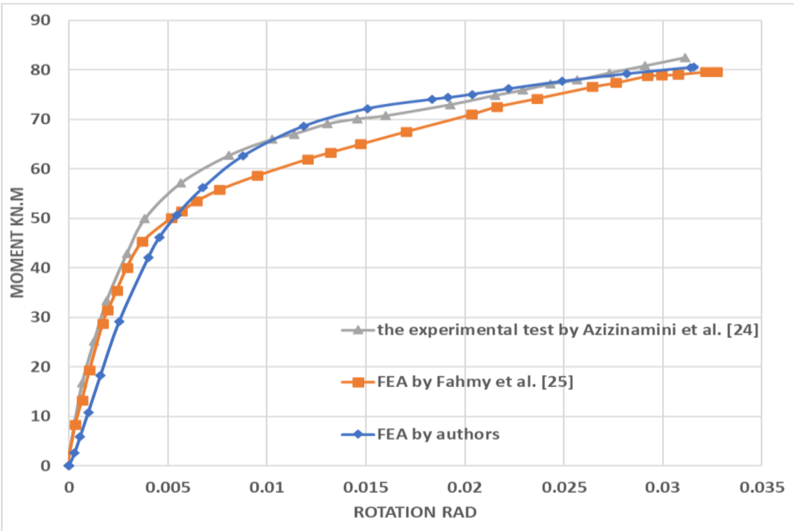


Fig. 9. Moment rotation curves comparison between the experimental test (Azizinamini et al. [24]), Previous FEA, 2019 (Fahmy et al. [25]) and FEA by authors, 2024

Discrepancies between the results of the numerical and the experimental models may arise from:

- Errors linked to the material stress-strain curve approximation
- Imperfections inherent in the experimental setup.
- Errors related to the adjustment of the experimental curve.
- Conclusively, the results affirm that the 3-D FEM serves as a valuable and potent tool for investigating steel connections.

4 Geometric Details of Connections

This study examined bolted top and seat angle connections with double web angles (TSDW) by investigating 10 models as detailed in Table 2 and Figure 10. All models in the study feature beams and columns with identical dimensions as outlined in Table 2, with top and seat angle stiffeners measuring 10 mm thickness and column panel zone stiffeners measuring 10 mm thickness, strategically aligned with beam flanges to optimize their impact on strengthening the impedance of the column flange in bending, as well as the tension and compression zones of the column web.

Table 2. Types and details of the considered specimens in this study.

Specimen number	Flange-Angle size (mm)	Web-Angle size (mm)	Bolt diameter *d* (mm)	Column stiffeners	T&S Flange stiffeners
TSDW 12	180*180*18	90*90*9	12	Yes	No
TSDW 16	180*180*18	90*90*9	16	Yes	No
TSDW 24	180*180*18	90*90*9	24	Yes	No
TSDW 140x14	140*140*14	90*90*9	20	Yes	No
TSDW 150x14	150*150*14	90*90*9	20	Yes	No
TSDW 160x16	160*160*16	90*90*9	20	Yes	No
TSDW 180x18	180*180*18	90*90*9	20	Yes	No
TSDW 180x18-1	180*180*18	90*90*9	20	No	No
TSDW 180x18-2	180*180*18	90*90*9	20	Yes	Yes
TSDW 180x18-1-2	180*180*18	90*90*9	20	No	Yes

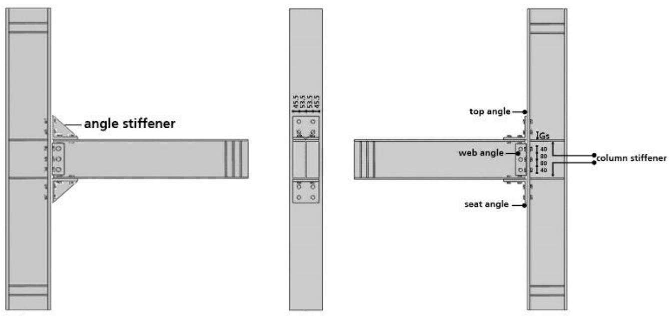


Fig. 10. Details of studied TSDW connections (dimensions in mm)

5 Finite Element Modeling

The behavior of bolted angle connections under monotonic loading was simulated using the finite element software ABAQUS, where all connected components (beams, columns, angles, bolts and stiffeners) were modeled with a continuum three-dimensional eight-nodded brick element (C3D8) to capture elastoplastic material behavior considering non-linearities from contact, plasticity, and large displacements. Steel plate stress-strain relationships were defined as elastically-perfect plastic using a Poisson's ratio of 0.3, with different yield strengths and elastic moduli for plates thicker than 16 mm (363 MPa and 204,227 MPa) and thinner than 16 mm (391 MPa and 190,707 MPa). Stress-strain relationships for bolts were specified according to Table 3 and pretension forces were determined based on AISC LRFD guidelines outlined in Table 4, ensuring a coherent modeling approach aligning nodes of beams, columns and angles to account for contact interactions between adjacent nodes.

