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FE ANALYSIS ON PRYING OF TOP- AND SEAT-ANGLE CONNECTIONS

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1. INTRODUCTION

Semi-rigid connection has probably become one of the most popular buzzing term in the research community working in the area of steel frame analysis and design in recent years. With the availability of more sophisticated computational and analytical tools; and with the enhanced understanding of the connection behavior, researchers became more interested to implement more realistic and rational analysis that is to say semi-rigid frame analysis. Many connections used in practice can be categorized as semi-rigid connections. Top- and seat-angle connection as shown in Fig. 1 is a good candidate of semi-rigid connection and can draw attention because of the following reasons: (i) this type of connection is easy to fabricate, expensive field welding is not required; and (ii) this connection has sufficient ductility and energy absorption capacity to resist earthquake and can be used as semi-rigid connection in seismic design.

The subject of prying force working on top- and seat-angle connection assemblage drew attention a number of researchers in their experimental and analytical studies (Fleischman, 1988 and Chasten et al., 1989); and on extended end-plate connection to (Krishnamurthy, 1978, Packer and Morris, 1977, Mann and Morris, 1979, Rajasekharan et al., 1974, Chasten et al., 1989 etc.). A variety of opinions are reported in the aforementioned researches. Some researchers were in the opinion to ignore the prying force arguing its insignificant share to the connection failure. But most of the researchers disagreed with this proposition. Some of them indicated that the prying force can be as high as 33% of the bolt force and hence, cannot be ignored.

Recently, top- and seat-angle connections are designed to resist moment by using equal size angles attached at the top and bottom beam flange. The bolts in the connections are subjected to direct tensile loading, due to beam end moment and vertical leg of top-angle is frequently used to transfer tensile load to the bolts. The deformation of the angle vertical leg can produce an increase in the tensile force on the bolts. This phenomenon is commonly called prying action and the increased tensile bolt force is called prying force.

In the LRFD specification for the design of steel connections (1994), AISC presented prying force formulas for tee-hanger connections. The formulas are to be used in the design of top- and seat-angle with or without double web-angle connections. The manuals are not considered the angle deformations of real top- and seat-angle with or without double web-angle connections to establish those formulas for prying action. This unawareness tends to make a folly design of connection's bolts.

This study is aimed to extend the authors recent research works which will establish several findings: (1) Examine the validity of the finite element (FE) technique and power model (Kishi and Chen, 1990) of predicting moment-rotation characteristics of top- and seat-angle connection comparing with experimental results; (2) observing the influence of bolt pretension on moment-rotation behavior of the connection and on prying action at the ultimate state condition of the connection and (3) to visualize the effect of prying action on bolt implying FE techniques.

2. TOP- AND SEAT-ANGLE CONNECTIONS

This type of connection is composed with two angles to connect a beam to a column. These are top-and seat-angles located above and below the beam flanges and bolted to the beam and column flanges. A typical connection is shown in Fig. 1. Two tests connections are taken from Azizinamini et al.'s test data (1985) and another is taken from Harper's test data (1990) to study for this research. The connections geometrical properties are shown in Table 1. The geometries for connections a1, a2 and t3 are similar with those of ap1, ap2 and tp3, respectively; as shown in Table 1. The analyses identifyed with a1, a2, ap1 and ap2 are taken from Azizinamini's test data (1985); and t3 and tp3 are taken from Harper's test data. Harper identified the test as 'TEST3` in his Ph.D. thesis (1990).

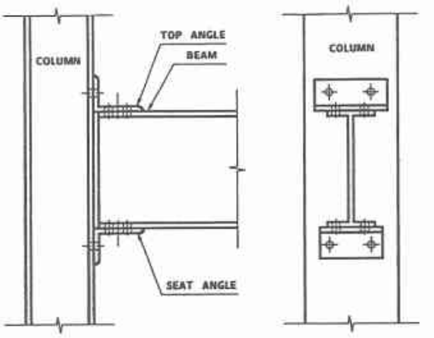


Fig. 1. A typical top- and seat-angle connection

Table 1 Geometrical properties of connections used in the analysis

FE Analysis ID	Column section	Beam section	Top- and seat-angles						Bolt diameter in.
			Angle section	Length in.	Gage on column flange, in.	Gage on beam flange, in.	Bolt spacing on column flange, in.	Bolt spacing on beam flange, in.	
*a1, ap1	W14×38	W14×38	6×4×$^3/_8$	8	2½	$2^1/_4$	5½	2½	$^7/_8$
*a2, ap2	W14×38	W14×38	6×4×½	8	2½	$2^1/_4$	5½	2½	$^7/_8$
*t3, tp3	W8×24	W8×21	6×3½×$^3/_8$	6	2	$2^1/_4$	3½	2½	$^7/_8$

*a1, a2, t3: bolt pretension is ignored; and ap1, ap2, tp3: bolt pretension is considered.

