A Finite Element Model for the Prediction of the Behavior of an Unstiffened Top and Seat Angle Connection with Various Top Angle Bolt Gage Distances

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Abstract
This study aimed at proposing a finite element model for predicting the initial rotational stiffness and plastic moment capacity of the Type A top and seat angle connection without double web angles. The main parameter of the 3D nonlinear finite element analysis was the bolt gage distance of the top angle. The finite element analysis resulted not only in the rotational stiffness and the plastic moment capacity, but also in the stress distribution and the plastic hinge location. The study verified the applicability of the finite element model by comparing the results of the finite element analysis with those of existing experimental studies.

Keywords: top and seat angle connection; initial rotational stiffness; plastic moment capacity; three-dimensional finite element analysis

1. Introduction
A top and seat angle connection under various loads is one of the connection types suitable for low- and medium-rise steel buildings. Many experimental and theoretical studies have been conducted to understand the behavior of, and propose a design equation for, the top and seat angle connection3). Recently, more studies tend to perform a finite element analysis together with experimental studies of the top and seat angle connection. Although a finite element analysis may allow one to accurately determine the stress distribution, deformation, plasticity process and other characteristics applied to the top and seat angle connection, such an accurate estimation of the behavior of the connection should be based on the premise that the properties of each material used in the modeling of the connection are accurately determined. Other points to be ensured: that suitable mesh forms are selected, that contact and bearing between materials are properly considered, and that the initial tension force of high strength bolts is introduced. Thus, many existing studies that use a finite element analysis apply these elements as their parameters to accurately estimate the behavior of the top and seat angle connection9).

This study aimed to determine the behavior of the Type A top and seat angle connection without double web angles, defined by the AISC LRFD specifications2), and propose a 3D nonlinear finite element analysis model that can predict the initial rotational stiffness and the limit state plastic moment of said connection. The proposed finite element analysis of the top and seat angle connection was modeled with the gage distance of the high strength bolts on the top angle as its parameter. It also considered the introduction of the initial tension force of the high strength bolts and the contact and bearing between the materials.

2. Finite Element Analysis of the Top and Seat Angle Connection
2.1 Modeling of the top and seat angle connection
Existing finite element analyses of the top and seat angle connection have attempted to determine the stiffness and strength of the connection with the use of parameters including the friction coefficient between materials, the initial tension force of high strength bolts, the top angle thickness, and the gage distance of the high strength bolts8,9). Among these parameters, this study only used the gage distance of the high strength bolts on the top angle connection, which has the most effect on the behavior of the top and seat angle connection. As shown in Fig.1., the top angles used in this study were the L-100x100x7, L-100x100x10, and L-100x100x13 equilateral angles, and the seat angle was an L-100x100x10 equilateral angle. The gage distance of the high strength bolts of each top angle was set to gₜ = 45, 55 and 65 mm, respectively. The top and seat angles were modeled in such a way that they were fastened by F10T-M20 bolts. These bolts had pretension force of 165kN to the top and bottom flange of each column and beam.

The material properties of the top and seat angles and high strength bolts required for the finite element
The study used ABAQUS (ver. 6.9.2) to model the top and seat angle connection and selected C3D8R (eight-node brick element with reduced integration) as the element for the top and seat angles, high strength bolts, nuts, and washers that made the top and seat angle connection. In proposing the finite element analysis model, the contact and bearing between elements and the pretension of high strength bolts were considered. The contact and bearing phenomenon was simulated by ABAQUS *MPC, TIE option and *FINITE, SMALL SLIDING option. The initial tensile force of high strength bolts was simulated by ABAQUS *INTERLOCKING option to maintain the initial tensile force. The nonlinear behavior of the connection was determined using the Newton-Rhapson method. The load was applied to each connection by using the *PRESSURE LOAD option on the end of the beam until a sufficient yield occurred. The bolt head of high strength bolts was modeled as the hexagonal bolt head. The friction coefficient between members was set to 0.3. As shown in Fig.3., the finite element analysis model for the whole top and seat angle connection consisted of a total of 49,994 elements and 151,960 nodes, and it took about 250 minutes to execute the analysis of one model.