Table 3. Material properties for high strength bolts by Yongjiu Shi et al. [22]

Stress (MPa)	Strain (%)
0	0
990	0.483
1160	13.60
1160	15.00

Table 4. Minimum pretension forces in bolts according to AISC-LRFD.

Bolt diameter, d (mm)	Pretension force (kN)
12	69
16	114
20	179
24	257

In the proposed model, the bolt comprises a head screw and a nut, where the head screw is represented by a rod with a constant cylindrical diameter equal to 1.5 times the shank radius, while the head of the bolt is depicted by a solid cylinder with a thickness 1.25 times that of the bolt shank and the nut is portrayed as a solid cylinder with a thickness 1.5 times that of the bolt shank. A mesh convergence analysis was conducted to determine an optimal mesh density for obtaining accurate results within a practical computational timeframe. A maximum mesh spacing of 20 mm was applied to the beam, column and angles, while a 5 mm mesh was utilized for bolts and holes. Establishing contact between various components of the model is a pivotal stage. Surface-to-surface contacts were defined for interactions such as angle-beam, angle-column, bolt head-angle, bolt shank-hole, bolt head-beam and bolt head-column to accurately model the connections. These contacts were established from the initial step through to bolt pretension and loading steps, guided by tangential and normal behavior properties for the contact surface interaction, with a frictional coefficient of 0.44 for tangential behavior using the same value as employed in the experimental test conducted by Yongjiu Shi [22] and a "hard" contact assumption for normal behavior, ensuring constraints only when surfaces are in direct contact to prevent sticking.

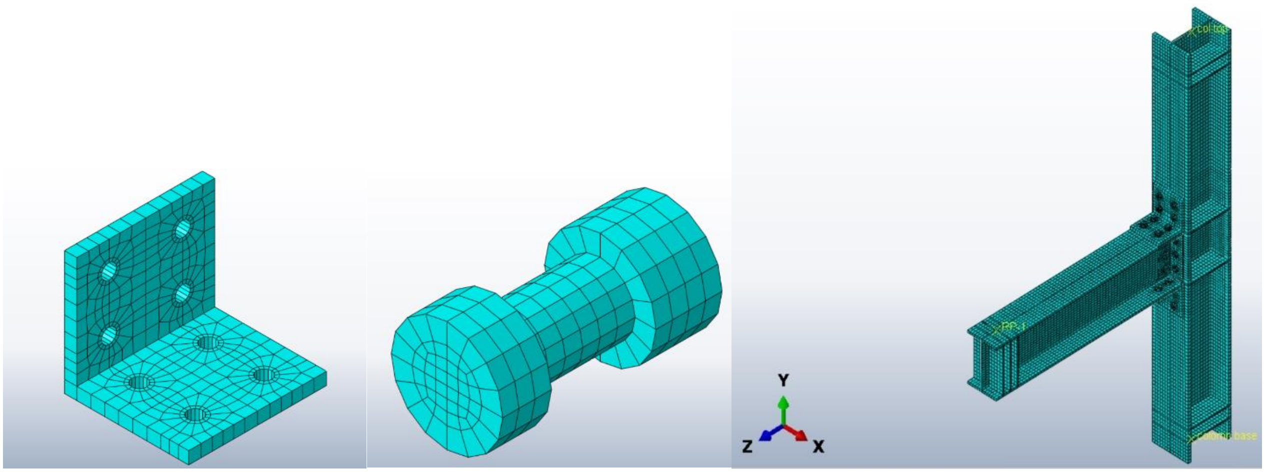


Fig. 11. Finite element mesh

5.1 Boundary Conditions

To prevent movement, all degrees of freedom beyond the symmetric plane were constrained, with nodes along the (Y and Z) plane passing through the connection centerline restricted from translating in the X-direction and from the rotation around the Y and Z-directions. Imitating the experimental setup, the column was constrained near its ends against Z-direction translation and restricted against translation in the X, Y, and Z-directions at one end, aligning with the configuration detailed in the study by Yongjiu Shi et al. [22]. The finite element model's dimensions and loading arrangements for both connection types matched those utilized in the experimental tests are illustrated in Figure 12.