3. FINITE ELEMENT ANALYSIS

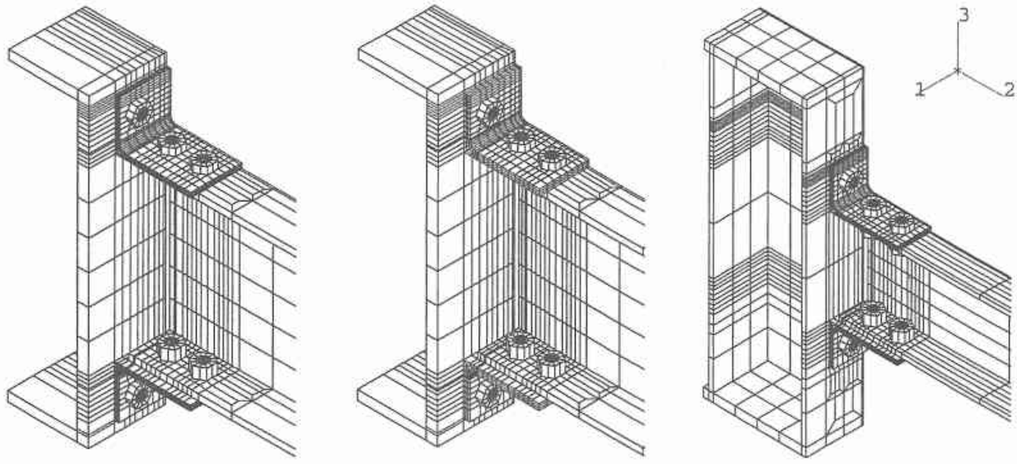
Three-dimensional (3D) FE models are set with the ABAQUS (1998) code in order to verify the accuracy of the proposed model simulating moment-rotation behavior of top- and seat-angle connections and to visualize the influence of prying action on bolts and connection behavior. The model has been chosen according to author's previous paper (1999). The connections are modeled using eight-node linear brick element. Mesh patterns of the connections are shown in Fig. 2.

3.1. Boundary Conditions

Due to symmetry, half of the connection was considered. Therefore, to enforce connection symmetry, all nodes of the stab column in the middle of 3-1 plane were restrained displacement degrees of freedom in the 1 and 2 directions and parallel to the middle section of the beam in the 2-3 plane, all nodes were constrained in direction 1 (Fig. 2). To produce only vertical reaction force at the end support, the beam was considered as a simply supported member with a span equal to the test beam length. Six FE analyses have been done for three test connections. Among those in a1, a2 and t3 analyses bolt pretension are ignored and the other three ap1, ap2 and tp3 analyses have been made implementing pre-stress in bolts. The bolt pretension level is taken as equal to 20% of the ultimate tensile strength of the bolt.

3.1. Material Properties

Material properties used in the analysis are collected from relative tests data. The yield stress and ultimate



(a) a1 & ap1 (b) a2 & ap2 (c) t3 & tp3

Fig. 2. Mesh of top- and seat-angle connections

strength for angels are taken from the mean value of coupon test results and similar values are assumed for beam and column. Bolt yield stress and ultimate strength are assumed based on the nominal properties of A325 steel, since no coupon test results were reported for beam, column and bolt. The material behavior of steel is represented by a bilinear elasto-plastic stress-strain curve. Isotropic strain-hardening is taken into consideration in the constitutive model. Effective material properties of connection assemblages are shown in the Table 2.

Table 2 Material properties of connection elements used in the analysis

FE Analysis ID	Connection components	Yield stress, ksi	Ultimate strength, ksi	Elongation %	Modulus of elasticity, ksi	Poisson's ratio	Steel designation
a1, a2, t3, ap1, ap2, ap3	Bolt	92.0	120.0	8	29000	0.3	A325
a1, ap1	Angle, beam, column	53.00	80.00	20	29000	0.3	A36
a2, ap2	Angle, beam, column	39.55	67.95	20	29000	0.3	A36
t3, tp3	Angle, beam, column	43.00	70.17	32	29000	0.3	A36

3.4. Loading

Imposed displacement was employed as the method of loading. The middle surface in 1-3 plane of the stub column was displaced vertically parallel to same plane as shown in Fig. 3. Automatic load increment scheme is preferred because ABAQUS code can select increment size based on computational efficiency. It may help to achieve better convergence rate resulting efficient computation to bring the initial state into the equilibrium state.

