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STUDY OF MOMENT ROTATION BEHAVIOR FOR SEMI RIGID CONNECTIONS CONSISTING OF BOLTS AND ANGLES

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ABSTRACT

The objectives of this paper are to study the effect of different parameters for steel bolted angle connection on moment-rotation behavior under monotonic loading. ABAQUS software is used to develop analytical models based on the previous experimental studies and their accuracy is examined. Using verified analytical models, a parametric study is then carried out to study the moment-rotation behavior with variations in: beam size, top angle thickness, and bolt gauge distance. From the results, the bi-linear moment rotation diagram for the connection is determined and the following results were obtained with respect to the initial stiffness, post-limit stiffness, plastic flexural resistance moment, plastic rotation, ultimate moment, and ultimate rotation. Finally, the effect of each parameter on moment-rotation behavior of the bolted angle steel connection is discussed in detail, and a proposed formula between each parameter and results is estimated.

1. INTRODUCTION

The behavior of steel framed structures extremely depends on the behavior of beam to column connections. Structural engineers have carried out many researches on the behavior of structural joints particularly bolted and welded connections, so far. The research findings show that connections have distinctively nonlinear behavior. This is mainly due to the fact that a connection is a collection of different components and the interaction between these components is complex.

In general, the connections are subject to axial force, shear force, and bending moment for its in-plane behavior. However, the deformation of the connections caused by axial and shear forces are usually small when compared to the deformation caused by bending moment. Consequently, for practical purposes, only the effect of moment on the rotational deformation of connections shown in Figure 1 needs to be considered.

The behavior of beam-to-column moment-resisting joints in steel-framed buildings is represented by a M-Φ curves (moment vs. rotation) illustrated in Figure 2. These curves describe three main properties: the rotational stiffness, rotation capacity and moment resistance.

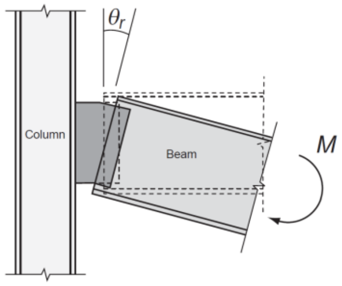


Figure 1 Rotational deformation of a connection [1]

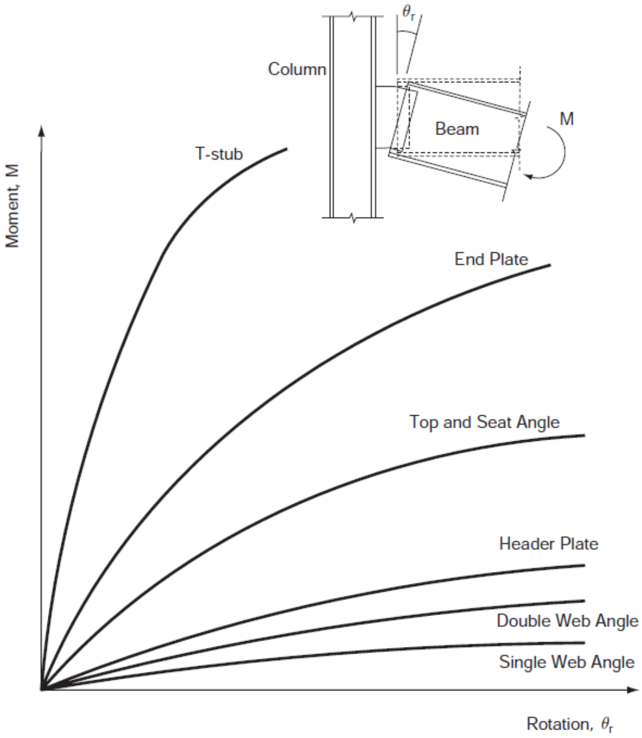


Figure 2 Moment-rotation curves of semi-rigid connections [1]

Top and seat angle connection with double web angles (TSADWA) is generally considered as semi-rigid and partial strength category and it is widely used in steel framed buildings. and generally used for low-rise buildings. There are some design specifications such as Eurocode 3 [2], for the prediction of stiffness and strength of this type of connection but there are no rules for characterization of the ductility of this joint.

To predict the behavior of bolted angle connection, many studies using analytical and experimental methods have been carried out to determine an accurate method for predicting the connection rotational behavior under the monotonic and cyclic loadings. The main experimental work conducted on TSADWA connections was carried out by Azizinamini et al. (1985) [3]. Azizinamini investigated 20 TSADWA connections under monotonic loadings and some specimens were studied under cyclic loading.

Calado et al. (2000) [4] carried out 15 TSADWA connections tests, Three different sizes of top, bottom and web angles were considered. The purpose of the experimental study was to study the behavior of TSADWA connections for both monotonic and cyclic loading. Similarly, Komuro et al. (2003 or 2004) [5] studied 1 TSA and 2 TSADWA connection under both monotonic and cyclic loading.

Several researchers have been using the FEM to investigate joint behavior, Three-dimensional finite element models were analyzed by A. Pirmoz [6], M. Ghindea [7], And K. Al Fakih [8], to evaluate the moment-rotation behavior for bolted angles connections.

Yang et al. (2000) [9] investigated double angle connections welded to the beam web and bolted to the column flange. Citipitioglu et al. (2002) [10] presented an approach for refined parametric 3D analysis of partially-restrained bolted steel beam-to-column connections. Akbar Pirmoz (2008) [11] studied the effect of web angle dimensions on moment–rotation behavior of bolted top and seat angle connections, with double web angles. Several 3D parametric finite element (FE) models are presented in this study whose geometrical and mechanical properties are used as parameters.

