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The Seat Angle Role on Moment-Rotation Response of Bolted Angle Connections

A. Pirmoz*
F. Danesh
K. N. Toosi University of Technology, Tehran, Iran

*Email: a.pirmoz@gmail.com

ABSTRACT: Effect of the seat angle stiffness on moment-rotation response of the bolted top-seat angle connections is studied in this paper by using finite element method (FEM). All of the connection components, such as beam, column, angles and bolts are modeled using solid elements. The effect of interactions between components, such as slippage of bolts and frictional forces, are modeled using surface contact algorithm. Bolt pretensioning force is applied on bolt shanks as the first load case to evaluate the behavior of connection more precisely. The Results of this numerical modeling are compared with the results of experimental works done by other researchers and good agreement was observed. It has been shown that the beam length has a considerable effect on connection moment-rotation behavior, especially in the nonlinear range of the connection behavior.

1 INSTRUCTION

Bolted top and seat angle connections are mainly designed to sustain gravitational loads of the beam ends and are considered as pinned connections according to the (AISC-LRFD, 1999) specifications. However, their considerable moment capacity makes it possible to take into account their economically benefit contribution in the beam moment redistribution, column effective length deduction (Kishi et al, 1997) and also the lateral resistance of the frame. After the Northridge and the Kobe earthquakes, using of the bolted connections instead of the welded connections has become one of the major issues in the earthquake engineering and the seismic design of the steel structures (Nader & Astaneh-Asl, 1996; Danesh, 1996; Elnashi et al, 1998; Maison et al, 2000; Pirmoz, 2006; Danesh & Pirmoz, 2007; Pirmoz, 2008-a; Akbas & Shen, 2003).

Analyzing and designing a semi-rigid frame requires a clear understanding of the moment-rotation relations of its connections. Many studies have been performed world-wide to estimate the moment-rotation behavior of bolted top and seat angle connections. The ductility and favorable seismic performance of semi-rigid frames with bolted connections with respect to the corresponding welded frames has been studied (Azizinamini, 1982; Azizinamini & Radziminski, 1989; Kukreti & Abolmaali, 1999; Calado, 2003). The behavior of bolted angles under cyclic loads has been extensively studied in (Mander et al, 1999; Shen & Astaneh-Asl, 1999; Garlock et al, 2003; Lin & Sugimoto 2004).

Recently, the advent of high speed computers has made it possible for numerical modeling methods, like the finite element method (FEM), to be used by researchers to study the connections behavior. (Citipitioglu et al, 2002) used the FEM to study the moment-rotation behavior of bolted top and seat angle connections. In this research, the effect of bolts pre-tension and the friction coefficient on the connection moment-rotation behavior is studied. In addition, the accuracy of the pull tests is studied to predict moment-rotation behavior of such connections. All connection components were modeled using solid elements and the effect of adjacent surfaces interactions is considered using contact elements. (Kishi et al, 2001) studied the applicability of the three-parameter power model of Kishi-Chen (Kishi & Chen, 1990) to predict the moment-rotation behavior of top-seat bolted angle connections using the FEM. In their models, connection components are modeled using solid elements, and contact elements were used to model the separation of the discrete components. Ahmed et al. (Ahmed et al., 2001) performed a parametric study on the prying action of the connection bolts. They concluded that decreasing the vertical leg of the top angle increases the prying force of top angle-column flange bolts. (Kumoro et al, 2004) studied the ability of the FEM to predict the moment-rotation relations of bolted top-seat angle connections with three experimental tests. Their study showed that nonlinear finite element analysis method can estimate connection behavior until the final state of connection loading. (Danesh et al, 2007) and (Pirmoz et al, 2008) studied the effect of shear force on the initial rotational stiffness of bolted top and seat angle connections with double web angles and proposed equations to predict the reduction factor of initial connection initial stiffness due to the shear force. (Pirmoz, 2008) and (Pirmoz & Mohammadrezapour, 2008) studied the moment rotation response of bolted top-seat angle connections under combined axial tension and moment loading. (Pirmoz, 2008) studied the performance of the bolted top-seat angles with double web angles in progressive collapse conditions of the semi-rigid frames using nonlinear FEM.