4. ANALYSIS RESULTS

4.1. Comparison of Moment-Rotation behavior

To examine the validity of FE technique three bolted top- and seat-angle connections, two are taken from

Azizinamini et al.'s test data (1985) and another is taken from Harper's dissertation thesis (1990), are analyzed. The analyses have been done in two phases: (1) Considering bolt pretension; and (2) ignoring bolt pretension; to observe the influence of bolt pretension on moment-rotation behavior and prying action effects on bolts implying FE analysis technique. The $M-\theta_r$ curves obtain from FE analysis together with Kishi-Chen power model (1990) and experimental data (Azizinamini et al., 1985 and Harper, 1990) are shown in Fig. 3. The connection moment M is evaluated multiplying reaction force and minimum distance between the supporting point of beam end and the instantaneous center of rotation. The value of relative rotation evaluated from the results of FE analysis is:

$$\theta_r = \frac{\delta_t - \delta_b}{D_b - t_f} \tag{2}$$

where D_b is the depth of beam, t_f is the thickness of flange angle; δ_t and δ_b are the horizontal displacements at the upper and lower edges of beam flanges, respectively. Analytical values of initial connection stiffness and ultimate moment capacity are listed in Table 4. The figures show a good approximation of FE technique and power model comparing with experimental $M-\theta_r$ curves.

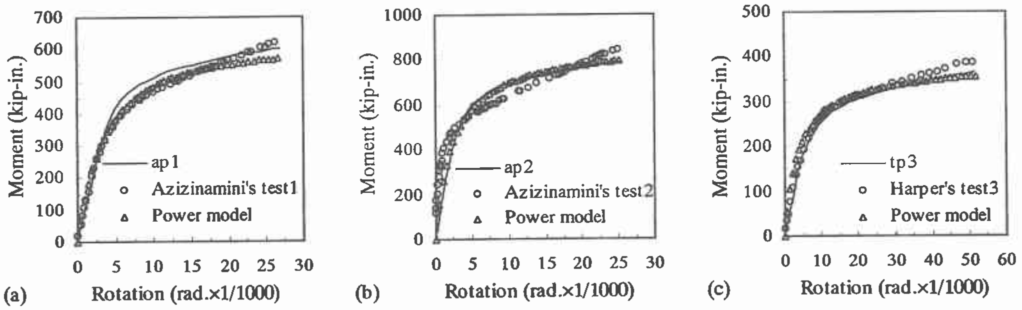


Fig. 3. Comparison among FE analysis, power mode and test

4.2 Bolt pretension effect on moment-rotation behavior

Fig. 4 shows the influence of bolt pretension on $M-\theta_r$ curves predicting by FE analyses. Fig. 4 reveals that FE analysis can produce a little effect of bolt pretension on moment-rotation behavior of top- and seat-angle connection. Consideration of bolt pretension increases the initial connection stiffnesses from 32.6% up to 68.7% and the ultimate moment capacities 0.2% to 0.4%.

Table 4 Predicted initial connection stiffness and ultimate moment

FE analysis ID	Initial connection stiffness (kip-in./rad.)		Ultimate moment (kip-in.)	
	Power model	FE analysis	Power model	FE analysis
ap1	0.1518×10^6	0.1273×10^6	621.2	637.8
ap2	0.3974×10^6	0.2731×10^6	892.5	872.9
tp3	0.1203×10^6	0.4814×10^5	395.0	386.4
a1	0.1518×10^6	0.8704×10^5	621.2	636.1
a2	0.3974×10^6	0.1619×10^6	892.5	869.3
t3	0.1203×10^6	0.3630×10^5	395.0	384.7

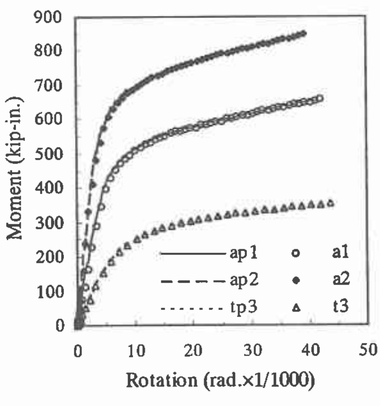


Fig. 4. Influence of bolt pretension on moment-rotation behavior

4.3 Bolt pretension effect on prying action

The pretension force 14.43 kips ($0.2F_u$) is implemented for connection ap2 and pretension phenomenon is absolutely ingrate in the FE analysis a2. It is evident that the increments of reaction force in bolt are practically the same for both cases at higher loads. However, the analysis ignoring pretension (i.e. FE analysis a2) shows the earlier response of prying action than analysis implying bolt pretension (i.e. FE analysis ap2). This phenomenon is shown in fig. 5.