The first objective of this paper after studying the previous researches is to develop a reliable three-dimension Finite Element model for the analysis of bolted angles steel connection including bolt pretension force, initial imperfection, and modeling of contact between different surfaces and compare the results with those of available published experiments.

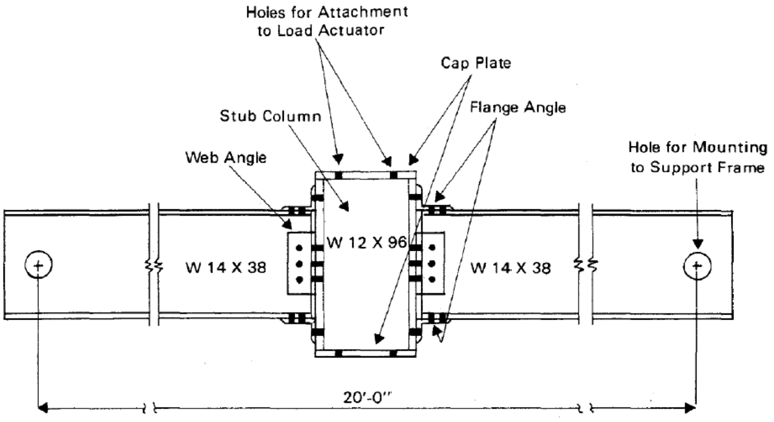
Due to a lack of sufficient information on the effect of different geometrical dimensions on the connection behavior, the second objective is to use the proposed Finite Element model to carry out an extensive parametric study to investigate the effect of different parameters on the behavior of bolted angles connection.

2. 3D FINITE ELEMENT MODELING

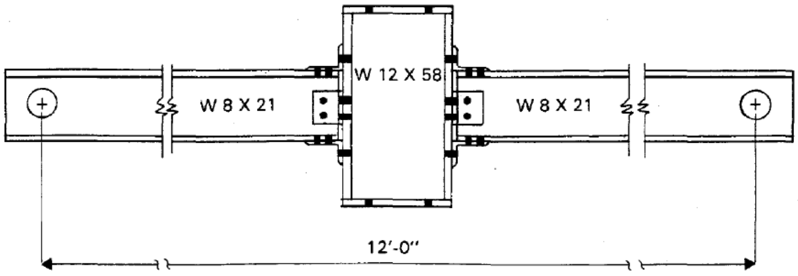
The finite element Software ABAQUS is used to simulate the behavior of bolted angles connections under monotonic loading. to confirm the accuracy of the 3D model. Experimental data obtained by Azizinamini et al. [3] for steel bolted angle connections with double web angles under monotonic loading are used to verify the numerical results from computer analyses. A total of 11 members were tested under monotonic loading and two specimens were chosen (8S1 and 14S1) for validation. The 8S1 and 14S1 tests are used because they are contrasted in terms of beam depth and beam flange angle. Details of these specimens are shown in Table 1 and Figure 3.

Table 1. Geometric properties of the benchmark specimens (dimensions in mm) [3]

Specimen	Bolt Dia. (mm)	Column section	Beam section	Top and Seat angle			Web angle	
				angle	Length (mm)	Bolt spacing (mm)	angle	Length (mm)
8S1	19.1	W12X58	W8X21	L6×3 1/2×5/16	15.24	8.89	2L4×3 1/2×1/4	139.7
14S1	19.1	W12X96	W14X38	L6×4×3/8	20.32	13.97	2L4×3 1/2×1/4	215.9



a. W 14 X 38 BEAM·TEST SPECIMEN



b. W 8 X 21 BEAM TEST SPECIMEN

Figure 3 general configurations of the test specimens [3]

In the present Finite Element model, all connected members including the beam, column, angles, and bolts were modeled using the continuum three-dimensional eight-nodded brick element with reduced integration technique (C3D8R). The structural steel components such as steel beam, steel column, and bolt are modeled as an elastic– plastic material in both tension and compression. ASTM A36 steel was used for steel beam, column and angles. Yield and ultimate tensile strength as well as Young's modulus (E) is obtained from the test results carried by Azizinamini et al. [3], while yield stress and ultimate strength of bolts are assumed based on nominal properties of A325 bolts. Material properties are listed in table 2.

Table 2. Material Properties used in FEA [3]

Type of element	Material	Yield stress	Ultimate stress	Modulus of Elasticity	Poisson ratio
		MPa	MPa	GPa	
Beam, Column and angles	ASTM A36	295	450	210	0.3
Bolts	ASTM A325	660	830	210	0.3

True stress and true strain are used to define the non-linear behavior of material properties. The Equations 1 and 2 are used to covert nominal strain to true strain and nominal stress to true stress, respectively. Stress- strain relations for A36 and A325 are shown in figure 4.

$\varepsilon_{true} = \ln(1+ \varepsilon_{nom})$ (Eq. 1)