Because of the complexity of the 3D nonlinear finite element method required to estimate connection moment-rotation behavior, several analytical equations have been proposed to estimate the behavior of this type of connection (Kukretti & Abolmaali, 1999), (Kishi et al. 1988), (Chen & Kishi, 1989). Using the experimental test results, (Shen & Astaneh-Asl 1999, 2000) proposed a three-linear moment-rotation behavior based on the fiber element formulation. A semi analytical method is proposed by (Pirmoz et al, 2008) to estimate moment-rotation response of bolted top-seat angle connections. The method has the applicability to take into account the effect of an initial axial tension force imposed on connection. Using an Artificial Neural Network (ANN) method, (Pirmoz & Golizadeh, 2007) and (Salajegheh et al, 2008) have estimated the behavior of bolted top-seat angle connections with web angles. Results of these studies showed that ANN method has higher speed and accuracy with respect to other methods.

In most of the previously proposed analytical models for moment-rotation response of the bolted top-seat angle connections, the top angle is considered as the major part of the connection and based on its behavior; the analytical models has been created. As will be shown later in this paper, the effect of the seat angle is related to the beam length and thus could be assessed by altering the beam length. None of the previous studies is considered this parameter. By using FEM, the effect of the beam dimensions on connection behavior is studied.

2 FINITE ELEMENT MODELING OF THE CONNECTION

(Azizinamini, 1982) tested 18 specimens of bolted top and seat angle connections with web angles and two specimens with no web angles, which are named A1 and A2. The objective of these tests was to investigate the effects of different geometrical properties of connection, such as top and web angles dimensions, bolt spacing and beam depth, on connection moment-rotation behavior. In the current study, the accuracy of the FE models with A1 and A2 specimens as the base model is evaluated.

The Azizinamini test setup (Azizinamini, 1982) includes two beam segments with equal lengths that are symmetrically bolted to a stub column. The beam ends are simply supported, the stub column can move vertically and the applied load at the center of the stub column applies the moment on the connection. Figure (1-a) shows the test setup configuration for the A2 and A1 specimens. Geometrical properties of connections A1 and A2 selected for validating the accuracy of the FE modeling technique are listed in Table (1).

(Komuro et al, 2004) also studied the applicability of a nonlinear FEM to estimate the moment-rotation relations of top-seat web angles with and without web angles until the final stage of connection monotonic loading. Results of their FE models were validated by results of their 3 experimental tests. The web angle length was taken as parameter in the specimens and one of the specimens had no web angles (W00). The W00 specimen is chosen to be used as another test specimen for validation of the FE models of current study. The test setup is composed of a cantilever beam mounted vertically by the top-seat angle to a horizontal column fixed to a rigid floor. Figure (1-b) shows the test setup, and geometrical properties of the specimens are presented in Table (1).

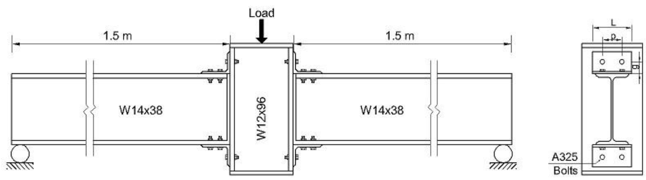

Figure 1-a) Test setup configuration and Connection parameters of A2 & A1 specimens