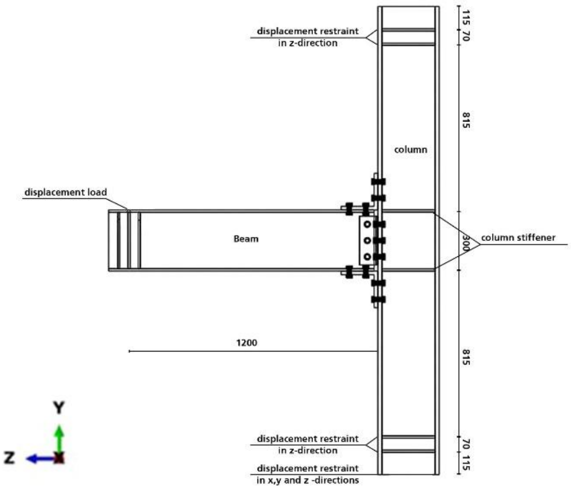


Fig. 12. Dimensions and loading arrangement of the FEM with the same values of the experimental test by Yongjiu Shi et al. [22] (all dimensions are in mm).

6 Results and Discussion

6.1 Definition of the Moment-Rotation Curve:

The subsequent validation and parametric investigation revolve around analyzing the moment-rotation (M-θ) curves of each connection. The joint moment, denoted as M_j, is determined as the load multiplied cantilever length which is 1200 mm (as illustrated in Fig. 12). The joint rotation θ of the connection is characterized as the proportional rotation between the centerlines of the top flange and bottom flange at the beam end, encompassing two primary components: the shear rotation originating from the panel zone of the column and the end gap rotation between the angle and the column flange. This includes the bending deformation of the angle and column flange as well as the extension of bolts. The initial rotational stiffness, denoted as $S_{j,ini}$, is described as the slope of the curve during the initial linear phase (as demonstrated in Figure 13).

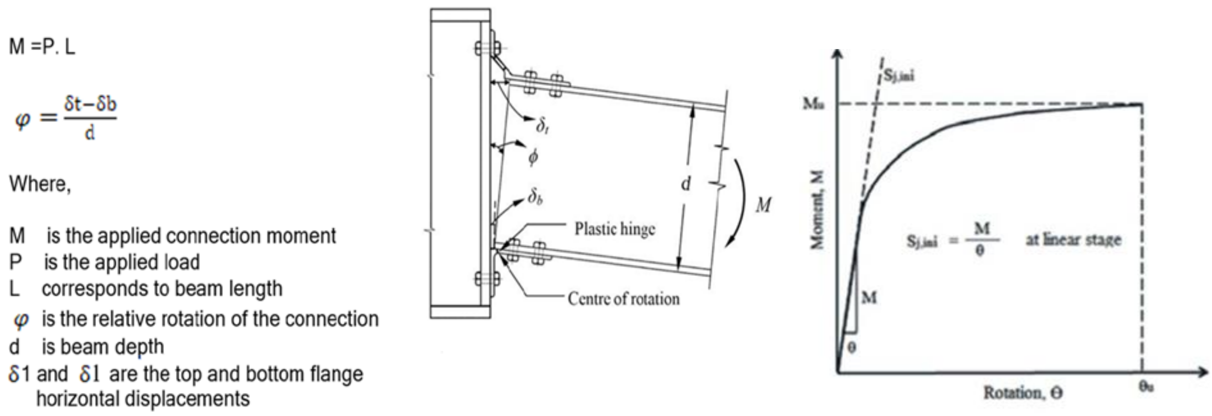
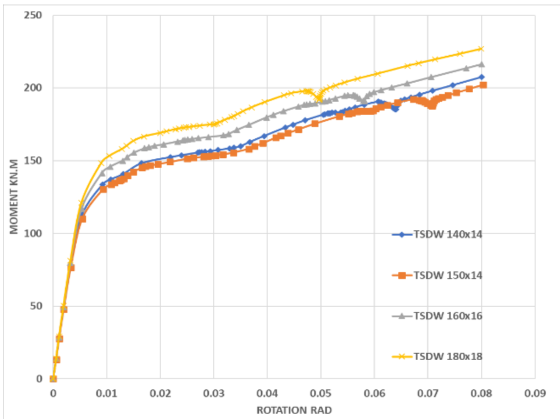


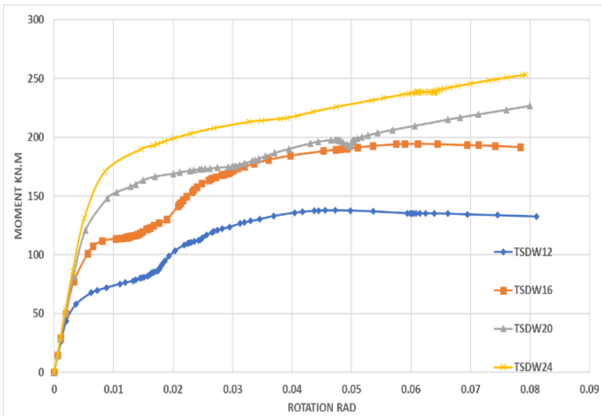
Fig. 13. Definition of joint rotation, φ and joint initial rotational stiffness, $S_{j,ini}$