$\sigma_{true} = \sigma_{nom}(1+ \varepsilon_{nom})$ (Eq. 2)

where

ε_{true} is the true strain

ε_{nom} is the nominal strain

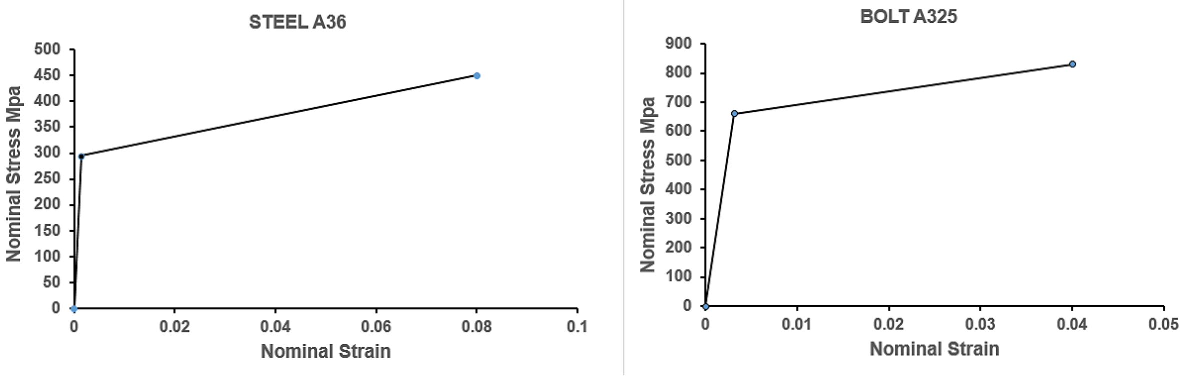


Figure 4 stress–strain relation for A36 and A325

A mesh convergence study was performed to obtain an appropriate mesh density to achieve reliable results in reasonable computation time. The maximum mesh distance is 20mm for the beam and column, 3mm mesh used for bolts and holes and the angles have a mesh of 6mm. The resulted meshing is presented in Figure 5.

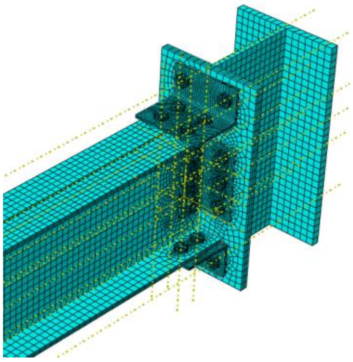


Figure 5 Finite element mesh

Modeling the contact between the different model parts is one of the most critical processes. The contact between angle and column, angle and beam, bolt shank and hole, bolt head and angle, bolt head and beam, bolt head and column are defined as a surface-to-surface contact. These contacts were all created in the initial step propagating to bolts pretension and loading steps, as shown in Figure 6. Two relevant properties were considered: the first one is tangential behavior and the other is normal behavior of the contact surface interaction considering finite sliding surface-to-surface contact. Tangential behavior is defined with a frictional coefficient of 0.5 using penalty stiffness formulation. Normal behavior is defined as “hard” contact. This property assumes that constraints related to contact can only occur, when the surfaces are touching no sticking between the contact surfaces.

a. column and top angle

b. column and web angle

c. bolt shank and hole

d. bolt head and column

Figure 6 contacts used for bolted angles connection

The first step in loading in this model is simulating bolts pretension. In these simulations, different components (bolt head, bolt shank and nut) were modeled with three dimensional solid elements. The interactions between surfaces of the bolt were defined and for effect of tightening of the bolt, the pretension force of the bolt was simulated.

Since there is no information presented in the research of Aziznamini's tests about applied pretension force in the bolt, and as per AISC," minimum pretension force shouldn't be less than 0.7 of the minimum tensile strength of bolt", then pretension force was taken as 145 KN for (19.1mm) bolt.

The following boundary conditions were set for the modeling. For both ends of the column, all translational degrees of freedom are restrained (pinned connection). All translational degrees of freedom and the rotation for beam ends are fixed in the initial step before applying the load. At the load step, all degrees of freedom are released except for the translation at the x-axis (lateral buckling) and rotations around the axis of the beam (lateral torsional buckling). Furthermore, it was decided to apply a displacement instead of a force to make the bending moment increases smoothly.

3. VALIDATION OF THE 3D FINITE ELEMENT MODEL

Validation of the proposed model is examined by comparing the present numerical results with those of experiments conducted by Azizinamini (1985) [3], in terms of load-displacement characteristics, moment-rotation characteristics and failure modes of the connections. The force at the loading point was identified and its peak value was taken as the loading capacity of each of the connection specimens. The resulting moment and relative connection rotation are evaluated by equations (3) and (4), respectively:

$$M = P.\,L \qquad (3)$$

$$\varphi = \frac{\delta t - \delta b}{d} \qquad (4)$$

Where,

M is the applied connection moment
P is the applied load
L corresponds to beam length
φ is the relative rotation of the connection
d is beam depth
$\delta 1$ and $\delta 1$ are the top and bottom flange horizontal displacements, Figure 7

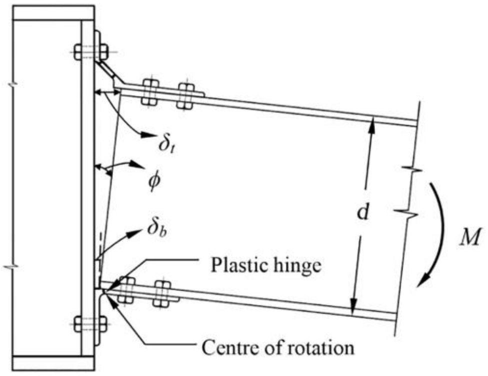


Figure 7 Deformation of top-seat angle

A good correlation of M–φ curves obtained from the Finite Element model are found as shown in Figure 8. It can be seen that the experimental and Finite Element results match better in the starting part than in the ending part. The results of the Finite Element and those of experiment, in the nonlinear range of response, are very close to the case of specimen14S1. Small variance is found in the case of specimen 8S1 during the nonlinear stage. Table 3 shows comparisons of the moment resistance, rotation capacities, and initial stiffness of all of these connections.