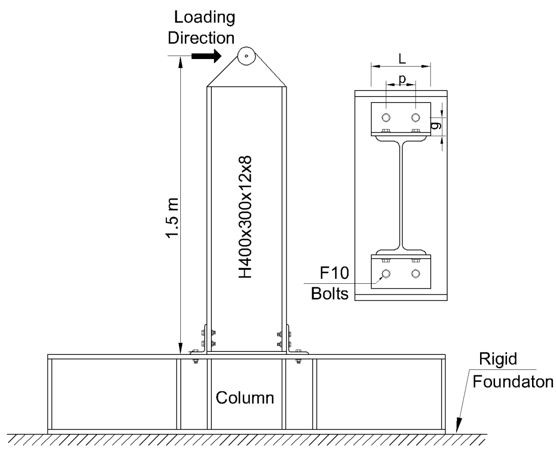

Figure 1-b) Test setup configuration and Connection parameters of W00

ANSYS multi-purpose finite element modeling code is used to perform numerical modeling of the connections. The FE models created using ANSYS Parametric Design Language (APDL). Geometrical and mechanical properties of the connection model were defined as parameters, thus the time required to create new models was considerably reduced. Numerical modeling of the connection included the following considerations: all components of the connection such as the beam, column, angles and bolts head are modeled using eight node-first order SOLID45 elements and bolt shanks are modeled using SOLID64 elements, which can apply a thermal gradient on it to pretension the bolts. Bolt holes are 1.6 mm larger than the bolt diameter. Just half of the connection is modeled because of the symmetry about the web plane. The model contains just the flange and stiffeners of the column, assuming it has high rigidity due to stiffeners.

ANSYS can model contact problems using contact pair elements CONTA174 and TARGE170, which pair together in such a way that no penetration occurs during the loading process. Thus the effect of adjacent surface interactions, including angle-beam flange, angle/beam flange-bolt head/nut, bolt hole-bolt shank and effect of friction, are modeled usingthe mentioned contact elements. Bolt heads and nuts were modeled as hexagons, and were similar to their actual shape. To consider the frictional forces, Coulomb's coefficient is assumed to be 0.25, which had better agreement with test results. It should be noted that in the pretension cases, the bolts are considered "slip critical," and in this case the friction coefficient allowed by AISC (AISC-LRFD, 1995) for design is 0.33. Figure (2) shows the FE model of connection A2 with 27206 elements and 44512 nodes and figure (3) shows some adjacent surfaces that are coupled together by contact elements.

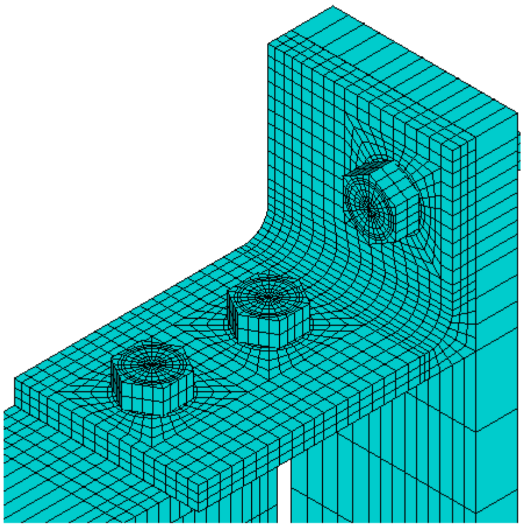

Figure (2): FE model and mesh pattern of the connection

To satisfy symmetry conditions, all web plane nodes were restrained against outward motion. Here it should be noted that, since the beams of the connections are compact sections, the local buckling instabilities occur in the inelastic range or at high stress levels, while the von Mises stress distribution in FE models clarifies that the beam remains almost elastic. Therefore, the local buckling failure mode can be ignored the FE models.

Bolt pretension is applied as the first load case. For this purpose a thermal gradient is applied on the bolt shanks to yield an equivalent pretension force. Since there is no information about the amount of bolts pretension in this experiment, design values of pretension force described by AISC are applied [1]. To apply bolt pretension, a thermal gradient was imposed on the bolts shanks as the first loading case. A 50 mm vertical displacement is applied on the nodes of the beam end to impose the moment on the connection. The value of the beam end displacement yields a rotation near 0.03 rad. The resulting moment and relative connection rotation are evaluated by equations (1) and (1), respectively:

$$M = P.L \qquad (1)$$

$$\theta = \frac{\varepsilon_1 - \varepsilon_2}{h} \qquad (2)$$

Where, M is the applied connection moment: P is a summation of the reactions of the applied displacement on the beam end nodes; L corresponds to beam length; θ is the relative rotation of connection; h is beam depth; and ε_1 and ε_2 are the top and bottom flange horizontal displacements, relatively.