Table 1. Material Properties of the Angle Specimens and High Strength Bolt

|               | Young's Modulus (N/mm²) | Yield Stress (N/mm²) | Tensile Strength (N/mm²) |
|---------------|--------------------------|----------------------|--------------------------|
| Angle         | 206.0210                 | 280.0                | 449.8                    |
| Bolt          | 229.2020                 | 1,026.5              | 1,094.1                  |

![Fig.1. Geometry of the Angle Specimens Used in the FEM](image1)

![Fig.2. Stress-strain Curve of Angle Specimens](image2)

![Fig.3. 3D Nonlinear Finite Element Analysis Model of the Top and Seat Angle Connection](image3)

### 2.2 Moment-angle relation of the top and seat angle connection

The results of the existing finite element analyses showed that the initial tension force of the high strength bolts and the friction coefficient between the members had little impact on the rotational stiffness and plastic moment. The thickness of the top and seat angles and the gage distance of the high strength bolts, on the other hand, significantly affected the moment-rotation relation, rotational stiffness, and plastic moment. Accordingly, this study examined the moment-rotation relation of the top and seat angle connection while changing the bolt gage distances such as \( g_r = 45, 55 \) and \( 65 \) mm on the connections whose top angle thickness was \( t_a = 7, 10 \) and \( 13 \) mm respectively. The finite element analysis was conducted until the rotation angle on the connection exceeds 0.04 rad, causing sufficient yield on each member.

The change in the rotational angle and the moment at each connection was evaluated by Equation (3) and Equation (5), respectively. The moment-rotation curve of the top and seat angle connection, obtained from the finite element analysis, offers the initial rotational stiffness \( (K_r) \), plastic rotational stiffness \( (K_p) \), reference moment \( (M_0) \), and curve sharpness parameter \( (n) \). All of these provide key information in determining the behavior of the connection by applying the Richard model in Equation (7). The accuracy of regression analysis is generally determined.
by analyzing the correlation coefficient ($R$), the coefficient of determination ($R^2$), and the adjusted coefficient of determination (adj. $R^2$). That is, if these values approach 1.0, the regression analysis becomes more accurate. As shown in Table 2., the coefficient of determination ($R^2$) is 0.99. Richard model shows almost identical behavioral characteristics with those of the moment-rotation relationship curve acquired from the finite element analysis. Highly accurate initial rotation stiffness and reference moment values are therefore obtained. The reference moment, in particular, as shown in Fig.4, is the moment of the intercept at which the y axis (the moment axis) meets the slope of the moment-rotation curve of the plastic moment hardening area of the connection. That is, the reference moment in the Richard model is identical to the plastic moment capacity of the connection that exhibits the plastic moment hardening stiffness defined by Jaspart et al. \(^7\) and Chen et al. \(^4\).

![Moment-rotation Curve](image)

**Fig.4. Example of the Regression Analysis**

Fig.5. shows the moment-rotation curve of the top and seat angle connection when the gage distance of the high strength bolts on the top angle is set to the parameter. It is shown that the slope of the moment-rotation curve increases if the thickness of the top angle increases or the gage distance of the high strength bolts decreases. Such a phenomenon becomes clearer once the regression analysis of the moment-rotation curve is performed, as in Table 2.

### 2.3 Stress distribution of the top and seat angle connection

Once load is applied to the top and seat angle connection, the connection starts to rotate, at about an arbitrary point on the corner of the seat angle in the direction of the load, and the corner of the top angle is parted from the top flange of the column. As the load increases, the corner of the top angle enters into the top flange of the beam and starts to be deformed. At this point, the stress becomes further concentrated on the part where the washer meets with the top angle leg fastened to the column flange with high strength bolts and the part which is apart from the fillet at a specified distance. Similarly, the seat angle exhibits further deformation in the direction of the load, and the stress becomes more and more concentrated onto the fillet of the seat angle. When the moment at the connection exceeds the reference moment of each connection, such stress concentration on the top and seat angle becomes so much greater that the angle finally yields and enters into the plasticity stage.