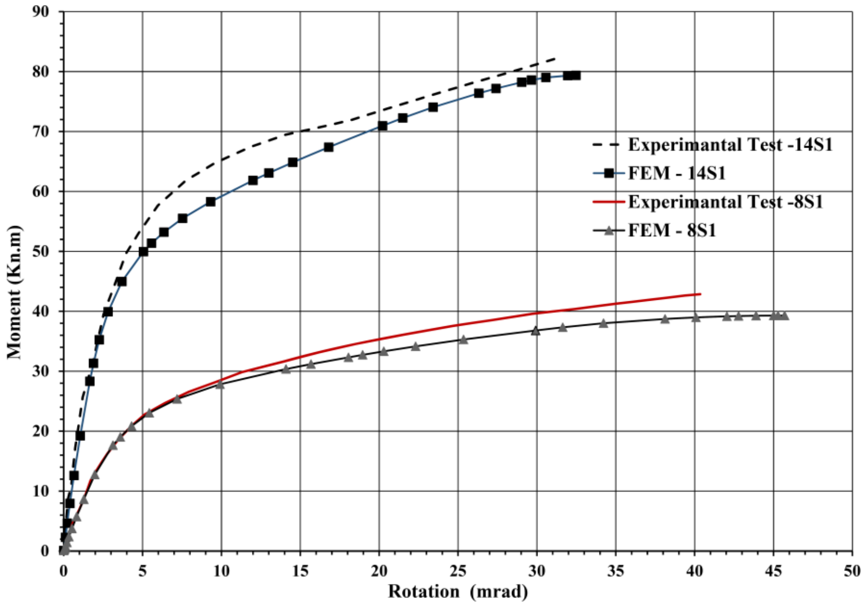


Figure 8 Moment-rotation curves for specimens 8S1 and 14S1

Table 3. Comparison between FEA and tests [3]

No	Moment resistance	Moment resistance	Diff. %	Initial stiffness	Initial stiffness	Diff. %	Rotation capacity	Rotation capacity	Diff. %
	KN.m	KN.m		kN.m/rad	KN.m/rad		mrad	mrad	
	Test	FEM		Test	FEM		Test	FEM	
8S1	42.9	39.3	8.3	7536	7240	3.9	40.35	45.70	13.2
14S1	82.2	79.4	3.4	22032	20418	7.3	31.25	32.47	3.9

Despite the noticeable differences in rotation capacity for specimen 8S1 (13.2%) which can be due to the variance between assumed ultimate stress for top angle and real value, the minor deviation was observed for both specimens in the linear and nonlinear range and the overall performance of the FE models may be considered acceptable

4. PARAMETRIC STUDY

Moment-rotation behavior depends on the connecting elements such as angles, bolts, column flange, and stiffeners, by EuroCode 3 [2]. To conduct the parametric study, the determination of the range of input variables is very important. Therefore, the geometric parameters are selected and varied within the comprehensive practical ranges of bolted angles connections. Figure 9 shows the different parameters selected for Finite Element Analysis.

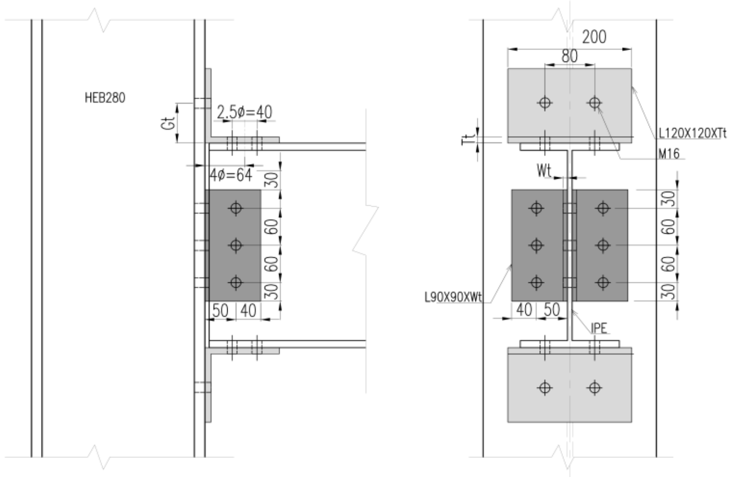


Figure 9 Connection with variable parameters under consideration

Table 4 Shows the range of selected parameters of the connection. Only one parameter was changed at one group so as to clarify its effect. They are considered to be the most influential factors for the considered connections. A total of 128 models are analyzed to study the behavior of the connection. However, due to limited space, some of the results are presented here.

Table 4 Different parameters selected for Finite Element Analysis

Parameter	Range of selected parameters			
Beam Size	IPE300	IPE330	IPE360	IPE400
Top and seat angle thickness	T_t =8 mm	T_t =10 mm	T_t =12 mm	T_t =15 mm
Bolt gauge distance	G_t =56mm (3.5d)	G_t =64mm (4d)	G_t =72mm (4.5d)	G_t =80mm (5d)
Web angles thickness	W_t = 7mm	W_t = 9mm	W_t = 11mm	W_t = 13mm

The numerical or experimental nonlinear moment-rotation curves are generally approximated with a bilinear response as shown in Figure 10. They are characterized by the following features: the plastic flexural resistance, M_R, the maximum bending moment, MU, the initial stiffness, Ki, the post-limit stiffness, Kp, the moment corresponding to the maximum load level, Mu and the rotation capacity, φu