The stress-strain relation for all connection components of Azizinamini's tests (Azizinamini, 1982) is represented using a tri-linear constitutive model. The isotropic hardening rule with von Mises yielding criterion is applied to simulate plastic deformations of connection components. The FE method can not model the fracture or cracking of the material because two elements can not be separated and thus the material fracture is not considered. ASTM A36 steel was used for the beam, column and angles of A1 and A2 specimens. Since no coupon test results were reported for the bolts, the yield stress and ultimate strength of bolts are assumed based on the nominal properties of A325 bolts. Bolt materials were modeled as bilinear with 634.3 MPa yield stress and an ultimate stress of 930 MPa at 8% strain (Citipitioglu, 2002). The modulus of elasticity and Poisson's ratio were considered to be 210 GPa and 0.3, respectively. Figure (4) shows the idealized stress-strain relation of A36 steel used for the beam and angle material of A1 and A2 in the current study. Mechanical properties of the W00 specimen are considered almost same as the presented uniaxial test results in [23].

Table 1. Geometrical properties of tested connections

Specimen number	Bolt diameter (mm)	Column section	Beam section	Top and Seat angles			
				angle	length (mm)	Gauge(g) (mm)	Bolt spacing (p)(mm)
A1	22	W12X96	W14X38	L6X4X3/8	203.2	63.5	139.7
A2	22	W12X96	W14X38	L6X4X1/2	203.2	63.5	139.7
W00	20	H400x300x12x8	H400x300x12x8	L150X100X12	200	55	120

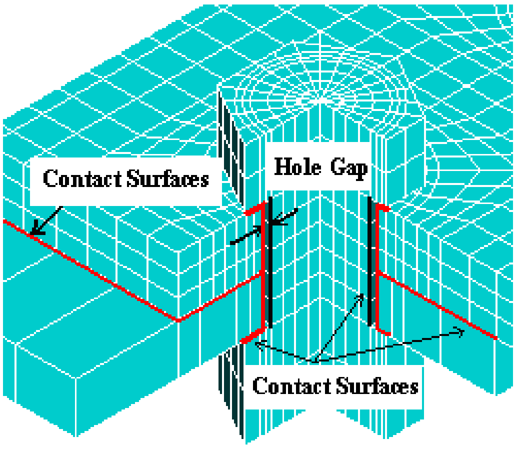

Figure (3): contact surfaces of components

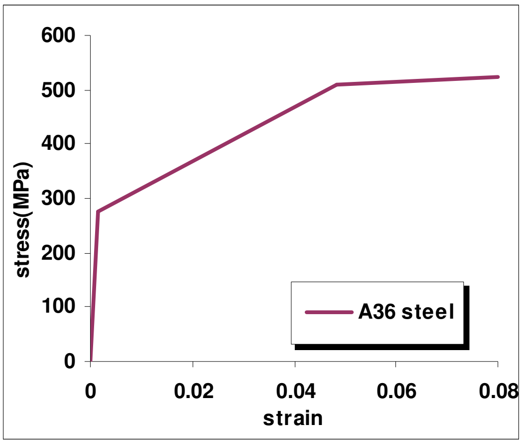

Figure (4): stress-strain relations of the material

3 VALIDATION OF THE FE MODELS

To evaluate the accuracy of finite element modeling approach, FE models of the three specimens are created and the results are compared with test results. Figures (5-a) shows the pretension stress of the top angle bolt shank in the compressive stresses of the angle hole at the first load case. Figures (5-b) shows the deformed shape and von Mises stress distribution of the top angle at 0.03 radian of rotation. A comparison between moment-rotation relations of FE modeling and test data is shown in Figure (6). As it can be seen from these figures, results obtained by FE models have a good agreement with tests. Difference between numerical simulation and test results may be raised from several causes, like numerical modeling simplification, test specimen defects, residual stress and bolts pretension.