![Moment-rotation Curve of Each Connection](image)

**Fig.5. Moment-rotation Curve of Each Connection**

### Table 2. Regression Analysis Result of the Moment-Rotation Curve of the Top and Seat Angle Connection

| Specimen  | $K_e$ (kN·m/rad) | $K_p$ (kN·m/rad) | $M_n$ (kN·m) | $n$ | $R^2$ |
|-----------|------------------|-----------------|--------------|----|------|
| T7-S10-G45 | 13,267.3         | 1,102.64        | 19.24        | 2.13 | 0.99 |
| T7-S10-G55 | 6,802.70         | 803.32          | 16.89        | 2.35 | 0.99 |
| T7-S10-G65 | 3,628.80         | 602.30          | 13.25        | 1.55 | 0.99 |
| T10-S10-G45 | 48,373.22        | 1,440.77        | 40.04        | 2.43 | 0.99 |
| T10-S10-G55 | 24,781.20        | 1,052.33        | 35.21        | 2.42 | 0.99 |
| T10-S10-G65 | 13,258.19        | 791.97          | 26.32        | 2.43 | 0.99 |
| T13-S10-G45 | 124,264.63       | 1,858.42        | 66.26        | 1.81 | 0.99 |
| T13-S10-G55 | 64,337.40        | 1,355.28        | 58.36        | 2.03 | 0.99 |
| T13-S10-G65 | 34,402.74        | 1,031.77        | 46.85        | 2.01 | 0.99 |
The application of the load causes the moment at the connection, as shown in Equation (5), due to which the angle leg of a top angle connected to the top flange of a beam receives the shearing force, as shown in Equation (6). Such shearing force exerts tensile force on the high strength bolts fastened to the column flange, and the tensile load-bolt force curve per bolt changes accordingly, as shown in Fig.7. The axial force of the bolts, which had initially showed the behavior of a gradual, linear increase, began to rapidly and nonlinearly increased as the displacement at the corner of the top angle increased. It is believed that the reason for such a drastic increase of the axial force of the bolts is the prying action effect of the bolts. Therefore, any consideration of the initial rotational stiffness and limit state plastic moment of the top and seat angle connection must include the effect of the prying action. Shown in Fig.8, is the stress distribution of the high strength bolts used on the top angle, depending on the change in applying load.

3. Top and Seat Angle Connection Stiffness and Strength Prediction Model

As shown in the moment-rotation relation curve, the rotational stiffness at the connection starts to drastically decrease in the transition zone at which the plastic rotational stiffness decreases by about 6,586.6% (T13-S10-G45) at maximum, compared to the initial rotational stiffness. To achieve a stable connection behavior, the connection should be designed in such a way that its rotational stiffness does not pass through the initial rotational stiffness zone. In other words, the connection moment should not pass through the reference moment of the moment-rotation relation curve. Therefore, to design a stable connection, it is critical to propose an accurate analysis model and determine the corresponding reference moment so as to predict the initial rotational stiffness of the connection.

3.1 Initial rotation stiffness analysis model

Chen et al. proposed a prediction model of the initial rotation stiffness of the top and seat angle connections, as shown in Equation (8), which idealized the top angle as a cantilevered beam while considering the effect of shear deformation at the same time. In doing so, they assumed that the connection rotates about an arbitrary point in the fillet of the seat angle and that the moment-resisting capacity of the seat angle at this rotational point can be neglected. Therefore, any consideration of the initial rotational stiffness and limit state plastic moment of the top and seat angle connection must include the effect of the prying action.
\[ K_{e,C-K} = \frac{3EI_{a,\text{top}}}{1 + 0.78(t_{a,\text{top}}/g_{C-K})} \left( \frac{d_1^2}{g_{e,m}} \right) \] (8)

\[ g_{C-K} = g_e - \frac{(d_e / 2)}{-t_{a,\text{top}} / 2} \] (9)

Yang et al. proposed a prediction model of the initial rotation stiffness of the top and seat angle connections with the top angles having various thicknesses, as shown in Equation (10) [5]. They assumed the top angle as a clamped end-free end plate and considered the prying action effect, using the variable \( \alpha \) Thornton (1985) suggested.

\[ K_{e,Yang} = \left[ \alpha', \left\{ \frac{E}{4(1-v^2)} \frac{d_1^2}{g_{e,Yang}} \right\} \right] \] (10)

\[ g_{e,Yang} = g_e - t_{a,\text{top}} - 0.3 \cdot r_{a,\text{top}} \] (11)

By substituting the material properties and geometric shapes applied to the finite element analysis into Equations (8) and (10), the study compared and examined the initial rotational stiffness. As shown in Table 3., the initial rotational stiffness from the finite element analysis differed from that of the Chen-Kishi analysis model by up to 1,671.5% (T7-S10-G65), and from that of the Yang analysis model by up to 36.8% (T13-S10-G45). It is believed that the main reason for such errors is the \( g_{e,m} \) in Equation (9) and \( g_{e,Yang} \) in Equation (11) that were proposed by the Chen-Kishi model and the Yang model, respectively.