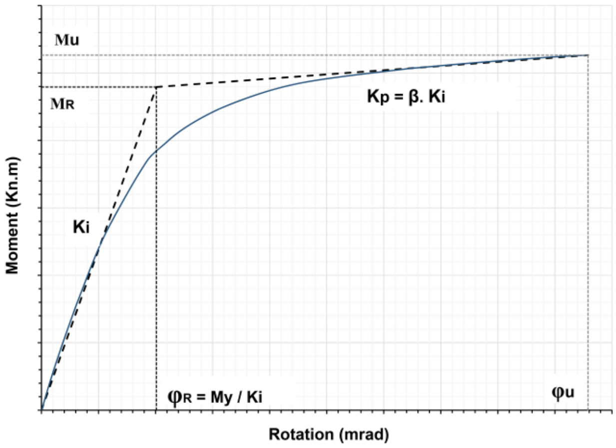
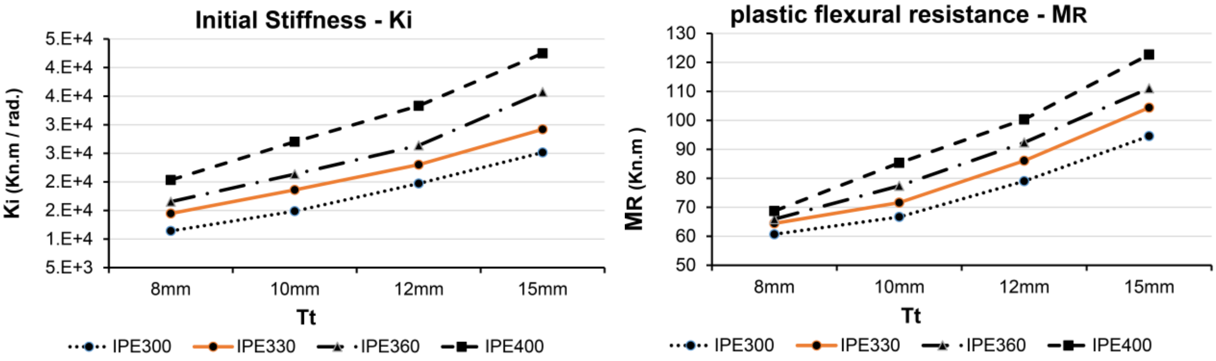


Figure 10 Proposed bilinear moment-rotation graph

5. ANALYSIS OF RESULTS

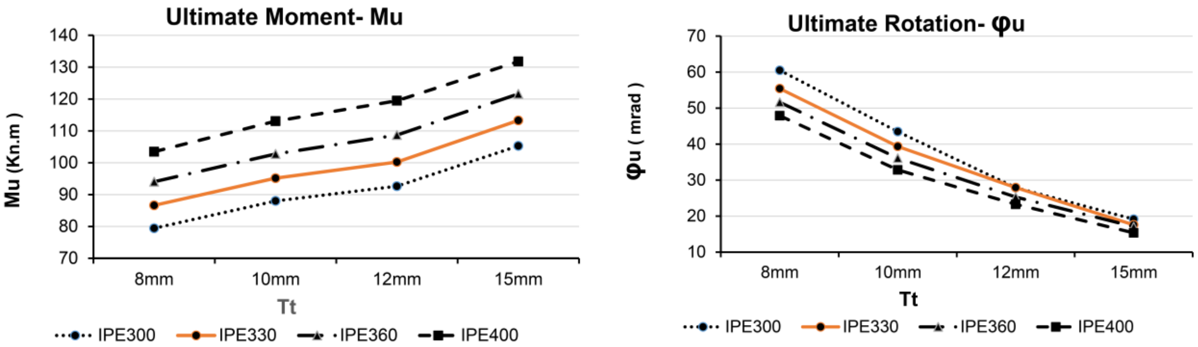
5.a. Effect of angle thickness

The thickness of the top angle has been indented as one of the significant parameters in the flexural condition. Figure 11 shows the effect of different angle thickness (top and seat angles) on the moment-rotation parameters with four values of angle thickness, 8, 10, 12 and 15 mm for four different beam sizes. It can be noticed that increasing of top angle thickness increases the initial stiffness, the plastic moment resistance and the ultimate moment while decreases the ultimate rotation. The lowest initial stiffness, moment resistance and ultimate moment are found in the case when angle thickness is 8mm. In this case, the failure is due to top angle fracture, due to yielding of the bolt, which causes the ductile failure of the connections and causes loss of resistance in bending.



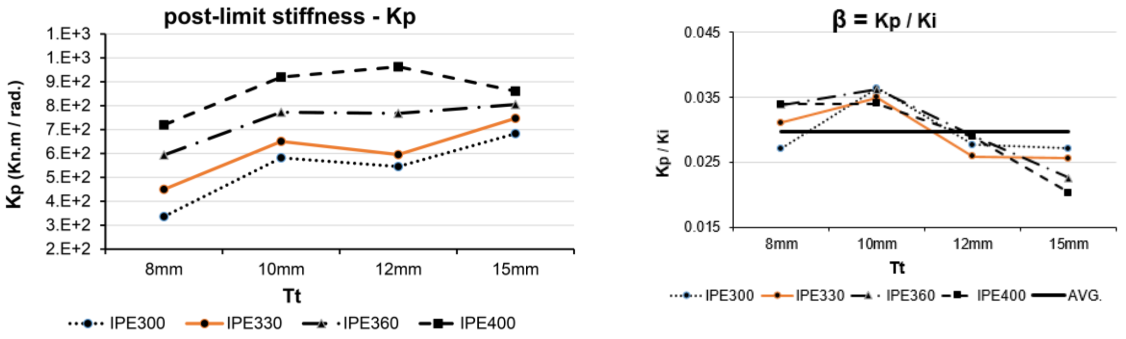
a) Effect on initial stiffness

b) Effect on plastic flexural resistance



c) Effect on ultimate moment

d) Effect on ultimate rotation



e) Effect on post limit stiffness

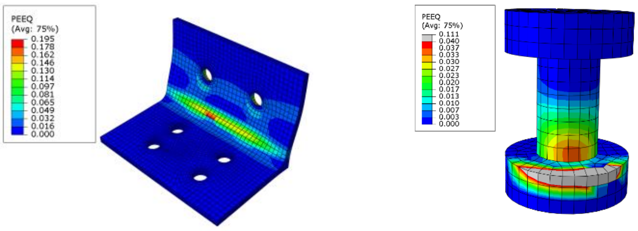
f) Effect on β ratio (Kp/Ki)

Figure 11 Effect of angle thickness on moment-rotation parameters

Precisely, for beam size IPE300, increasing the angle thickness from 8 to 15 mm increases the initial stiffness, the plastic moment resistance and ultimate moment by about 102.7%, 56.02%, and 32.5%, respectively. While the ultimate rotation decreases by 68.3%.