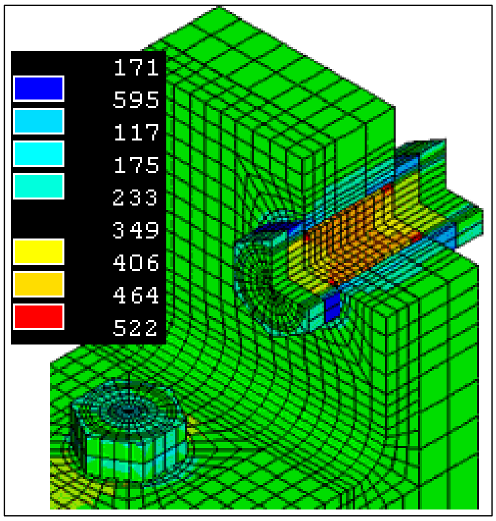

Figure (5-a) pretension force in the bolt shank

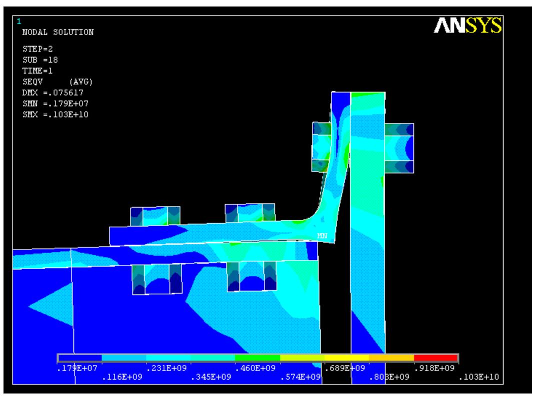

Figure (5-b) deformed shape; von Mises stress distribution and component interactions

Komuro et al have shown that von Mises yielding criterion can be used to estimate the failure mode of the connection comparing a failed bolt to von Mises stress distribution pattern in the corresponding bolt of the FE model. A large portion of the bolt shank of their FE model had a stress level beyond the ultimate stress of the bolt material. This has happened at 0.1 rad of connection rotation. However, in the current study only a small region of the bolt shank near the bolt head has a higher von Mises stress at 0.03 rad of rotation and the stress level in other parts of the shank is far below the ultimate stress of the material of the bolt and thus it can not be a representative of the bolt fracture or the failure of the connection (Fig. 5-b).

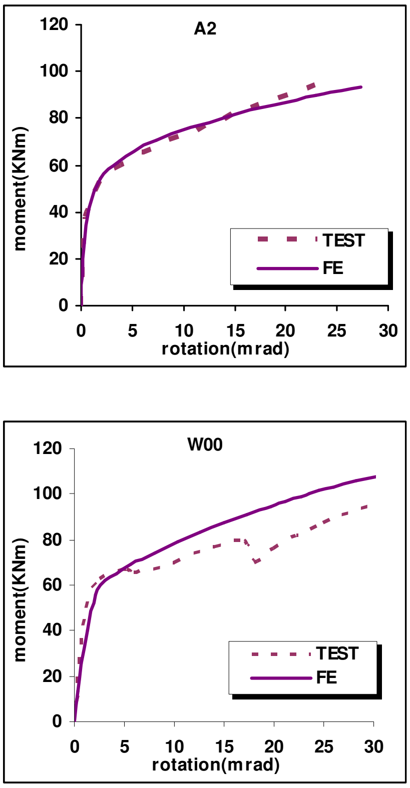

Figure (6): moment-rotation response of the FE models and the tests

The difference between test data and numerical models grows in nonlinear portion of curves. A major cause is the nonlinear constitutive laws for materials, especially for situations where only uniaxial values of the stress-strain curves are available.

4 EFFECT OF THE BEAM LENGTH ON CONNECTION BEHAVIOR

In most of the previously proposed analytical models of the bolted top-seat angle connections (Garlock et al, 2003; Kishi et al, 1988; Shen J & Astaneh-Asl, 2000), the top angle is considered as the major affecting part of the connection and based on its behavior; the analytical model has been created. Although the seat angle also has a rotational stiffness due to the flexural stiffness and moment capacity of its horizontal leg, it was not considered in previously proposed models. The vertical reaction of the seat angle caused by its flexural stiffness, R_S, time the distance of its location from column flange, e, imposes a resisting moment on the connection. As discussed later in this paper, the stiffness of the seat angle has a relation with the beam length. Figure (7) shows the concept and the location of the main resisting factors.

