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An improved polynomial model for top -and seat- angle connection

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Abstract. The design provisions for semi-rigid steel frames have been incorporated in codes of practice for steel structures. In order to do the same, it is necessary to know the experimental moment-relative rotation (M-θ_r) behaviour of beam-to-column connections. In spite of numerous publications and collection of several connection databases, there is no unified approach for the semi-rigid design of steel frames. Amongst the many connection models available, the Frye-Morris polynomial model, with its limitations reported in the literature, is simple to adopt at least for the linear design space. However this model requires more number of connection tests and regression analyses to make it a realistic prediction model. In this paper, 3D nonlinear finite element (FE) analysis of beam-column connection specimens, carried out using ABAQUS software, for evaluating the M-θ_r behaviour of semi-rigid top and seat-angle (TSA) bolted connections are described. The finite element model is validated against experimental behaviour of the same connection with regard to their moment-rotation behaviour, stress distribution and mode of failure of the connections. The calibrated FE model is used to evaluate the performance of the Frye-Morris polynomial model. The results of the numerical parametric studies carried out using the validated FE model have been used in proposing modifications to the Frye-Morris model for TSA connection in terms of the powers of the size parameters.

Keywords : semi-rigid analysis; top and seat-angle connection; Frye-Morris polynomial model, Moment-relative rotation (M-θ_r).

1. Introduction

Conventional steel design codes for various countries recommend the use of two types of connection for design and analysis, namely, (i) rigid and (ii) flexible. The assumption in extreme types of connection cases such as totally rigid and purely flexible is simple and convenient for analysis and design purposes but they do not represent the real behaviour in most situations. Connection design is very important not only from the strength point of view but also from the economy point of view, as connections are expensive. Semi-rigid connection design which has an economic advantage is not popular with the

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designers, as their designs are not well understood. In the case of semi-rigid designs, the development of design code provisions or improving them is a continuous process and requires a wide range of experimental studies. Large experimental data on various types of semi-rigid connection is needed to establish an analytical procedure. Several researchers have published papers discussing the influences of connection rigidity on the behaviour of steel frame structures. For example, Goverdhan (1983) presented a database on moment-rotation characteristics and tried to formulate a prediction equation for each type of connection. Nethercot (1985) carried out an extensive literature survey of steel beam-to-column connection test data and their corresponding M - θ_r curve representations from the period of 1915 to 1985. Kishi and Chen (1986) and Chen and Kishi (1989) also collected experimental test data published from 1936 to 1985 and presented a database. Based on these studies, connection models such as (i) polynomial model, (ii) power law model (iii) exponential model and (iv) three parameter model have been proposed. Out of these, as mentioned earlier, the polynomial model is simple to adopt, but it needs large experimental data to evaluate the powers of the exponents of size parameters that influences the connection behaviour. Also, Indian standard code IS: 800 (2005) suggests the Frye Morris polynomial model for the design of semi rigid frames. Performing a number of experiments is costly, time consuming and hence uneconomical. In this context, if a finite element model of the problem is calibrated with test results, the calibrated FE model can be used for further studies by varying the parameters.

One of the main objectives of the present work is the evaluation of Frye-Morris (1975) polynomial model for the semi-rigid design of top and seat angle bolted connection. The experimental study carried out on the connection is explained and the results are presented. Three-dimensional (3D) elasto-plastic nonlinear finite element analysis is carried out using ABAQUS, software. The finite element model is validated using experimental results, based on the moment-rotation behaviour, stress distribution and the failure mode of the connection. Parametric studies are carried out by varying the size parameters using the validated finite element model. Till now, no analytical model is available with air gap parameter for top- seat- angle connection, parametric studies are conducted by varying the air gap distance between beam and the column. Based on the analysis results, the Frye-Morris (1975) model is re-evaluated by incorporating the air gap parameter.

2. Review of literature

Several experimental and numerical studies have been reported by various researchers on different types of connections. The experimental results are used to validate the FE method and to check the performance of various analytical models. Frye and Morris (1975) developed a polynomial expression to predict the behaviour of different types of connections based on experimental studies. Driscoll (1987) has given a special way of defining the structure geometry, which makes it possible to analyse structures with top and seat angle semi-rigid connections using ordinary structural analysis computer programs with line type bending members. Kishi and Chen (1990) developed M-θ_r relationships for semi rigid steel beam-to-column connections and reported that the power model is simple to use. Barakat and Chen (1991) proposed models associated with the simplified analysis procedure for un-braced flexible steel frames. Richard *et al.* (1993) presented a method for modeling connection moment-rotation curves. Abdalla and Chen (1995) expanded the existing database of semi-rigid steel connections and compared the experimental moment rotation curves with several analytical models describing these curves. Kishi *et al.* (1997) provided an analytical evaluation of the Eurocode 3 classification on the three types of beam-to-column connections in steel construction. Kim and Chen (1998) provided a practical method for the design of Type PR (Partially restrained) construction for design office use and presented the three-parameter power model for connection moment-rotation curves. Dhillon *et al.* (1999) presented an integrated analysis and design procedure for the design of PR-type steel frames. The Frye and Morris polynomial model is adopted for modeling the semi rigid connections. Kishi *et al.* (2001) examined four FE models to find the one that best estimates M-θ_r characteristics of top- and seat-angle with double web-angle connections using ABAQUS and recommended the use of power model. Pucinotti (2001) proposed a simplified mechanical model for the top- and seat- and web angle connection. The application of the model, and its comparisons with experimental curves and the Eurocode application have revealed the excellent quality of the simplified model. Citipitioglu *et al.* (2002) gave a methodology for modeling the moment-rotation response of top and seat-angle connection with and without web angles using ABAQUS. Lee and Moon (2002) proposed a two parameter log model to describe the non linear M-θ relationship of semi rigid connections. The proposed model accurately describes the M-θ behaviour of all connections by controlling shape parameters α and n. Hong *et al.* (2002) studied the nonlinear behavior of a double web angle and double channel beam-to-column connection subjected to shear loads. Komuro *et al.* (2004) established a numerical analysis method for evaluating M-θ_r relations of top- and seat-angle with or without web angles under monotonic loading. Taufik and Xiao (2005) presented a three dimensional finite element methodology to predict the behaviour of top and seat-angle connection with mild carbon steel and high strength steel and found that stress-strain curve is a very important parameter for accurate prediction of angle bolted connection behaviour with high strength steel.