6.2 Parametric Investigation

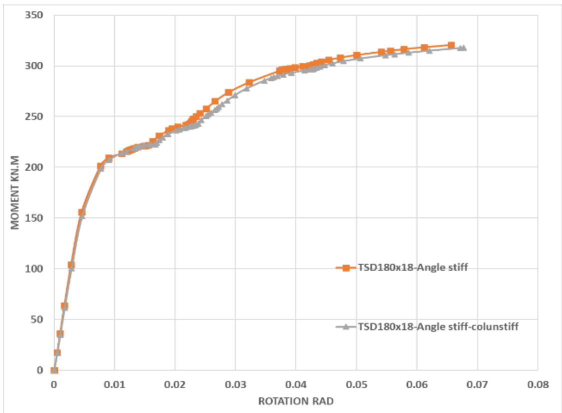
To conduct a comprehensive parametric analysis on the top and seat with double angle connections (TSDW), four key parameters were selected for inspecting the behavior of the connections. These parameters encompass the angle thickness, bolt diameter, gauge distance, presence of column panel zone stiffeners and the stiffening status of the top and seat flanges. Ten finite element (FE) models, configured according to the dimensions outlined in Table 2, were accurately constructed utilizing the ABAQUS program. Subsequently, the results were graphed and deliberated upon to ascertain the impact of each parameter on the overall behavior of the connections. The (M-θ) curves of all connections considered in this study are shown in Fig. 14



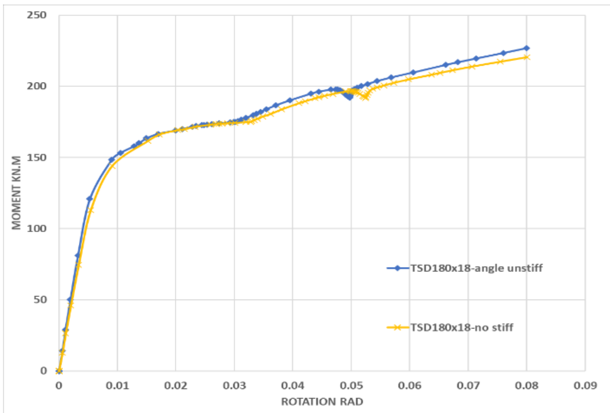
a) Angle thickness effect



b) Bolt diameter effect



c) Angle stiffeners effect



d) Column stiffeners effect

Fig. 14. Comparison of moment-rotation curves for all connections

Table 4 presents the initial rotational stiffness, moment capacity and ultimate rotation values for all connection types. Based on the data depicted in Figure 14 and Table 5, it is evident that the initial rotational stiffness and moment capacity of the top and seat with double web angle connections have ascended. However, the ultimate rotations of the connections have decreased as a result of augmenting both the angle thickness and bolt diameter.

Table 5. Details of model connections

Specimen number	The moment resistance $M_{j.Rd}$ (kN.m)	Variation in $M_{j.Rd}$ (%)	Rotational stiffness S_J (kN.m/rad)	Variation in S_j (%)	Ultimate rotation capacity θ_u (rad.)	Variation in θ_u (%)
TSDW 180x18	226.85	-	26204.9	-	0.0799	-
TSDW 12	132.62	- 41.54	22400.15	- 14.52	0.0811	+ 1.5
TSDW 16	191.48	- 15.6	26012.92	- 0.73	0.0796	- 0.375
TSDW 24	253.27	+11.65	28420.42	+8.45	0.0792	- 0.870
TSDW 140x14	207.42	- 8.50	25413.28	- 3.00	0.0800	+ 0.125
TSDW 150x14	202.26	- 10.84	24565.40	- 6.25	0.0803	+ 0.500
TSDW 160x16	216.29	- 4.65	25736.69	- 1.78	0.0800	+ 0.125
TSDW 180x18-1	220.64	- 2.74	22889.02	- 12.65	0.0800	+ 0.125
TSDW 180x18-2	320.75	+ 41.40	36721.90	+40.13	0.0656	- 17.900
TSDW 180x18-1-2	317.74	+ 40.00	34282.94	+30.80	0.0677	- 15.270
EEP1	289.60	+27.66	27416.00	+4.60	0.0830	+3.880

The variance in values is determined by comparing them with TSDW180x18 for all connections. A negative (-ve) sign indicates a decrease, while a positive (+ve) sign denotes an increase. The information regarding specimen EEP1, which serves as the comparison model, is sourced from Fattouh M.F. Shaker et al. [23].