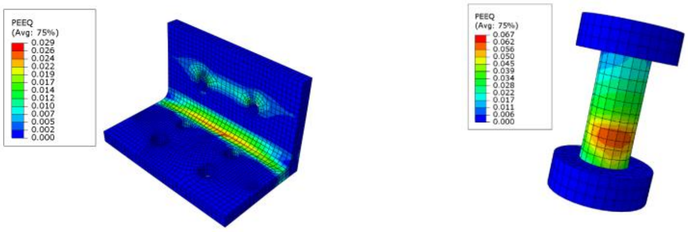
It can be observed that post limit stiffness is increasing with the same pattern as initial stiffness. The ratio between post limit stiffness and initial stiffness as shown in Figure 10(f) shows that the average ratio between post limit stiffness and initial stiffness can be taken as 0.03 (β = .03)

When the angle thickness increases, the failure mode changes from angle fracture to bolt fracture as shown in Figures 12 and 13. It can be noticed that with 8mm angle thickness the failure mode was angle fracture with yielded bolts which changes to bolt fracture with yielded angles with increasing the thickness to 15 mm



a) Top angle b) Top bolt

Figure 12 Equivalent plastic strain (IPE300 –Tt = 8mm) –Top angle fracture

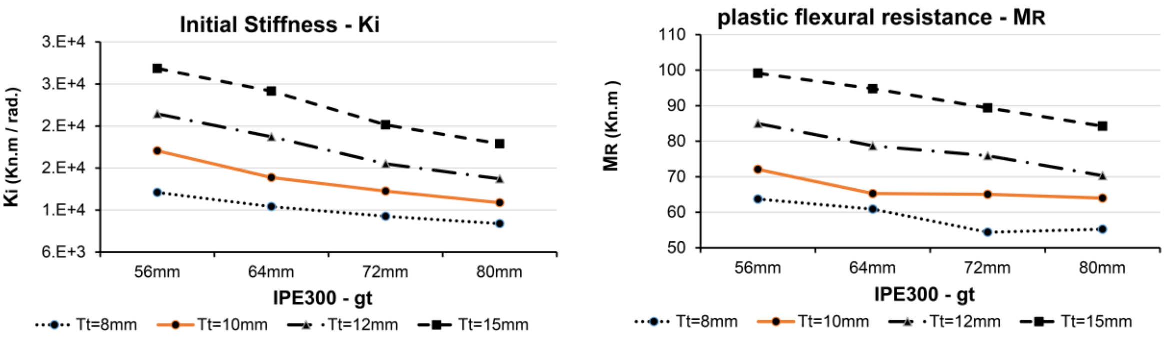


b) Top angle b) Top bolt

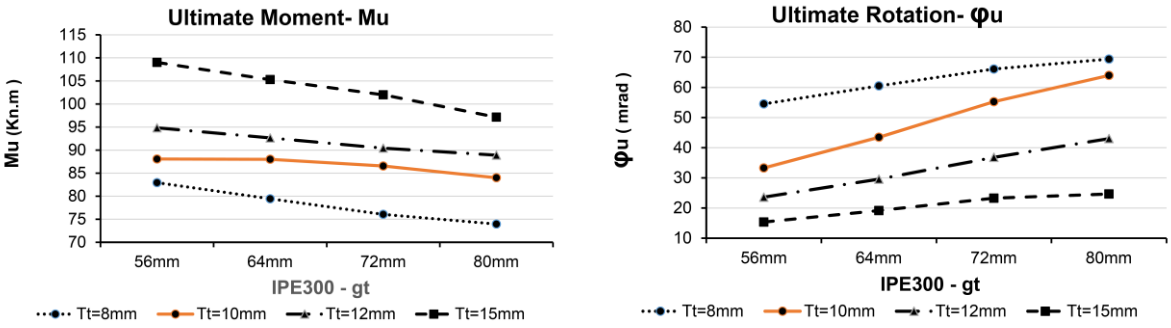
Figure 13 Equivalent plastic strain (IPE300 –Tt = 15mm) – Top bolt fracture

5.b. Effect of gauge distance for top bolts

To study the influence of gauge distance for top bolts, four models with different values of gauge distance, 56mm, 64mm, 72mm, and 80mm, are analyzed. The influence of gauge distance on moment-rotation parameters are plotted in Figure 14. It can be observed that increasing of gauge distance decreases the initial stiffness, the plastic moment resistance and the ultimate moment while increases the ultimate rotation. The lowest initial stiffness, moment resistance and ultimate moment are found in the case when gauge distance is 80mm.