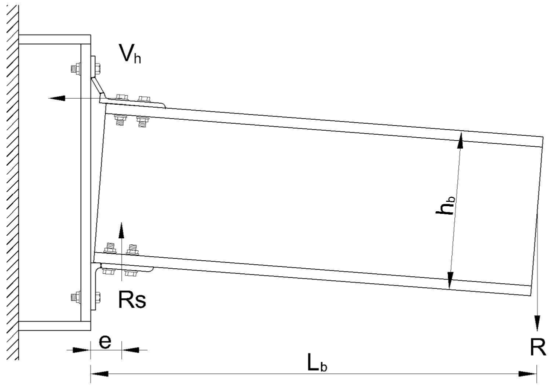

Figure (7): the main resisting component reactions affecting the connection behavior

From this figure, eq. (3) could be extracted for the moment imposed on the connection by the vertical load imposed at the beam end.

$$M = R.L_b = V_h.h_b + R_s.e \tag{3}$$

The vertical equilibrium of the imposed load, R, and its reaction on the seat angle, R_s, yields eq. (4):

$$R = R_s \tag{4}$$

According to eqs. (3, 4), eq. (5) could be written as bellow:

$$V_h.h_b = R.(L_b - e) \tag{5}$$

On the other hand, at a given rotation, θ, the horizontal reaction of the top angle assembly is V_h, corresponding to the top angle horizontal deflection and regarding to the beam length. The value of V_h at a given θ is constant for the connections with different beam lengths. Thus, at this θ rotation, for two connections with different beam lengths (L_{b1} and L_{b2}) eq. (6) could be written:

$$V_h.h_b = R_1.(L_{b1} - e) = R_2.(L_{b2} - e) \tag{6}$$

From this equation, at rotation θ for two assumed connections with different beam lengths, the equivalent reaction, R, for the shorter beam would be larger than the corresponding value of the longer beam and according to eqs. (3, 4) the obtained *M* also would be larger.

To prove this analogy, five FE models of connections with different beam lengths are created and analyzed. The obtained results are presented in figure (8) as moment-rotation curves.

From this figure it is clear that for a given rotation, the connections with shorter beams have larger resisting moment. In linear range, variation of the connection stiffness is trivial. However, in nonlinear range, the difference is visible and connections with shorter beams show high stiffness. The difference between the moment capacity of the connection with 60cm beam length and the connection with 250cm beam length at 30mrad of rotation is almost 10.7% and grows as the rotation increases.

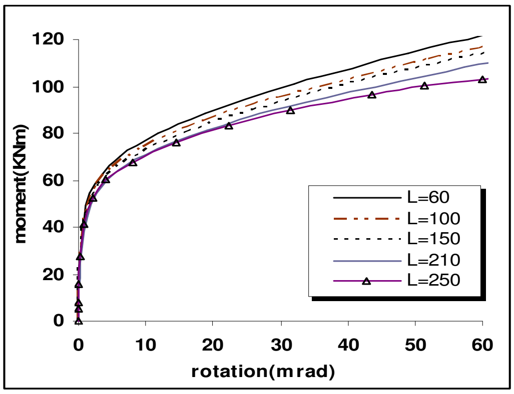

Figure (8): moment-rotation response of connections with different beam lengths

(Citipitioglu et al, 2002) studied the applicability of the pull tests in estimating the top-seat angle connections response. They have analyzed a model of the top angle under axial tension load representing the top angle of the connection. The obtained results (axial force and deformation) were converted to the corresponding moment-rotation response of the connection and it was observed that by using the pull test results, less stiffness obtains for the connection especially in the nonlinear range of the connection response. Pull test assembly represents a connection for which the beam length-depth ratio is theoretically infinite. Thus, the lower stiffness obtained by pull tests results, may be due to the absence of the seat angle vertical reaction, as illustrated previously.

As a result, an accurate estimation of a top-seat angle connection behavior needs to take into account the vertical stiffness of the seat angle and also the beam length. For connections with heavier seat angles with respect to top angle, this effect may be more sever.

5 CONCLUSION:

In this paper, the influence of the seat angle on moment-rotation response of the top and seat angle connections is studied. Nonlinear FEM is used in this study and several FE models were created and verified by precedent experimental studies. Comparison of results showed a good accuracy for finite element simulation. A parametric study is done considering the beam length as the parameter to study the role of the seat angle vertical reaction. Moment-rotation curves of the connections are derived and the change of the rotational stiffness and its sensitivity to seat angle is studied. It was cleared that considering the stiffness of the seat angle affects the moment-rotation response of the connections and its effect decreases as the beam length increases. As a result, the models which are based on the top angle assembly can not cover the effect of the seat angle stiffness and the beam length and as a result, need to be improved. The role of the beam length for connections which have different top and seat angles or have double web angles may be investigated further.

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