Conversely, the ultimate rotations of top and seat with double web angle (TSDW) connections decreased with an increase in bolt diameter when the top angle thickness reached 18 mm. Notably, for the (TSDW12) connection with a 12 mm bolt diameter, failure transpired in the bolts (experiencing brittle failure with limited rotation capacity), while in the case of the (TSDW24) connection with a 24 mm bolt diameter, the failure was observed in the top angle (experiencing ductile failure with a substantial rotation capacity).

6.3 Effect of bolt diameter

The moment resistance of TSDW connections is significantly impacted by enlarging the bolt diameter rather than increasing the angle thickness. When transitioning from a 12 mm bolt diameter (TSDW12) to a 24 mm bolt diameter (TSDW24), the moment capacity surged by 90.97%. The initial stiffness of TSDW connections increased consistently when either the angle thickness or bolt diameter was increased. Moreover, the rotational stiffness of TSDW connections relies more on the bolt diameter than the angle thickness. Notably, as the bolt diameter increased from 12 mm (TSDW12) to 24 mm (TSDW24), the rotational stiffness amplified by 26.87% as shown in Figure 15.

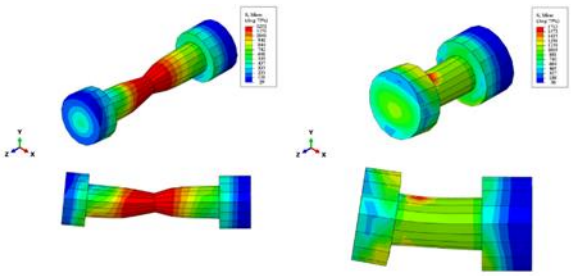


Fig. 15. Deformation of bolts 12 mm and 24 mm

6.4 Effect of angle thickness

When the top angle thickness increased from 14 mm (TSDW140x14) to 18 mm (TSDW180x18), the moment capacity only increased by 9.36% as shown in Figure 16.

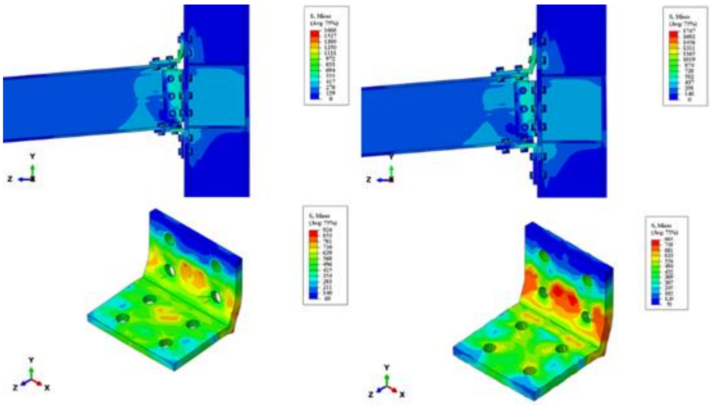


Fig. 16. TSDW140x14 and TSDW180x18 deformation

6.5 Effect of gauge distance

Investigating the influence of gauge distance for top bolts, two models with the same angle thickness but different gauge distances were studied: (TSDW140x14) and (TSDW150x14). Interestingly, an expansion in gauge distance resulted in a 3.45% decrease in initial stiffness and a 2.55% reduction in ultimate moment resistance, while boosting the ultimate rotation by 0.375% as shown in Figure 17.

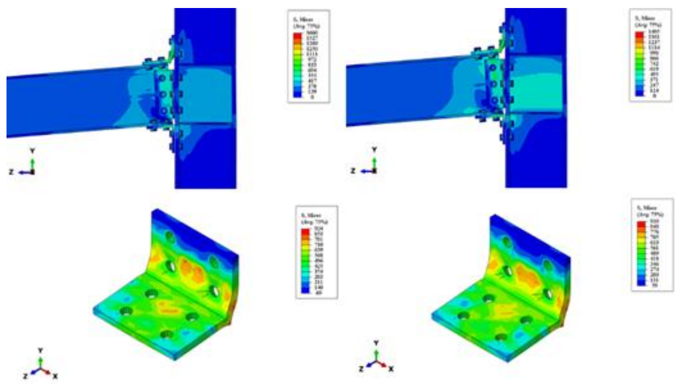


Fig. 17. TSDW140x14 and TSDW150x14 deformation

6.6 Effect of the horizontal column panel stiffeners

Further observations indicate that the initial rotational stiffness and ultimate moment resistance of TSDW connections diminish when the horizontal column panel stiffeners are omitted. For instance, the ultimate moment resistance and initial rotational stiffness of (TSDW 180x18-1) are lower than those of (TSDW 180x18) by 2.8% and 14.48%, respectively as shown in Figure 18.