Therefore, this study proposed a new equation, as in Equation (12), for \( g_{e,m} \), which is the distance between two points on which stress is concentrated, by analyzing the stress distribution of the top angle, as shown in Fig. 6. (a), at the last loading stage. This presents a linear, proportional relation between the moment-rotation curve and the connection based on the results of the finite element analysis. By substituting \( g_{e,m} \), evaluated in Equation (12), into Equations (8) and (10), the study compared and examined the initial rotational stiffness. As shown in Table 3., the result showed a decrease in errors by up to 142.2% (T7-S10-G65) and 27.2% (T13-S10-G45) compared to those of \( g_{e,C-K} \) and \( g_{e,Yang} \).

\[ g_{e,m} = g_e - t_{a,\text{top}} - 0.2 \cdot r_{a,\text{top}} \] (12)

### 3.2 Plastic moment analysis model

As has been discussed, plastic moment is defined as the moment at which the plastic moment stiffness hardening started to appear in the transition moment zone on the moment-rotation relation curve, a definition identical to the reference moment in the Richard analysis model. Therefore, as the top and seat angles pass through the transition moment zone on the moment-rotation relation curve, plastic hinges were formed at the exterior parts where the top angle and the high strength bolts met and fillets of the top angles, as shown in Fig. 6. (b). While there have been many studies on predicting the plastic moment of the top and seat angle connection, it is true that we need to propose a more exact analysis model.

### Table 3. Initial Rotational Stiffness Values at \( g_{e,m} \)

| Specimen          | \( g_{e,m} \) (mm) | \( g_{e,Yang} \) (mm) | \( K_e \) (kN · mm/deg) | Error** (%) |
|-------------------|-------------------|----------------------|------------------------|------------|
| T7-S10-G45        | -                 | -                    | -                      | -          |
| Proposed FEM      | 31.5              | -                    | 105,068.6 (91,944.6)   | 691.9 (593.0) |
| Chen-Kishi model  | -                 | -                    | 15,098.4 (13,874.9)    | 13.8 (4.6)  |
| Yang model        | -                 | -                    | 79,766.8 (71,968.0)    | 1,072.6 (957.9) |
| T7-S10-G55        | 41.5              | -                    | 71,039.9 (65,650.6)    | 4.4 (2.2)   |
| Proposed FEM      | -                 | -                    | 79,766.8 (71,968.0)    | 1,072.6 (957.9) |
| Chen-Kishi model  | 41.5              | -                    | 36,485.9 (34,222.6)    | 1,671.5 (1529.3) |
| Yang model        | 41.5              | -                    | 36,485.9 (34,222.6)    | 1,671.5 (1529.3) |
| T7-S10-G65        | 41.5              | -                    | 36,485.9 (34,222.6)    | 1,671.5 (1529.3) |
| Proposed FEM      | -                 | -                    | 36,485.9 (34,222.6)    | 1,671.5 (1529.3) |
| Chen-Kishi model  | 41.5              | -                    | 36,485.9 (34,222.6)    | 1,671.5 (1529.3) |
| Yang model        | 41.5              | -                    | 36,485.9 (34,222.6)    | 1,671.5 (1529.3) |

*Initial rotational stiffness of each connection at \( g_{e,m} \)
**Error = (Proposed FEM - analytical model) x 100 / proposed FEM
***Error at \( g_{e,m} \)
The plastic moment of the top and seat angle connection can be evaluated by Equation (13).

\[
M_{p, total} = M_{p, seat} + M_{p, top} + V_{a, top} \cdot d_2
\]  
(13)

\[
M_{p, seat} = \left( t_{a, seat} \cdot F_{y, seat} \cdot 4 \right)
\]  
(14)

\[
M_{p, top} = V_{a, top} \cdot g_2
\]  
(15)

To obtain \( V_{a, top} \) in Equation (13), Yang et al.\(^{12} \) proposed the work equation, as shown in Equation (16), based on the plastic hinge yield criterion. They applied the Drucker and Tresca yield criterion, as shown in Equation (17), to obtain the shearing force per unit length, \( V_{py} \), that is included in Equation (16). The pure shearing force of the top angle, \( V_{a, top} \), is evaluated by Equation (18). The plastic shear load capacity of the top angle, \( V_{a, top} \), is the sum of the \( V_{py} \), which is created along the edge of the top angle leg, as shown in Equation (19). Yang et al. also considered in Equation (19) the prying action effect of high strength bolts.