From the literature review it is inferred, though number of tests are reported for top seat-angle connections, it does not involve systematic change of size parameters. Hence many of the results reported in the literature, cannot be used to modify the Frye-Morris model (1975) model. It needs number of experimental and numerical parametric studies by varying one size parameter while all the other size parameters are kept constant.

3. Experimental program on top and seat-angle connection

The prediction of exact moment rotation behaviour of any connection can be done only through experimental investigations. This section describes an experimental program conducted to predict the moment rotation behaviour of top and seat angle connection. The values of the geometric variables for top and seat angle connection are presented in Table. 1.

The experimental set up for TSA connection (Raman 2005) is illustrated in Fig. 1. The set-up consists of two beams of length 1.1 m connected to a central stub column of height 650 mm. The beams and the stub column used in the test are Universal Beam, UB 306.6 × 165.7 × 11.8 × 6.7 × 46.1 sections of Fe 420 W [mild carbon, 420 MPa UTS (Ultimate Tensile Strength) weldable] steel. Indian Standard Angle, ISA 65 × 65 × 6 sections are used as top and seat angles for a length of 165.7 mm which is equal to the width of the beam flange. The far ends of the beams are supported on roller at one end and hinge at other end to simulate simply supported conditions. Roller and hinge supports are made of mild steel. The length and diameter of the roller was 200 mm and 90 mm respectively. The hinge was designed in such a way that the support allows a maximum rotation of 28.03°. High strength friction grip (HSFG) bolts of diameter 16 mm are used to connect the ends of the beams to the central stub column. A pre torque of 214 Nm (70% of the yield strength of the bolt) was applied to all the bolts. The advantage of the present setup is that since the column does not rotate and displaces only up and down, the relative rotation between the column and the beams is due to the contribution of the connection deformation alone. The strains are measured using strain gauge, which is pasted on the top/seat angle. Three dial gauges D1-D3 (Fig. 1) with

Table 1 Dimension of the experimental specimen

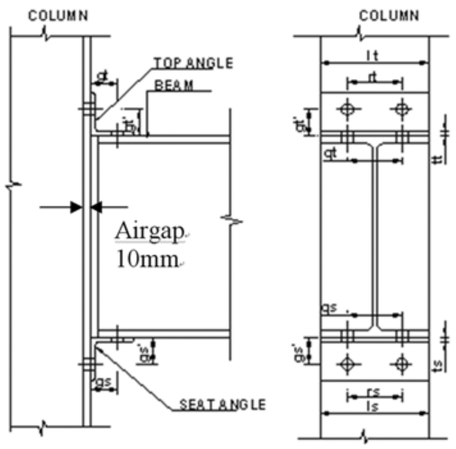
H. S. F. G BOLT
- DIAMETER : 16 mm
- AREA : 201.06 mm^2
- PRE-TORQUE: 214 Nm

BEAM & COLUMN PROFILE
- ROLLED SECTION REFERENCE: UB 306.6 × 165.7 × 11.8 × 6.7 × 46.1
- bf : 165.7 mm
- tf : 11.8 mm
- hw : 306.6 mm
- tw : 6.7 mm
- weight : 46.1 Kg/m

ANGLE- ISA 65 × 65 × 6

gt : 40 mm	gs : 40 mm
gt' : 40 mm	gs' : 40 mm
rt : 86.7 mm	rs : 86.7 mm
lt : 165.7 mm	ls : 165.7 mm
tt : 6 mm	ts : 6 mm
qt : 86.7 mm	qs : 86.7 mm