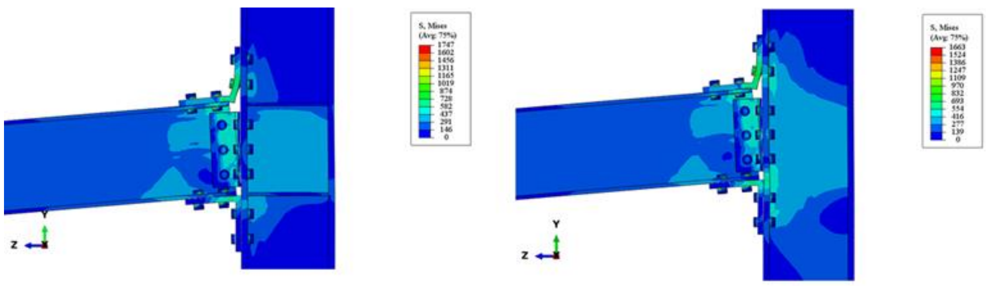


Fig. 18. Horizontal column panel stiffeners Effect

6.7 Effect of angle stiffener

Conversely, the inclusion of top and seat angle stiffeners elevates the ultimate moment resistance and initial rotational stiffness. Specifically, the ultimate moment resistance and initial rotational stiffness of (TSDW 180x18-2) surpass those of (TSDW 180x18) by 41.39% and 40.13%, respectively as shown in Figure 19.

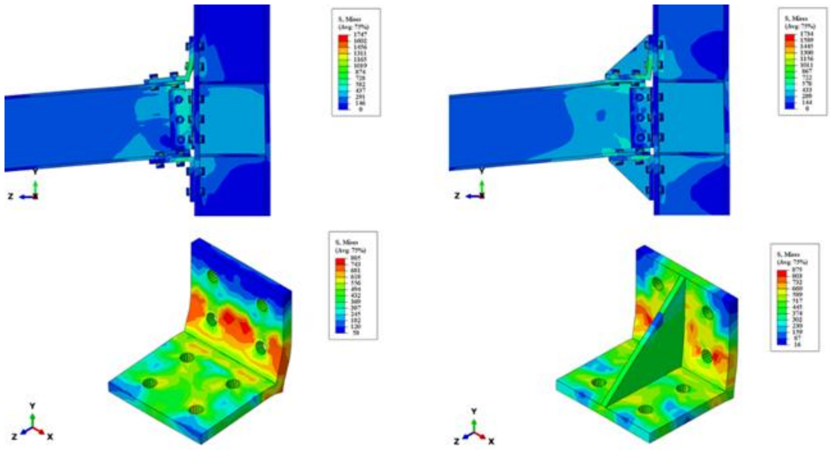


Fig. 19. angle stiffeners Effect

Evidently, enhancing the bolt diameter of the connection is more effective in augmenting the moment capacity of TSDW connections compared to increasing the thickness of the top angle. The primary factor influencing the maximum rotation of TSDW connections is the moment rotation of the T&S stiffener angle in combination with the shearing rotation of the column web panel.

7 Conclusions

Steel connections are commonly categorized as either pinned or rigid, but considering semi-rigid connection behavior is crucial for achieving more realistic and cost-effective outcomes. In the examination of steel top, seat and double web angles connections, one model was validated against experimental tests conducted by Yongjiu Shi et al. [22] and Fattouh M.F. Shaker et. al. [23] and [26] exhibiting closely aligned values. Another model was cross-validated with experimental tests carried out by Azizinamini [24], also demonstrating close agreement.

The present study introduces a three-dimensional finite element model for analyzing steel bolted angle connections under monotonic loading, aiming to investigate the impact of various parameters on connection behavior, including bolt diameter, angle thickness, stiffening of the column panel zone, , bolt diameter and stiffening of the top and seat angles, on initial stiffness, moment resistance and ultimate rotation of the connection. Ten specimens were simulated using the ABAQUS program. The key findings from the cases considered in this investigation are summarized as follows:

1- The initial stiffness and ultimate moment resistance rise by approximately 9.36% when the top and bottom angle thickness is increased from 14 mm to 18 mm.
2- The ultimate rotations of TSDW connections diminish as the bolt diameters and end plate thickness increase.
3- With an increase in bolt diameters, the initial stiffness and ultimate moment resistance surge by 26.87% and 90.97%, respectively.