\[
2M_{py} \theta_y = V_{py} \cdot g_{y, Yang} \cdot \theta_y
\]  
(16)

\[
\left( \frac{V_{py}}{V_{0, top}} \right)^4 + \frac{g_{y, Yang} \left( V_{py} \right)}{t_{a, top}} = 0
\]  
(17)

\[
V_{a, top} = (t_{a, top} \cdot F_{y, top} / 2)
\]  
(18)

\[
\gamma_{Yang} V_{a, top} = \alpha \cdot V_{py} \cdot t_{a, top}
\]  
(19)

Table 4. Plastic Moment Capacity Values at \( g_{w,m} \)

| Specimen          | \( g_{w,Yang} \) (mm) | \( g_{w,m} \) (mm) | \( M_{p,Yang} \) (kN.m) | Error (%) |
|-------------------|-----------------------|-------------------|-------------------------|-----------|
| T7-S10-G45        | -                     | -                 | -                       | -         |
| Proposed FEM      | -                     | -                 | 19.24 (*)               | -         |
| Faella model      | -                     | -                 | 43.10 (18.86)           | 124.0 (2.0) |
| Yang model        | -                     | -                 | 15.55 (19.23)           | 19.2 (0.04) |
| T7-S10-G55        | -                     | -                 | -                       | -         |
| Proposed FEM      | -                     | -                 | 35.21                   | -         |
| Faella model      | -                     | -                 | 28.87 (15.16)           | 70.9 (10.3) |
| Yang model        | -                     | -                 | 13.25 (15.61)           | 21.5 (7.6) |
| T7-S10-G65        | -                     | -                 | -                       | -         |
| Proposed FEM      | -                     | -                 | -                       | -         |
| Faella model      | -                     | -                 | 52.94 (31.50)           | 50.3 (10.5) |
| Yang model        | -                     | -                 | 25.50 (32.18)           | 27.6 (8.6) |
| T10-S10-G45       | -                     | -                 | -                       | -         |
| Proposed FEM      | -                     | -                 | -                       | -         |
| Faella model      | -                     | -                 | 26.32                   | -         |
| Yang model        | -                     | -                 | 41.33 (26.01)           | 57.0 (1.2) |
| T10-S10-G55       | -                     | -                 | -                       | -         |
| Proposed FEM      | -                     | -                 | -                       | -         |
| Faella model      | -                     | -                 | 88.65 (74.37)           | 33.8 (12.2) |
| Yang model        | -                     | -                 | 49.72 (72.60)           | 25.0 (9.6) |
| T13-S10-G45       | -                     | -                 | -                       | -         |
| Proposed FEM      | -                     | -                 | -                       | -         |
| Faella model      | -                     | -                 | 58.36                   | -         |
| Yang model        | -                     | -                 | 76.80 (56.32)           | 31.6 (3.5) |
| T13-S10-G65       | -                     | -                 | -                       | -         |
| Proposed FEM      | -                     | -                 | -                       | -         |
| Faella model      | -                     | -                 | 46.85                   | -         |
| Yang model        | -                     | -                 | 64.03 (45.63)           | 36.7 (2.6) |

* Plastic moment capacity at \( g_{w,m} \)

** Error = \( \frac{\text{Proposed FEM} - \text{analytical model}}{\text{Proposed FEM}} \) x 100 / proposed FEM

*** Error at \( g_{w,m} \)
suggested \( d_2 \) in Equation (13), which includes the change in the distance between the plastic hinge lines, by Equations (25) and (26), respectively. Therefore, this study proposed a new equation, as in Equation (27), for \( g_{y,m} \), which is the distance between two points on which stress is concentrated, by analyzing the stress distribution of the top angle, as shown in Fig. 6. (b), at the loading stage after the connection reaches the reference moment, based on the results of the finite element analysis of the top and seat angle connection. By substituting \( d_2 \), evaluated by Equation (27), into Equations (19) and (20), the study compared and evaluated the plastic moment. As shown in Table 4., the result revealed a decrease in errors by up to 25.2\% (T13-S10-G55) and 122\% (T7-S10-G45) compared to those of \( d_2 \), Yang and \( d_2 \), Faella.