Air gap : 10 mm



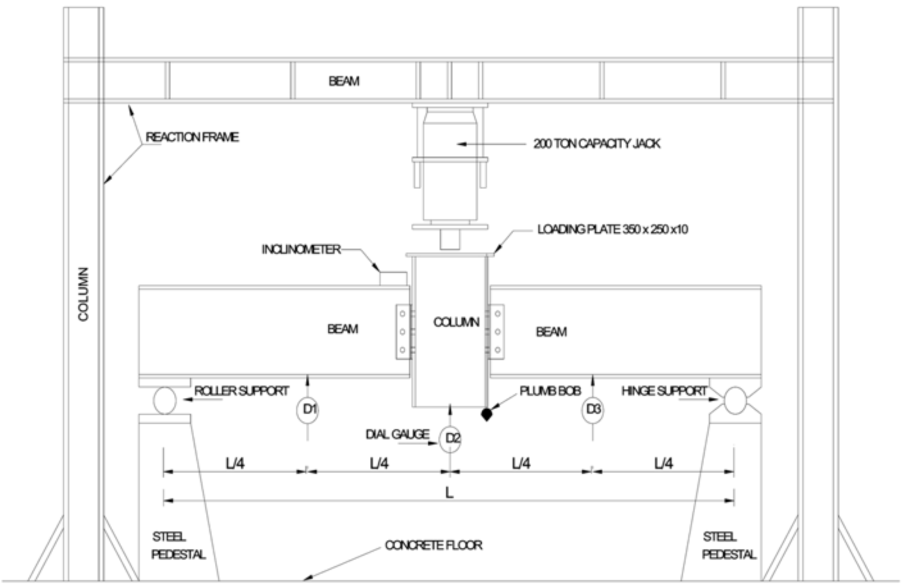


Fig. 1 Test setup and Instrumentation

a least count 0.01 mm are used to measure deflection. An Inclinometer is used to measure the beam-column relative rotation. The load is gradually applied over the center of stub column at top of the specimen by means of hydraulic jack. Dial gauge readings, rotations of beams and strain gauge readings are observed for frequent intervals of load up to the collapse load.

3.1 Experimental observations and results

Two stages of behaviour are identified before connection failure occurs. The stage I corresponds to the portion before air gap (shown in Table. 1) closure and the stage II after the closure of air gap and before failure. Initially, the load is carried by the tension of the seat angle beam flange leg and the top angle beam flange leg bolts experience shear. The top angle beam flange leg bolts fail in shear. In stage II, the load is carried by the compressive thrust of the beam on the flange of column and the tension by the bolts in the seat angle column flange leg. On further loading, the seat angle beam flange leg yields. Finally the plastic hinge is formed in the seat angle beam flange leg and it failed in tension. Photographic view of the tensile fracture failure mechanism is shown in Fig. 2.

Moment- rotation curves based on the inclinometer readings on the two beams on either side of the column are shown in Fig. 3. Initially, there is a steep curve (initial stiffness) up to 0.25 degree rotation due to the top angle beam flange leg bolts loaded by shear. Then there is a flat curve up to 1 degree, because of the top angle beam flange leg bolts loaded by shear and trying to close the air gap. Then the rotation increases gradually because of yielding the seat angle. The variations of deflection at one fourth span locations and midspan are given in Fig. 4. Deflection patterns at locations D1 and D3 are same which indirectly verified the symmetric loading of the frame. Eight strain gauges are used to measure the strain variation in the angles. Two strain gauges are pasted in the top angle column flange legs, two are pasted in the top angle beam flange leg, two pasted in the seat angle column flange leg and two are pasted in the seat angle beam flange leg. Strain variation with applied load is shown in Fig. 5. The strain variation in the top angle beam flange leg (S2 and S4) and strain variation in the seat angle column flange leg (S5 and S7) are more compared to other strain gauges (S6, S8, S1 and S3). This is because of the shear in the top angle beam flange leg bolts in the first stage and the tension in the seat angle column flange leg in the second stage.

4. Finite element analysis of the top and seat-angle connection

Three dimensional (3D) elasto-plastic nonlinear finite element analysis (Prabha 2007) have been carried out for evaluating the moment-rotation behaviour of TSA connection using ABAQUS software. The experimental specimen of the TSA connection has been modelled using the software. Finite element model of the TSA connection is shown in Fig. 6.

