# BEHAVIOR OF BOLTED TOP-SEAT ANGLE CONNECTIONS UNDER COMBINED AXIAL TENSION AND MOMENT LOADING

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**ABSTRACT:**
Bolted top and seat angle connections are mainly designed to sustain gravitational loads of simply supported steel beams. However, the inherent flexural resistance of such connections may not be ignored when an accurate analysis of semi-rigid steel frames is desired. Current research aims at studying moment-rotation behavior of this type under combined moment and axial tension force. Several refined 3D finite element (FE) models were created based on the previous experimental studies and their accuracy is examined comparing by results of previous experimental studies. This study showed that axial tension force reduces connection rotational stiffness and moment capacity. Based on the results obtained from analyzing a series of finite element models under combined axial tension and moment loading an equation is presented to estimate affected moment-rotation response of such connections in terms of the connection geometrical properties, its moment-rotation response in the case of zero axial force and an expected axial tension force.

**KEYWORDS:**
Bolted angles, moment-rotation relation, nonlinear finite element, axial tension;

## 1. INTRUDUCTION:

Having moment-rotation relations of semi-rigid frame connections, will able the designer to use the inherent beneficial of such connections for an economic design. Many studies have been performed world-wide to estimate the moment-rotation behavior of bolted top and seat angle connections. Also the ductility and favorable seismic performance of semi-rigid frames with bolted connections with respect to the corresponding welded frames has been studied [1-3].

The behavior of bolted top and seat angle connections with and without web angles has been investigated and equations have been proposed to model the behavior of this type of connections under cyclic loads [4-7]. The behavior of bolted angles under cyclic loads is studied in [8, 9].

Citipitioglu et al [10] 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 [11] studied the applicability of the three-parameter power model of Kishi & Chen [12] 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. [13] 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. Pirmoz [14] studied the behavior of bolted angle connections under cyclic loads using a nonlinear FEM. Despite the accuracy of the FEM, this study showed that it is a time consuming method to predict the connection behavior under cyclic loads. In this study, all connection components were modeled using solid elements, and the interaction of adjacent surfaces was considered using a contact surface algorithm. Danesh et al [15] and Pirmoz et al [16] 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. Kumoro et al [17] 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.
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.

Azizinamini & Radziminski [5] proposed an analytical equation to predict the initial stiffness of the bolted top-seat angles with web angle connections considering the shear and flexural stiffness of the connection components. Kukretti & Abolmaali [6] proposed four methods to predict the moment-rotation behavior of bolted top-seat angle connections using a cure fitting technique. These methods were based on the results of 12 specimens which were cyclically loaded. Chen & Kishi [18] developed a data bank of tested, semi-rigid connections and a computer program to estimate connection behavior, with or without curve fitting. Using the experimental test results, Shen & Astaneh-Asl [19] proposed a three-linear moment-rotation behavior based on the fiber element formulation. Based on the strength of the angles relative to the bolt strength, two mechanisms were formed in the specimens of the tests of Shen and Astaneh-Asl [8]. For connections with thinner angles, plastic hinges were formed in the outstanding leg of the angles, and for relatively thick angles, the plastic hinge was formed at the central line of the column bolts together with plastic deformations of the bolts. Using an Artificial Neural Network (ANN) method, Pirmoz & Golizadeh [20] and Salajegheh et al [21] 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 respect to other methods.

## 2. BENCHMARK TEST SPECIMENS

Azizinamini [4] 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. Numerical modeling and validation of the specimens with web angles have also been investigated [14-16]. 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 [4] 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. Komuro et al [17] 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.

## 3. FINITE ELEMENT MODELING

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 [14-16]. 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 using the 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 for design is 0.33. Figure (1-a) shows the FE model of connection A2.