4- Boosting the bolt diameter of TSDW connections is more effective in enhancing moment resistance compared to increasing the end plate thickness.
5- The ultimate moment resistance and initial rotational stiffness of TSDW connections decrease by 2.8% and 14.48%, respectively when column panel zones are left unstiffened.
6- When top angle stiffeners are incorporated, there are substantial improvements in both joint stiffness and moment resistance compared to similar models without stiffening, increasing by 40.13% and 41.39%, respectively.
7- When comparing the use of angle cleats (TSDW180x18) instead of extended end plate (EEP1), the following observations are noted:
   - The weight of TSDW180x18 is 4.3% greater than EEP1.
   - The ultimate moment resistance and initial rotational stiffness of TSDW180x18 are 27.66% and 4.6% are lower than EEP1, respectively.
   - The ultimate rotations of TSDW180x18 are 3.88% less than EEP1.
8- When comparing the use of stiffener angle cleats with double web angle (TSDW180x18-2) instead of extended end plate (EEP1), the following observations are noted:
   - The weight of TSDW180x18-2 is 4.9% greater than EEP1.
   - The ultimate moment resistance and initial rotational stiffness of TSD180x18-2 are 10.75% and 33.94% greater than EEP1, respectively.
   - The ultimate rotations of TSDW180x18-2 are 26.5% less than EEP1.

8 RECOMMENDATIONS

To reduce the total structure weight and get the initial rotational and ultimate moment resistance stiffness; it is recommended that ECP should allow considering the effect of the stiffener angle cleats with double web angle connections rigidity in the analysis and design of steel structures.

9 REFERENCES

[1] The European Union Per Regulation, "EN 1993-1-8: Eurocode 3: Design of steel structures - Part 1-8: Design of joints," in *Eurocode 3: Design of steel structures - Part 1-8: Design of joints*, 2005.

[2] M. Ghindea, A. Cătărig, and R.-I. Ballok, "Semi-Rigid Behaviour of Bolted Connection Using Angle Cleats Part 2. Analytical and Numerical Evaluation of Beam-to-Column Joints," *Journal of Applied Engineering Sciences*, vol. 6, no. 2, May 2016, doi: https://doi.org/10.1515/jaes-2016-0004.

[3] T. T. T. Van, V. T. B. Quyen, and N. Le Thuy, "Optimization of plane frame structure with consideration of semi-rigid connections," in *Journal of Physics: Conference Series*, Institute of Physics Publishing, Jan. 2020. doi: 10.1088/1742-6596/1425/1/012098.

[4] S. Živković, N. Stojković, M. Spasojević-šurdilović, and M. Milošević, "Global analysis of steel constructions with semi-rigid connections," *Tehnicki Vjesnik*, vol. 27, no. 3, pp. 951–960, Jun. 2020, doi: 10.17559/TV-20180414100627.

[5] I. Faridmehr, M. Nikoo, R. Pucinotti, and C. Bedon, "Application of component-based mechanical models and artificial intelligence to bolted beam-to-column connections," *Applied Sciences (Switzerland)*, vol. 11, no. 5, pp. 1–21, Mar. 2021, doi: doi.org/10.3390/app11052297.

[6] Khaled M. Amtered El-Abidi and Budi Suswanto, "Experimental Study, Stiffness of Semi-Rigid Beam-to-Column Connections Using Bolts and Angles," in *3rd International Conference on Electrical, Electronics and Civil Engineering*, Jan. 2013.

[7] M. Ghindea, A. Cătărig, and R. Ballok, "Behavior of Beam-to-Column Connections with Angles. Part 1-Experimental Investigation," *JOURNAL OF APPLIED ENGINEERING SCIENCES*, vol. 5, no. 2, pp. 21–28, Dec. 2015, doi: https://doi.org/10.1515/jaes-2015-0017.

[8] V. M. Tusnina, "Semi-rigid steel beam-to-column connections," *Magazine of Civil Engineering*, vol. 73, no. 5, pp. 25–39, 2017, doi: 10.18720/MCE.73.3.

[9] P. Prabha, S. Rekha, V. Marimuthu, M. Saravanan, G. S. Palani, and M. Surendran, "Modified Frye–Morris polynomial model for double web-angle connections," *International Journal of Advanced Structural Engineering*, vol. 7, no. 3, pp. 295–306, Sep. 2015, doi: 10.1007/s40091-015-0100-y.

[10] A. Ahmed and R. Hasan, "Effect and evaluation of prying action for top- and seat-angle connections," *International Journal of Advanced Structural Engineering*, vol. 7, no. 2, pp. 159–169, Jun. 2015, doi: 10.1007/s40091-015-0089-2.

[11] Zhengyi Kong and Seung-Eock Kim, "New Moment Rotation Model of Single Web Angle Connections," *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, vol. 9, no. 7, pp. 851–854, 2015.