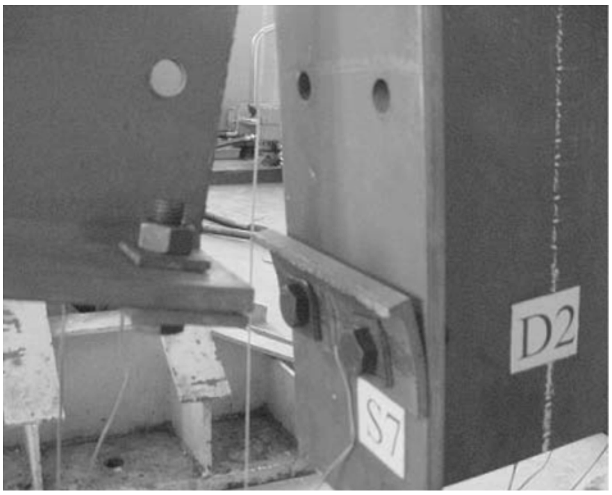


Fig. 2 Photographic view of plastic hinge line and failure pattern

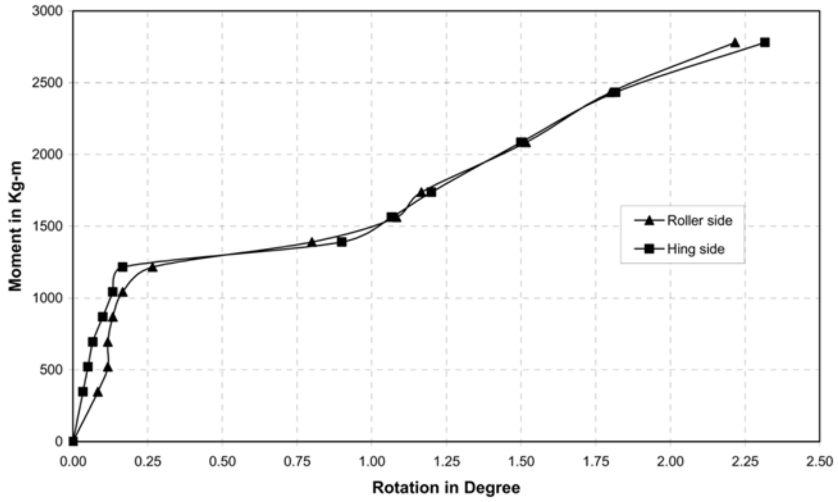


Fig. 3 Moment-Rotation curve

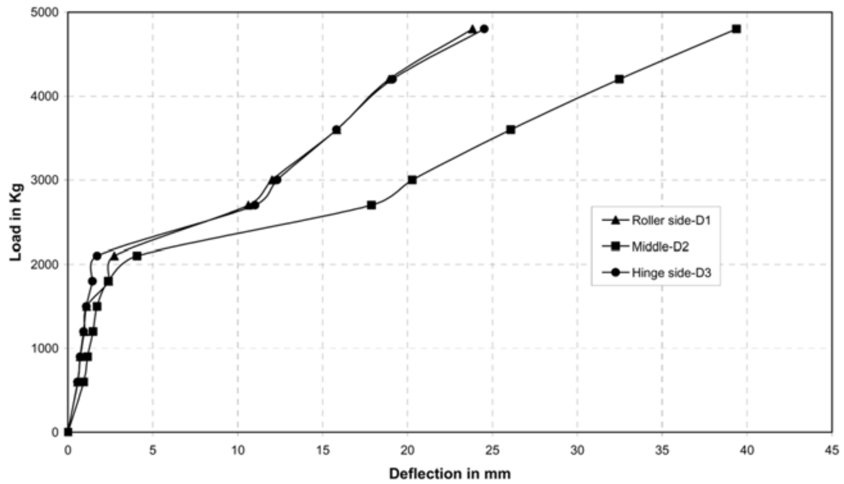


Fig. 4 Load versus deflection curve

4.1 Description of the model

The beam, the stub column and the connection components of the TSA connection are modeled using continuum eight-noded solid elements with reduced order integration (C3D8R). The element is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y, & z directions. Linear interpolation is used in each direction and hence they are called linear elements or first order elements. High strength friction grip bolts of 16 mm diameter (class 8.8) are used for the connection. An air gap of 10 mm is considered between the beam and the column. Hexagonal bolt heads and nuts are idealized as circular bolt heads and nuts to simplify the model. Washers are not modeled. Bolt holes are assumed to be 1.5 mm larger than the bolt size (D = 17.5 mm). The fillets in the angles are not modeled in order to reduce

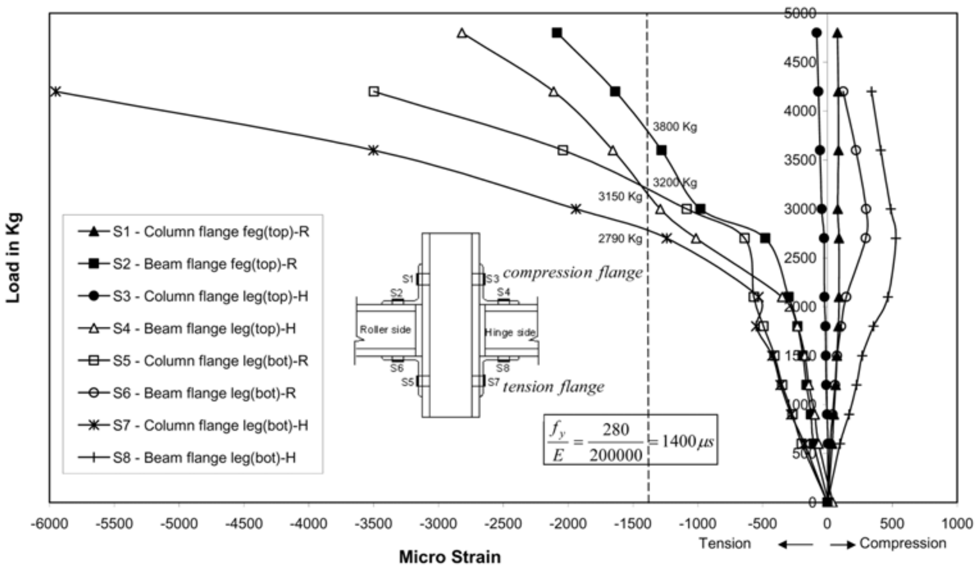


Fig. 5 Load versus micro strain

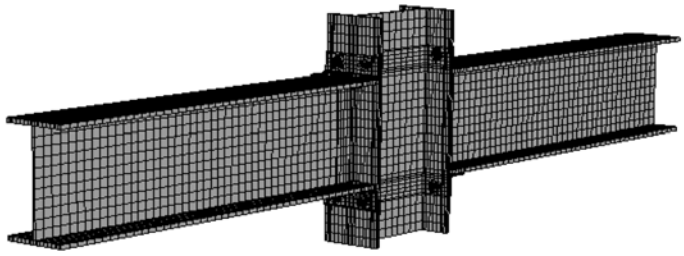


Fig. 6 ABAQUS model of TSA connection specimen

the complexity of the model.