## 4. BOUNDARY CONDITIONS AND APPLIED LOADS

To satisfy symmetry conditions, all nodes of web plane are restrained against outward motion. Here it should be noted that, since the beams of the connections are compact sections so the local buckling instabilities occur in the inelastic range or high stress levels, while the Von Misses stress distribution in FE models clarifies that the beam remains almost elastic and so the local buckling failure mode can be ignored the FE models. Bolts pretension is applied as the first load case, for this purpose a thermal gradient is applied on bolts shank 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 are applied. 178kN pretension force is applied to 22.3 mm bolt diameter and 133kN for 19.1 mm. To apply bolts pretension, a thermal gradient imposed on bolts shank as first loading case. The 50 mm vertical displacement is applied on the nodes of beam end to impose the moment on connection. This value of beam end displacement yields a rotation near to 0.03 rad. Resulting moment and relative rotation of connections are evaluated respectively by equations (4.1) and (4.2):

$$M = P.L \tag{4.1}$$

$$R = \frac{\varepsilon_1 - \varepsilon_2}{h} \tag{4.2}$$

Where M is applied connection moment, P is summation of the reactions of applied displacement on beam end nodes; L corresponds to beam length, R is relative rotation of connection, h is beam depth, $\varepsilon_1$ and $\varepsilon_2$ are relatively top and bottom flange horizontal displacements. Stress-strain relation for all connection components of A. Azizinamini's tests [4] is represented using bilinear constitutive model. Isotropic hardening rule with Von Mises yielding criterion is applied to simulate plastic deformations of connection components and fracture of material is not considered. ASTM A36 steel was used for the beam, column and angles. In the current study, the mechanical properties of beam, column and angles materials are taken from the mean values of coupon test results. Since no coupon test results were reported to bolts, the Yield stress and ultimate strength of bolts are assumed based on nominal properties of A325 bolts. Bolt materials modeled bilinear with 634.3 MPa yield stress and ultimate stress of 930 MPa at 8% strain. Modulus of elasticity and Poisson's ratio is considered 210 GPa and 0.3 respectively. Komuro et al [17] have presented true uniaxial stress-strain plots of connection angles and bolts. ANSYS can support the true non-linear stress-strain behavior of the material. So the presented stress-strain relations [17] are used in FE models using 10 points.

## 5. VALIDATION OF FE MODELS

Figure (1-b) shows the deformed shape of the A2 connection at 0.03 mrad of connection rotation. To evaluate the accuracy of the FEM approach, the obtained results are compared with test results, FE analysis results of Ahmed et al [13] and the Kishi-Chen [12] power model. This comparison is presented in figure (2), which shows that "W00" specimen results obtained from FE models have relatively good agreement in the linear range of the moment-rotation curve with test data. The difference between the test and FEM results grows in rotations between 15-30 mili-radians. This may be caused by slippage of connection components in the test, which could not captured in FE models. In rotations larger than 30 mili-radians the difference between the test and the FE model decreases. For specimen "A1" the FE results coincide in the linear range with the test results. However, in the nonlinear range, the FE model slightly underestimates connection moment capacity. Moment-rotation curves of specimen "A2" show that the results of numerical methods coincide in the linear range; however, the initial stiffness of the tested specimen is larger than all other numerically obtained results. This may be caused by deficiencies in the tested specimen which were not clear during testing or errors in measuring. In general, the difference between the numerical simulations and the test results may be due to several causes including numerical modeling simplification, test specimen defects, residual stress and bolt pretension. The difference between test data and numerical models increases in the nonlinear portion of the 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. Citipitioglu et al [10] showed that the friction coefficient and the level of pre-tensioning have a considerable effect on the connection response in nonlinear range.

## 6. DATA BANK CREATION

As shown previously, to find a relationship between the modification factors and connection geometrical or mechanical properties, a wide range of connections response is needed. To obtain these data, more FE models are created using parametric base models.