3.3 Verification of the finite element analysis model

Nethercot et al. (1987) and Kishi et al. (2009) conducted an experiment on the top and seat angle connection without double web angles. To verify the validity of the finite element analysis model proposed in this study, therefore, the study initially performed the finite element analysis model on the top and seat angle connection which Nethercot et al. and Kishi et al. had used for their studies. As shown in Figs. 9. and 10, the moment-rotation relationship curve acquired by the tests of Nethercot et al. and Kishi et al. exhibits very similar behavioral characteristics with those of the moment-rotation relationship curve acquired by finite element analysis.

As shown in Tables 5. and 6., the initial rotational stiffness from this study showed errors by only up to 0.2\% and 3.9\%, respectively, compared to those from the studies of Nethercot et al. and Kishi et al. Therefore, it is determined that the proposed finite element analysis model on the Type A top and seat angle connection is appropriate in determining the behavior and failure aspects of the connection.

4. Conclusions

This study proposed a 3D nonlinear finite element analysis model to determine the initial rotational stiffness and plastic moment capacity based on the bolt gage distances on the top angle of the top and seat angle connection. Results of the finite element analysis are as follows:

(1) Since the proposed finite element analysis model on the top and seat angle connection resulted in the initial rotational stiffness value with errors of only up to 0.2\% and 3.9\%, compared to the initial rotational stiffness values from the tests by Nethercot et al. and Kishi et al., respectively, it is believed that the

Table 5. Initial Rotational Stiffness Values from the Test by Nethercot et al. and theFinite Element Analysis, which Simulated the Test of Nethercot et al.

| Specimen         | g (mm) | \( K_e \) (kN \cdot m/rad) | Error* (%) | R²   |
|------------------|--------|--------------------------|------------|------|
| T8-S8-G35        | Nethercot's experimental test | 35          | 20,330.00  | -    | -    |
|                  | FEM    | 35                       | 20,291.55  | 0.2  | 0.99 |

* Error = (Nethercot's test - proposed FEM) x 100 / Nethercot's test

Table 6. Initial Rotational Stiffness Values and Plastic Moment Capacities from the Test by Kishi et al. and the Finite Element Analysis, which Simulated the Test of Kishi et al.

| Specimen         | g (mm) | \( K_e \) (kN \cdot m/rad) | Error* (%) | M₀ (kN \cdot m) | Error** (%) | R²   |
|------------------|--------|--------------------------|------------|----------------|-------------|------|
| T15-S15-G60      | Kishi's experimental test | 60          | 100,410.00 | -              | 160.3       | -    |
|                  | FEM    | 60                       | 96,602.71  | 3.9            | 153.2       | 4.6  | 0.99 |

* Error = (Kishi's test - proposed FEM) x 100 / Kishi's test

** Error = (Kishi's test - proposed FEM) x 100 / Kishi's test
The proposed finite element analysis model is appropriate in determining the behavior of the connection.

(2) The initial rotational stiffness evaluated by applying the newly suggested $g_{e,m}$ based on the results of the proposed finite element analysis, yielded smaller errors of 0.7% (T13-S10-G55) and 36.4% (T13-S10-G55) than those of the Yang model and the Chen-Kishi model, respectively. Thus, it is determined that the proposed finite element analysis model offers more accurate initial rotational stiffness values.

(3) The plastic moment resulting from the newly suggested $g_{y,m}$ based on the results of the proposed finite element analysis, yielded smaller errors of 1.6% (T10-S10-G45) and 1.0% (T10-S10-G45) than those of the Yang model and the Faella model, respectively. Thus, it is believed that the proposed finite element analysis model provides more precise plastic moment values.

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**List of Nomenclatures**

- $d_n$: the diameter of the nut
- $g$: the gap between the face of a column flange and the tip of a beam web
- $g_2$: the distance between plastic hinges developed in a top angle
- $B_{prep}$: the bolt pretension force
- $M_{py}$: the plastic moment capacity of a top angle per unit length
- $V_{py}$: the shear per unit length of a top angle
- $V_{top}$: the shear force developed at the top angle due to the applied load
- $V_{u,top}$: the plastic shear load capacity of a top angle
- $\theta_y$: the angular change of a top angle leg at yielding

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