Final arrangement of the finite element mesh is decided based upon the computer time, convergence of solution and by comparison with the experiment results. Proper care is taken to model the contacts, which plays a major role in a bolted connection. Mesh refinement is carried out for corners, holes and the angles, where stress concentration is expected to occur. The sizes of meshes are controlled between the components of connection to enable surface-to-surface contacts and easy convergence. Non-linear behaviour of the model under loading is accounted. Non linearity arises from large displacement effects, material and from boundary such as contact and friction. In the present study, the material and boundary nonlinearities are considered.

4.2 Contact modeling

Representation of contacts between the components has a major effect on the performance of the connection and its response. The pretension of the bolts and friction are critical parameters in bolted connections. The forces are transferred through friction due to the clamping between the members caused by the pre-tensioning of the bolts. Contact between all parts is explicitly modeled. The contact areas are the top and seat angles to the beam flange/column flange, bolt shank-to-bolt holes and bolt head-to-components. The interaction between contacting surfaces consists of two components, one normal to the surfaces and the other tangential to the surfaces. The tangential component consists of the relative motion of the surfaces, and possible, frictional shear stresses if the connection is by HSFG bolts. The angle portion/column flange in contact with the bolt head/nut is assumed to be hard introducing a tie constraint between them. The surfaces separate when the contact pressure between them becomes zero or negative. This behaviour is referred to as hard. When surfaces are in contact, they usually transmit shear as well as normal forces across their interface. Thus the analysis needs to take frictional forces, which resist the relative sliding of the surfaces. Tangential contact between the beam and stub column with the angles is modeled using penalty stiffness formulation with a friction value of 0.1. The tangential contact between the bolt shank and the bolt hole/beam/column/angle is considered as frictionless.

To accurately simulate the connection behaviour, small sliding contact pair definition is applied between two interacting surfaces, one of which is a master surface and the other is a slave surface. Small sliding transfers load to the master nodes according to the current position of slave nodes. Master surfaces of contact pair options represent the surfaces of column and beam flanges, beam web and bolts; whereas the surfaces interfacing master surfaces are defined as slave surfaces. The bolt clamps the components together in order to resist the applied rotation.

4.3 Material model

Stress-strain relation of steel is represented by a tri-linear constitutive model. The material model for beams, column, angles and bolts are shown in Fig. 7. Bolt yield stress and ultimate strength are assumed based on the nominal properties of grade 8.8 bolts. Effective material properties of the connection assemblage are shown in Table 2.

4.4 Boundary conditions and loading

The loading and the boundary conditions of the TSA connection are shown in Fig. 8. One end of the two beams is connected on either side of the flanges of the vertical stub column with top- and seat angles. The other ends of the beams are supported, one on roller and the other on a hinge to simulate simply supported conditions of the whole assembly of the two beams and the centrally connected stub column. The model is analyzed using two load steps.

In the first step, bolt pretension force of 72300 N equivalent to the experimental pre torque of 214 Nm is applied to the pretension node of a pre-defined section of bolt shank. In the second step, uniform pressure load is applied on the top of the column. Automatic load increment scheme is employed because ABAQUS selects increment size based on computational efficiency.

5. Comparison of numerical and experimental results and validation of FE model

The comparison of the finite element analysis results with that of experimental results is made by considering the following three aspects.

- Failure of the connection

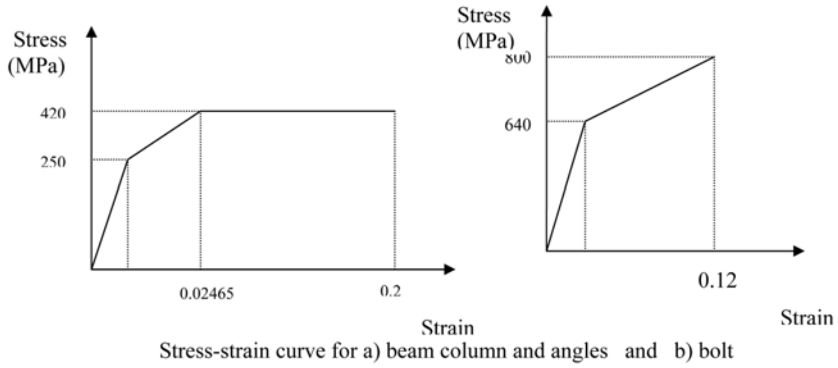


Fig. 7 Material model

Table 2 Lists of Material Properties

Connecting member	Young's modulus (GPa)	Poisson's ratio	Yield Strength f_y (MPa)	Ultimate strength f_u (MPa)	% Elongation
Beam, column and Angle	200	0.3	250	420	20
Bolt			640	800	12