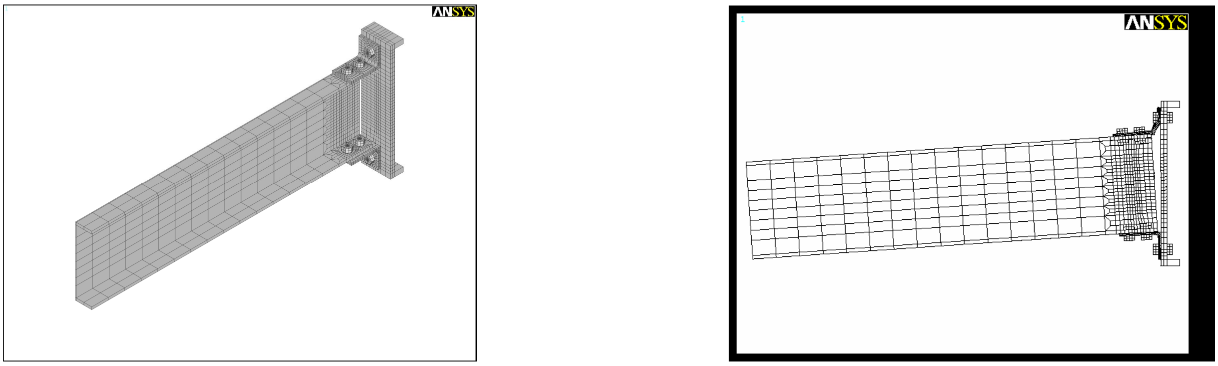
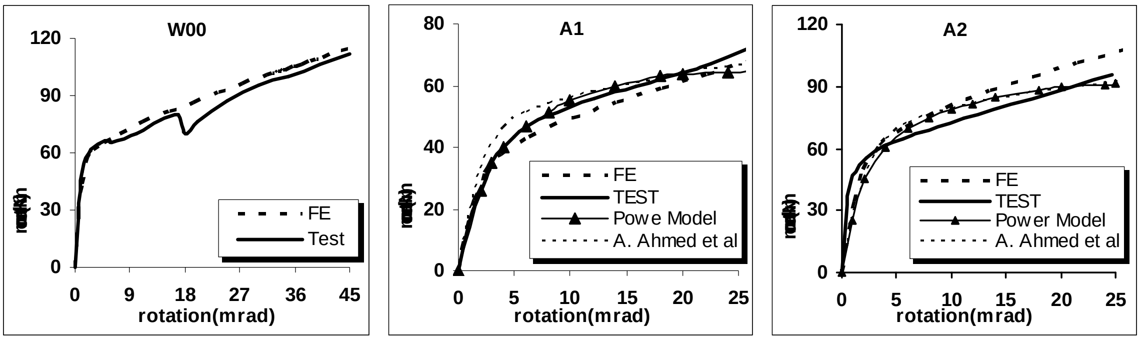



Figure 1 a) FE modeling of connection A2 b) deformed shape of A2 at 0.03 rad of connection rotation.




a): W00 specimen results b) A1 specimen results c) A2 specimen results

Figure 2 Comparison between FE, experimental and other numerical results

Table 1-geometrical properties of parametric models

| Specimen number | Bolt diameter (mm) | angle | length (mm) | Gauge(g) (mm) |
|---|---|---|---|---|
| A1 | 22.3 | L6X4X3/8 | 203.2 | 63.5 |
| A2 | 22.3 | L6X4X1/2 | 203.2 | 63.5 |
| A3 | 19.1 | L6X4X1/2 | 203.2 | 63.5 |
| A4 | 19.1 | L6X4X3/8 | 203.2 | 63.5 |