a) Effect on initial stiffness b) Effect on plastic flexural resistance

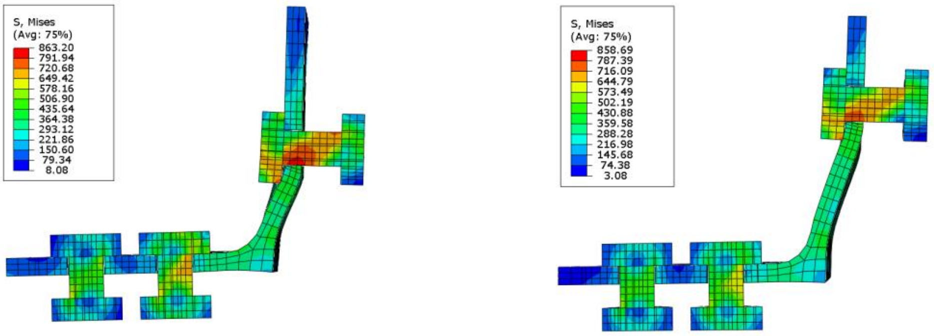


c) Effect on ultimate moment

d) Effect on ultimate rotation

Figure 14 Effect of gauge distance on moment-rotation parameters

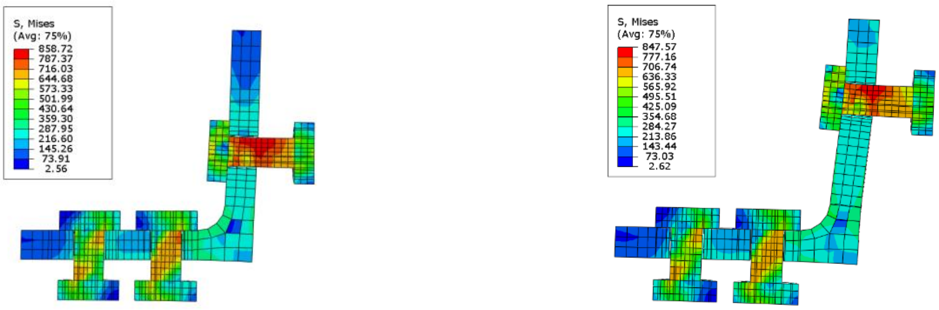
For beam size IPE300 with top and bottom angles thickness are 15mm, increasing the gauge distance from 56 to 80 mm decreases the initial stiffness, the plastic moment resistance and ultimate moment by about 32.2%, 16%, and 10.9%, respectively. While the ultimate rotation increases by 60.6%. Similarly, for same beam size with top and bottom angles thickness are 8mm, the initial stiffness, the plastic moment resistance and ultimate moment declines by 28.3%,10.2%, and 10.8%, respectively, while the ultimate rotation rises by 27.3%.
It can be noticed that there is no effect on failure modes for the same angle thickness as shown in Figures 15 and 16.



a) Gauge distance 56mm

b) Gauge distance 80mm

Figure 15 Stress distribution for top angle and bolts for IPE300 (Tt=8mm)



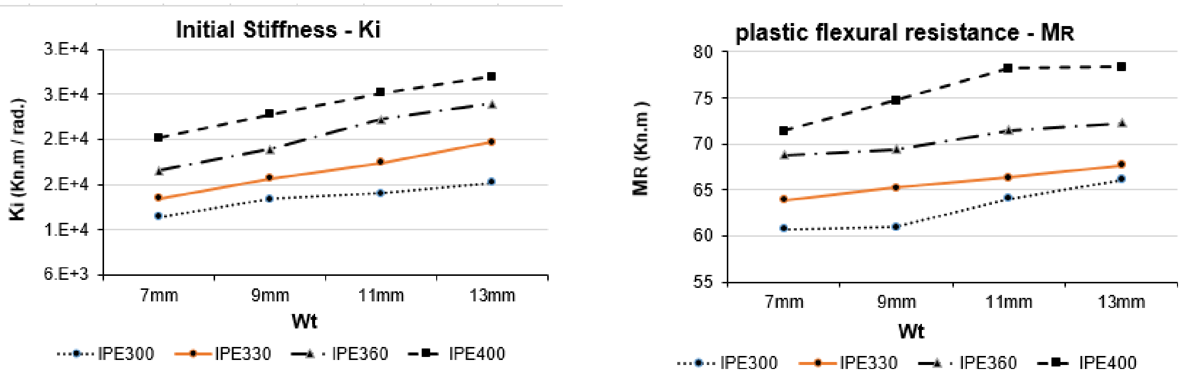
a) Gauge distance 56mm

b) Gauge distance 80mm

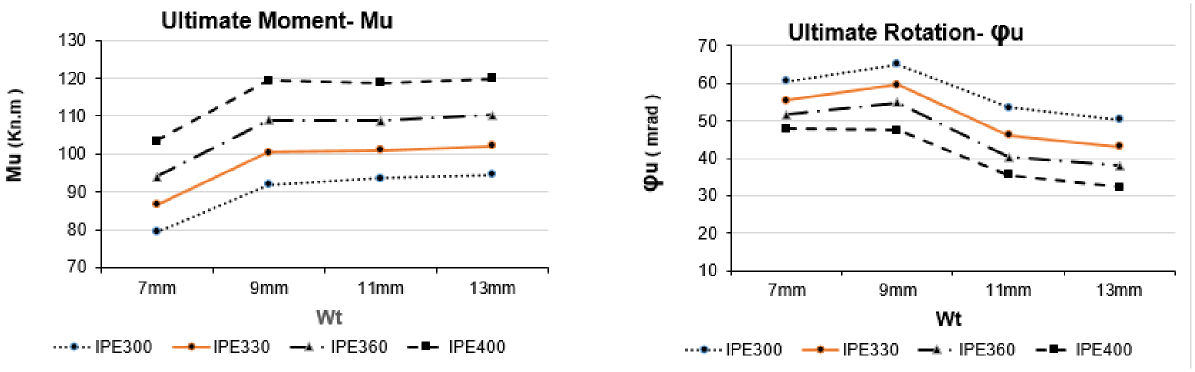
Figure 16 Stress distribution for top angle and bolts for IPE300 (Tt=15mm)