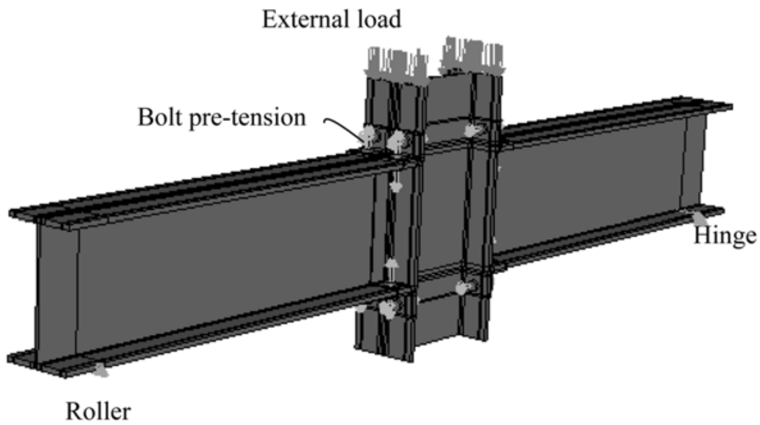


Fig. 8 Loading & Boundary conditions of TSA connection

- Moment-rotation behaviour
- Deformation and stress distribution in the connection

In an actual usage of a top- and seat-angle connection in a frame, 'top angle' always refers to the angle at the top which would be in tension. However, in the present study (for experimental convenience) the tension angle is provided at the bottom. Hence the word 'top angle' in the present study refers to the actual seat angle which provides shear resistance to the connection.

5.1 Failure of the connection

The deformed shape of the connection by finite element analysis at the ultimate stage is shown in Fig. 9. The behaviour of the FE model is found to be agreeing well with the experimental observations. The failure modes are compared with the experimental observation of failures, to validate the FE model (Fig. 10). The failure observed in both the finite element model and the experiment is similar.

5.2 Moment-rotation behaviour

The M-θ_r curves obtained from FE analysis and experimental studies are compared in Fig. 11. The connection moment M is evaluated by multiplying reaction force and the distance between the supporting point of beam end and the instantaneous centre of rotation. Relative rotation of the connection is measured using inclinometer in the test and in FE analysis; M is evaluated using the equation, $\theta_r = (\delta t - \delta b)/h$ where, δt and δb are the horizontal displacements at the face of the column. In Fig. 12, it is seen that the experimental and the FE model curves compare well up to the tearing of seat angle. The discrepancy in ultimate moment capacity between FE analysis and experimental results is about 0.2%. The flat plateau seen in Fig. 11 for the experimental curve is due to the bolt fracture in the compression side and the subsequent load distribution. In the case of the FE model this phenomenon takes place more gradually as shown in Fig. 11 as the present ABAQUS model could not capture it. Since it is known that in first stage the shear of the top bolt causes a displacement and the closing of the air gap, this displacement is added to the results of the FE model and the modified curve is shown in Fig. 11. With this modification, a very good correlation is obtained. This is normally not considered in the design process. As the failure load and the mode of failure agree reasonably well, this model is adopted for further parametric studies.

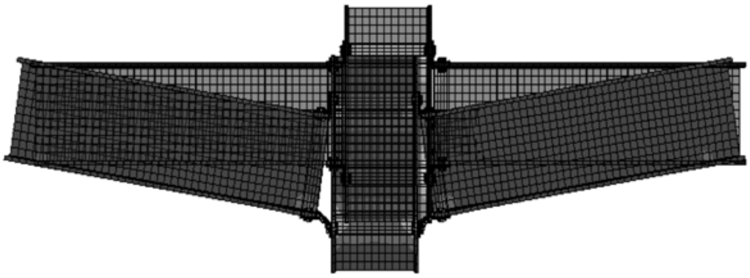
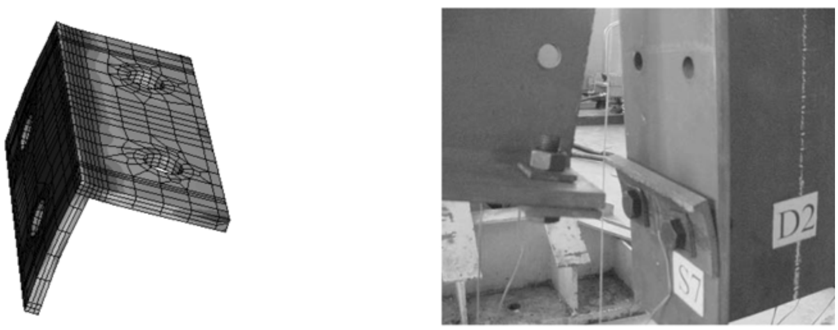