## 7. AXIAL TENSION FORCE EFFECT ON CONNECTION BEHAVIOR

Despite the fact that the top and seat angle connections are mainly designed to sustain shear force of gravitational loads, in some cases, this type of connection may be subjected to axial forces. Results of shaking table tests of Nader & Astaneh Asl [1] revealed that during an earthquake, considerable axial forces may be imposed on connections. During construction process and due to the beam shortness, even a few millimeters, axial tension forces could be developed in the same frame or adjacent frame connections. Effect of such axial tension forces on connection moment-rotation behavior is studied in this section. For this purpose, after applying bolts pretension, an axial tension force is applied on connection as the second load case and then monotonic moment loading is applied to connection as illustrated in previous sections. 10 models have been analyzed under tension and moment loading. Moment-rotation response of connections A1-A3 under different loading magnitudes is shown in figure (3). As it can be seen from this figure, axial tension load decreases the connection initial stiffness and its moment capacity. The numbers assigned for each curve denotes applied axial force on connection. A total of 19 models under axial tension and moment loading have been analyzed.

To estimate connection behavior under combined axial tension and moment loading (tension load completed before moment loading), first the rate of the changes in connection moment-rotation response due to an applied axial tension load is studied. For this, the ratio of Mt/Mo is plotted against the connection rotation for each specimen.

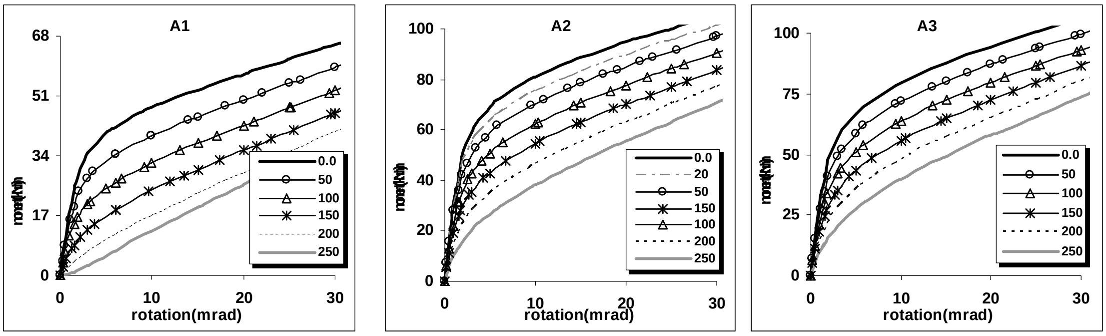



Figure 3 Moment-rotation behavior of top-seat angle connections subjected to tension and moment

"Mt" is the connection reduced moment capacity due to the applied axial tension force and "Mo" denotes the connection moment capacity without any axial tension force at a given rotation. The plots of the Mt/Mo are shown in figure (4). It can be seen that the rate of the connection moment changes is almost linear and for smaller rotations, moment capacity of the connection is more affected. Increasing connection rotation decreases the connection sensitivity to the applied axial force. Using linear interpolation technique, a line is fitted for each series of the data.

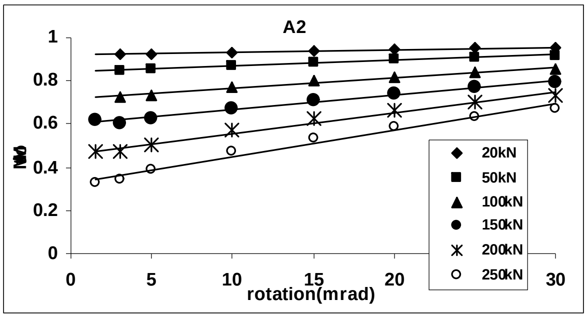



Figure 4 plots of Mt/Mo for A2 model for different axial tension forces

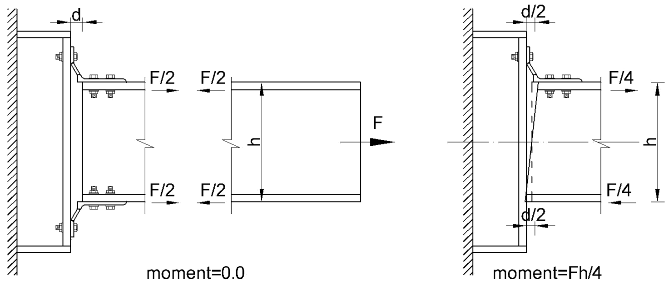
The obtained results show that a linear interpolation in its general form of eq. (7.3) can estimate connection response under a specific axial tension force accurately.