[12] S. Varsha and R. Senthil, "Semi Rigid Behaviour of Single Web Angle Connection," *International Journal of Mechanical And Production Engineering*, vol. 5, no. 3, pp. 2320–2092, Mar. 2017, doi: IJMPE-IRAJ-DOIONLINE-7298.

[13] A. Jabłońska-Krysiewicz and J. Gołowczyc, "Numerical simulation of beam-to-column joints with flange cleats," in *MATEC Web of Conferences*, EDP Sciences, Jun. 2018. doi: 10.1051/matecconf/201817403009.

[14] S. Yan, L. Jiang, and K. J. R. Rasmussen, "Full-range behaviour of double web angle connections," *J Constr Steel Res*, vol. 166, Mar. 2020, doi: 10.1016/j.jcsr.2019.105907.

[15] K. Al Fakih, S. C. Chin, and S. I. Doh, "Behavior of Double-Web Angles Beam to column connections," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Apr. 2018. doi: 10.1088/1757-899X/342/1/012023.

[16] Reinosa, ; Loureiro, ; Gutierrez, and ; López, "Advanced FE models of stiffened cleat angle connections," in *3rd International Conference on Mechanical Models in Structural Engineering*, Sevilla, España: Víctor Compán Cardiel, 2015, pp. 58–65.

[17] M. Ghindea, A. Cătărig, and R. Ballok, "Behavior of Beam-to-Column Connections with Angles. Part 2-Numerical Analysis," *Journal of Applied Engineering Sciences*, vol. 6, no. 1, pp. 35–40, May 2016, doi: https://doi.org/10.1515/jaes-2016-0004.

[18] K. Ahmed Al-Fakih, S. Choo Chin, and S. Ing Doh, "Behaviour of Top-Set with Double-Web Angle Steel Connections under Applied load," *Saudi Journal of Civil Engineering*, vol. 3, no. 1, pp. 39–45, Mar. 2019, doi: 10.21276/sjce.2019.3.3.5.

[19] M. Vishawadeep, S. Ghodajkar, and D. R. M. Sawant, "FEM Analysis of Steel Beam Column Joint by using Cantilever Weight and Acceleration," *Journal of Ceramics and Concrete Sciences*, vol. 3, no. 3, pp. 16–24, 2018, doi: 10.5281/zenodo.1997397.

[20] V. Gomes, A. T. Silva, L. R. O. de Lima, and P. C. G. da S. Vellasco, "Numerical investigation of semi-rigid connection ultimate capacity," *REM - International Engineering Journal*, vol. 71, no. 4, pp. 505–512, 2018, doi: 10.1590/0370-44672018710031.

[21] A. C. Aydin, A. Ardalani, M. Maali, and M. Kiliç, "Numeric modelling of innovative semi-rigid connections under cyclic loading," *Steel Construction*, vol. 14, no. 1, pp. 22–34, Feb. 2021, doi: 10.1002/stco.201900037.

[22] Y. Shi, G. Shi, and Y. Wang, "Experimental and theoretical analysis of the moment-rotation behaviour of stiffened extended end-plate connections," *J Constr Steel Res*, vol. 63, no. 9, pp. 1279–1293, Sep. 2007, doi: 10.1016/j.jcsr.2006.11.008.

[23] F. M. F. Shaker and W. M. Abd Elrahman, "Analytical behavior of steel pre-tensioned bolted connections with flushed and extended end plates under bending," *World Appl Sci J*, vol. 30, no. 6, pp. 673–684, 2014, doi: 10.5829/idosi.wasj.2014.30.06.14091.

[24] Atorod Azizinamini and James B. Radziminski, "Static and Cyclic Performance of Semi Rigid Steel Beam-to-Column Connections," *Journal of Structural Engineering,* vol. 115, no. 12, pp. 2979–2999, 1989, doi: https://doi.org/10.1061/(ASCE)0733-9445(1989)115:12(2979).

[25] A. S. Fahmy, Y. El Zeny, M. K. Abdulaziz, and Y. El Zeny, "Special Issue for ICASGE'19 Study of Moment Rotation Behavior for Semi Rigid Connection Consisting of Bolts and Angles Study of Moment Rotation Behavior for Semi Rigid Connections Consisting of Bolts and Angles," *International Journal of Advances in Structural and Geotechnical Engineering*, vol. 04, no. 04, pp. 24–39, 2020, doi: https://doi.org/10.21608/asge.2020.271203.

[26] F. M. F. Shaker and W. M. Abd Elrahman, "Behavior of flush and extended end-plate beam-to-column joints under bending and axial force," *World Appl Sci J*, vol. 30, no. 6, pp. 685–695, 2014, doi: 10.5829/idosi.wasj.2014.30.06.14092.