Fig. 9 Deformed shape of connection at the ultimate stage



Tearing of seat angle

Fig. 10 Comparison of failure of connection

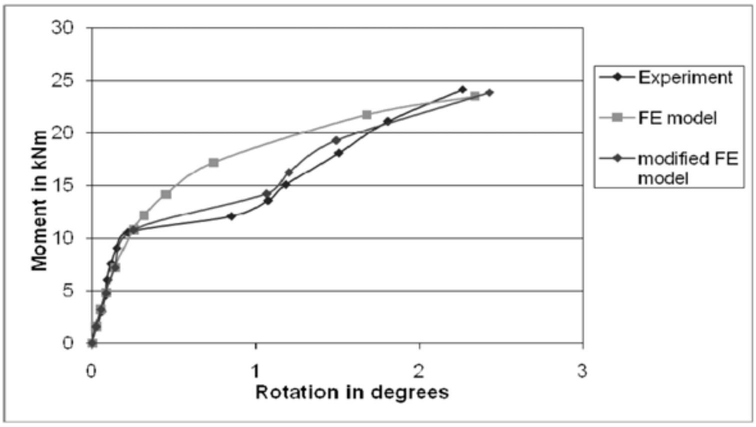


Fig. 11 Comparison of M-θr curves of experiment and FE model

6. Frye-Morris (1975) connection model

The Frye-Morris (1975) polynomial model [IS: 800 (2005)] is generally used to obtain the moment curvature relationship of semi-rigid connections. A typical moment-relative rotation relation is given by

$$\theta_r = C_1(KM)^1 + C_2(KM)^3 + C_3(KM)^5 \tag{1}$$

where, M is the Moment at the joint in KN m, K is a standardization parameter which depends on the connection type and geometry, and C_1, C_2, C_3 are curve fitting constants. For top and seat angle connection, the curve fitting constants are given as $C_1 = 1.63 \times 10^3$, $C_2 = 7.25 \times 10^{14}$, $C_3 = 3.31 \times 10^{23}$ and the standardization constant K is $d^{1.5}\, t_a^{-0.5}\, l_a^{-0.7}\, d_b^{-1.1}$, where 'd' is the depth of the beam in mm, 't_a' the thickness of the top angle in mm, 'l_a' length of the angle in mm, 'd_b' the diameter of the bolt in mm as shown in Table. 1.

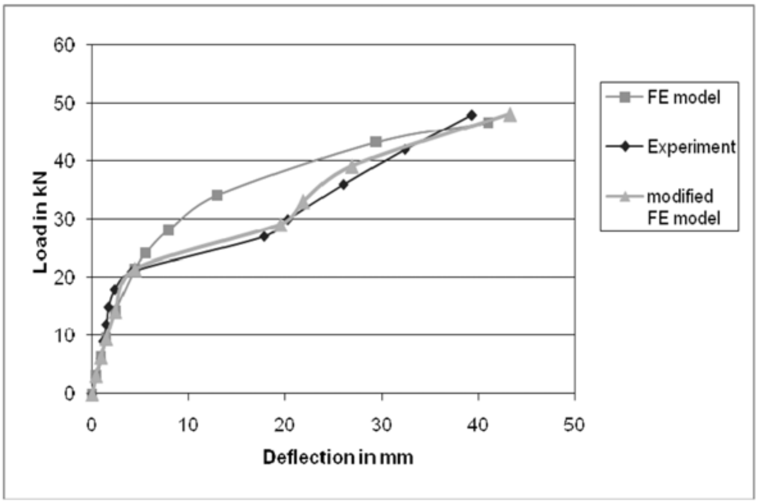


Fig.12 Comparison of load-deflection curves

6.1 Comparison of Frye-Morris model with the FE model results

The Frye-Morris model is plotted using the values as given above for the present case of top- seat-angle connection. The Frye-Morris model has been developed without considering the air gap between the beam and the column, whereas the present finite element model considers an air gap. Since the Frye-Morris model doesn't consider the air gap between beam and the column, another finite element model is developed without considering an air gap. The comparison of (M-θ_r) curves predicted by the Frye-Morris model and the finite element analysis (Fig. 13) shows that the Frye-Morris model predicts stiffer results than the finite element analysis. In some cases where the thickness of the connection angles is large, the Frye-Morris model shows a flexible behaviour. This stiff or flexible behaviour of the Frye-Morris model may possibly be due to the smaller number of test results based on which the original equation has been developed. Fig. 13 clearly shows that the exponents of the original Frye-Morris model (1975) need a revision.

7. Parametric studies

As mentioned earlier, the Frye-Morris model predicts a stiffer behaviour compared to the finite element model. The equation for finding standardization constant given by Frye-Morris for TSA connection includes four parameters: depth of the beam (d), length of the angle (l_a), thickness of the angle (t_a) and the diameter of the bolt (d_b). Using the validated finite element model, parametric studies are carried out for the TSA connection for the above parameters. Later these connection characteristics are mathematically correlated to give a moment rotation prediction equation for top- and seat-angle connection. Fifteen separate finite element models are developed for parametric studies by varying the air gap distance between the beam and the column (0, 5, 10 mm), beam depth (250, 306.6, 350 mm), angle thickness (65 × 65 × 6, 65 × 65 × 8, 65 × 65 × 10 mm), angle length (140, 165.7, 150 mm) and diameter of the bolt (12, 16, 20 mm). The results of the parametric studies are discussed in the next section.