$$y = a.x + b \tag{7.3}$$

However, for engineering applications we need a general equation to estimate a given connection response affected by a given axial load. To find "a" and "b" parameters, "a" and "b" of each equation of each FE model is plotted against the ratio of its Me/My. "Me" is defined as the "equivalent moment" and can be calculated based on the following philosophy: The effect of axial tension force on connection angles is set to be equal with the effect of a corresponding moment loading. In the other words, the horizontal displacement of top angle due to a given tension load needs a moment, (Me), which can be calculated using eq. (4) Visual illustration of the method is presented in figure (5-a).

$$M_e = Fh/4 \tag{7.4}$$

"My" is the yield moment of the connection and can be obtained according to figure (5-b):
Plots of "a" and "b" against the ratio of Me/My shown in figure (6) clarifies that a linear relation would be considered between these parameters and the ratio of Me/My.



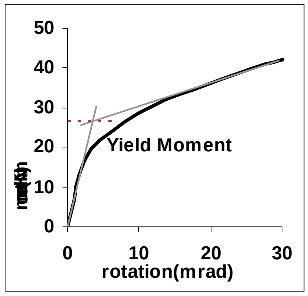




Figure 5: a) Visual illustration of the equivalent moment determination; b) the connection yield moment

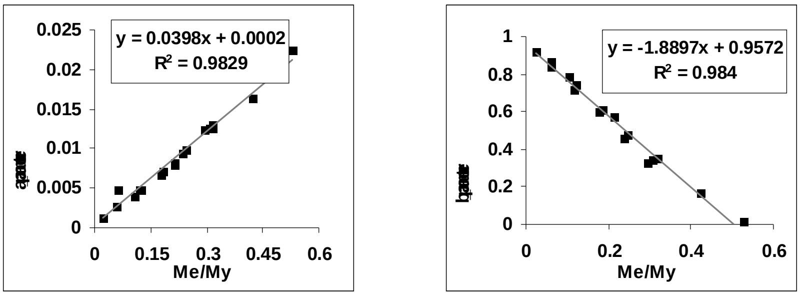



Figure 6 Plots of "a" and "b" parameters against Me/My.

According to figure (6) and a little simplification these two parameters will be calculated by eq. (5, 6):

$$a = 0.04\left(\frac{M_e}{M_y}\right) \tag{7.5}$$

$$b = 0.96 - 1.9\left(\frac{M_e}{M_y}\right) \tag{7.6}$$

Replacing eq. (7.5) and (7.6) in eq. (7.3) we have:

$$\frac{M_t}{M_o} = 0.04\left(\frac{M_e}{M_y}\right)R - 1.9\left(\frac{M_e}{M_y}\right) + 0.96 \tag{7.7}$$

## 8. CONCLUSION

Axial tension loading, developed in the connections of a semi-rigid frame during seismic excitations or construction process, can affect considerably connection moment-rotation response. Using nonlinear FEM a method is presented to study moment-rotation response of the connection under combined axial tension and monotonic moment loading. All the connection components are modeled using solid elements and contact elements are used to take into account the effect of the interaction of the adjacent components of the connection. Applying a negative thermal gradient on bolts shanks bolts pretension force is applied in the first load case. Several FE models are created and analyzed under different magnitudes of the axial tension and moment. Results of the analyzing these models cleared that the tension load decreases connection rotational stiffness and its moment capacity. Altering applied axial tension force into an equivalent moment and dividing this value by connection yield moment yielded a series of dimensionless data and using interpolation technique a formula is suggested to estimate connection moment-rotation behavior under combined tension-moment loading.

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