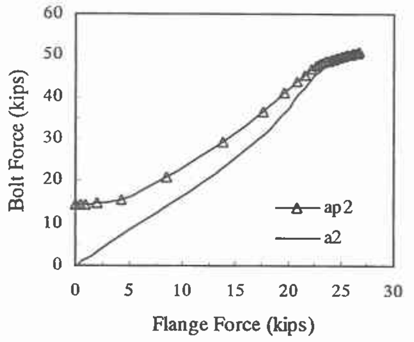


Fig. 5. Prying action on bolt

4.4 Influence of connection parameters on bolt prying

Flange angle thickness t_f and gage distance g, two connection parameters are studied in this phase. All geometrical parameters of connections ap1 and ap2 are the same with the exception of flange angle thickness. The flange angle thickness of connections ap1 and ap2 are 3/8 in. and 1/2 in., respectively. The fig. 6 shows that prying force in connection ap1 developed more rapidly than connection ap2 for less thickness of flange angle. On the contrary, the gage distances are 2.5 in. and 2 in. for connections ap1 and tp3, respectively, whenever their flange angle thicknesses are the same. The evident is that prying action can get higher with longer gage on vertical leg of flange angle (Fig. 6).

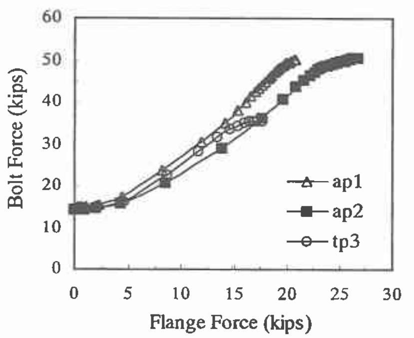


Fig. 6. Influence of connection parameters on bolt prying

4.5 Relation of bolt prying with connection strength

Relation of prying action with connection stiffness and moment is shown in the Fig. 7. In less stiffer connection, prying can grow adversely at higher loading stages. In other word, stiff connection can produce less prying than that of flexible connection. Prying force develops upholding nearly a linear relation with connection moment after some steps from initial loading and the increment of the prying can cause a substantial reduction of bolt ultimate load capacity. At the beginning of loading, prying force develops with slower rate with respect of connection moment.

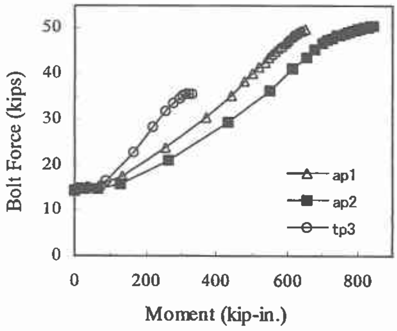


Fig. 7. Relation of prying action with connection moment

5. CONCLUDING REMARKS

This study is primarily verified FE technique and power model of predicting moment-rotation behavior of top- and seat-angle connections under monotonic loading. As a boundary condition of FE analysis, bolt pretension has taken into account in the computation to study its influence on overall connection behavior. This study exposes that,

A) The three-parameter power model can be used as an efficient and reasonably accurate prediction model of top- and seat-angle connections.

B) FE technique can also be a viable approach in establishing semi-rigid frame analysis particularly for the connections whose analytical formulations are not available.

C) FE analysis has a little effect of bolt pretension on moment-rotation behavior of top- and seat-angle connections. The connections behaved almost identically, independent of consideration of bolt pretension.

D) Bolt pretension has no influence on bolt prying at higher loading condition of connection.

Prying effects in bolt and on connection behavior; and influence of connection parameters on prying have also been investigated. This investigation furnished with following conclusions:

1) Reduction of flange angle thickness can develop large prying force.
2) Increment of gage on flange angle vertical leg can cause increasing of prying action in a significant quantity at ultimate state condition of bolt.
3) Prying develops more rapidly in weak connection than in stiffer one.
4) Prying action can cause a substantial reduction of ultimate strength of bolt.

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