5.c. Effect of thickness of web angles

The effect of web angle thickness on moment- rotation parameters (with top angle thickness 8mm) is shown in figure 17. it can be observed that the initial stiffness, plastic flexure resistance and ultimate moment increases with the increase of web angle thickness, while the rotation capacity declines. Precisely, increasing web angle thickness from 7mm to 13 mm, the initial stiffness, the plastic moment resistance and ultimate moment grows by 31-43%, 5-10%, and 16-19%, respectively, while the ultimate rotation drops by 17-32%. Increasing web angle thickness has a remarkable effect on failure modes which changes from top angle rapture to yield of the top angle as well as a shear failure of the bolts connecting the beam bottom flange with the seat angle for top angle 8mm thickness as shown in figures 18 and 19.



a) Effect on initial stiffness b) Effect on plastic flexural resistance

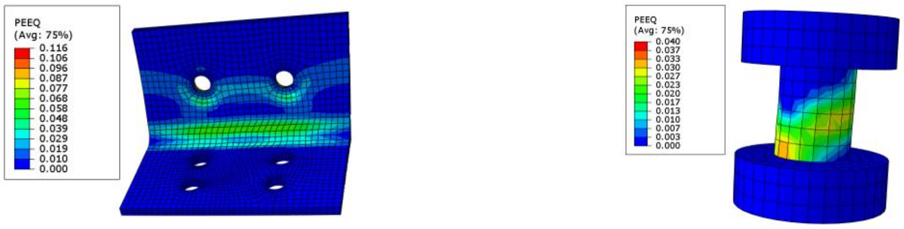


c) Effect on ultimate moment d) Effect on ultimate rotation

Figure 17 Effect of web angle thickness on moment-rotation parameters

a) Top angle b) bolts connecting the beam bottom flange

Figure 18 Equivalent plastic strain (IPE300- Tt=8mm, Wt=7mm)



a) Top angle

b) bolts connecting the beam bottom flange

Figure 19 Equivalent plastic strain (IPE300- Tt=8mm, Wt=13mm)

6. Development of simple formulas

The previous parameters were taken as variables to obtain simplified formulas. As constant parameters, the following ones were considered as the most commonly used in practice:

- The diameter for bolts is 16mm
- Steel grade A36
- Bolt grade A325
- Beam section IPE

All the results from the parametric study were used in nonlinear regression analysis to obtain simplified equations for estimation of the steel joint rotation parameters by using the following equations:

$$Ki = 10.355.H^{1.52}.Tt^{0.828}.Gt^{-0.859}.Wt^{0.334} - 6051.29 \quad \text{KN.m/rad} \tag{5}$$

$$Mr = 0.242.H^{0.994}.Tt^{0.908}.Gt^{-0.602}.Wt^{0.055} + 18.139 \quad \text{KN.m} \tag{6}$$

$$Mu = 24.408.H^{0.345}.Tt^{0.143}.Gt^{-0.086}.Wt^{0.113} - 158.33 \quad \text{KN.m} \tag{7}$$

$$\varphi u = 8623.659.H^{-1.037}.Tt^{-1.511}.Gt^{1.084}.Wt^{-0.207} \quad \text{mrad} \tag{8}$$

Where:

H, the height of beam in mm
Tt, top and seat angle thickness in mm
Gt, top bolt gauge distance in mm
Wt, web angles thickness in mm
Ki, the initial stiffness
Mr, the plastic flexural resistance
Mu, the maximum bending moment
φu, the rotation corresponding to the maximum load level, Mu and the rotation capacity

6. CONCLUSIONS

Steel connections are usually assumed to be pinned or rigid. Semi-rigid connection behavior should be considered to obtain more realistic and economical results. This study can be used to provide and define semi-rigid connections in terms of rotational spring stiffness which can be used in the analysis.

This study presents a three-dimensional finite element model, for the analysis of steel bolted angles connections subjected to monotonic loading, to study the effect of different parameters on connection behavior. For the cases considered in the present study, the following findings are summarized:

1. The comparisons between the experimental results and those obtained by present finite element model indicate that the present numerical model is able to simulate and predict, with relatively good accuracy, the behavior of the bolted angles connection in both elastic and plastic range.

2. Top and bottom angle thickness has a significant effect on moment-rotation behavior, increasing the angle thickness from 8 to 15 mm increase the initial stiffness, the plastic moment resistance and ultimate moment by about 102.7%, 56.02%, and 32.5%, respectively. While the ultimate rotation decreases by 68.3%. By increasing the angle thickness the failure mode changes from angle rapture to bolt failure.

3. Gauge distance has a big effect on ultimate rotation while it has a moderate effect on other parameters, increasing the gauge distance from 56 to 80 mm decreases the initial stiffness, the plastic moment resistance and ultimate moment by about 32.2%, 16% and 10.9%, respectively. While, the ultimate rotation increases by 60.6%. There is no noticeable effect on failure modes with changing gauge distance.

4. Increasing web angle thickness has a remarkable effect on failure mode, which changes from top angle fracture to shear failure of the bolts connecting the beam bottom flange with the seat angle (for top angle 8mm). The initial stiffness, the plastic moment resistance and ultimate moment grows by 31-43%, 5-10% and 16-19%, respectively, while the ultimate rotation drops by 17-32% with increasing web angle thickness from 7mm to 13mm.
5. Average post limit stiffness is found to be about 3% from initial stiffness
6. simplified formulas (equations 5 to 8) were suggested to estimate the steel joint rotation parameters which can be used to simulate the actual behavior of the structure.

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