7.1 Effect of air gap on the connection behaviour

Three finite element models were developed, one without air gap and other two with air gaps of 5 mm

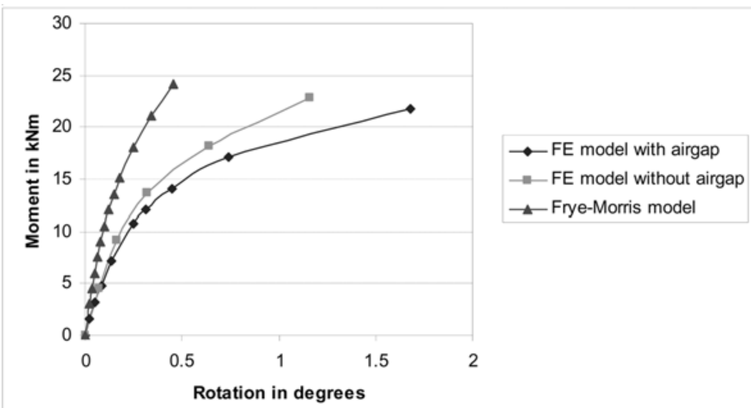


Fig. 13 Comparison of Frye-Morris model with FE model

and 10 mm between the beam and the column. The comparison of behaviour of the connection with varying air gaps is given in Fig. 14. The initial stiffness of the connection is almost same till 0.25 degrees of rotation, after which the stiffness varies with the air gap distance. The finite element model without air gap has higher stiffness than the other two models with 5 mm and 10 mm air gaps. The finite element model with 5 mm air gap behaves slightly stiffer than the finite element model with 10 mm air gap. The comparison shows that the inclusion of air gap between beam and the column affects the connection behaviour. As mentioned earlier, the Frye-Morris polynomial model does not consider the air gap distance between beam and the column. Based on the present study, it is proposed to include a new size parameter, air gap (a_g), in the equation for finding standardization constant.

7.2 Effect of beam depth on the behaviour

Three finite element models were developed, by varying the depth of the beam as 250 mm, 306.6 mm and 350 mm to predict the behaviour of the connection. The comparison of behaviour of the connection with varying beam depths is given in Fig. 15. The initial stiffness of the connection increases with the increase in beam depth. The finite element model with beam depth of 350 mm has higher stiffness than the other two models with 306.6 and 250 mm depth. The moment carrying capacity of the connection increases with the increase in beam depth.

7.3 Effect of angle thickness on the behaviour

The effect of thickness of the angle on the behaviour of the connection is given in Fig. 16. Three finite element models are created by keeping the angle size as 65 × 65 × 6, 65 × 65 × 8, and 65 × 65 × 10 mm. The comparison shows that the FE model with angle size 65 × 65 × 6 has higher stiffness than the model with angle size (65 × 65 × 8) mm until 0.5 degrees. However in general the stiffness increases with the increase in angle thickness. Since 6mm thickness angles have very less bearing strength, the air gap is closed very quickly and the initial stiffness is provided by the stage II mechanism of tension-compression system.

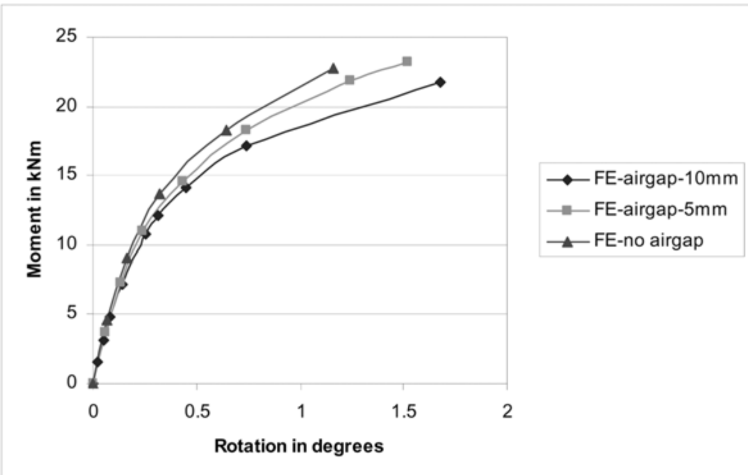


Fig. 14 Effect of air gap on the connection behaviour

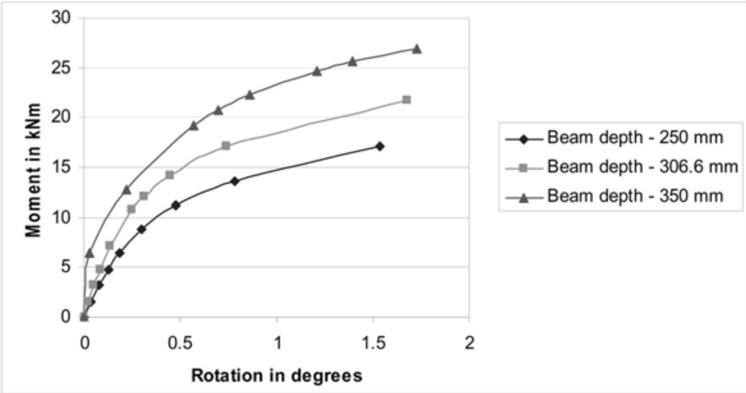


Fig. 15 Effect of depth of the beam on the connection behaviour

7.4 Effect of angle length on the behaviour

Three finite element models were developed to study the behaviour of the connection with varying angle length, 140,150,165.7 mm. The comparison of the behaviour is given in Fig. 17. The comparison shows that the stiffness of the connection increases with decrease in angle length. The initial stiffness of the connection is same for all the three angle lengths till 0.8 degrees rotation, after which the stiffness increases with decrease in angle length. Slight changes in angle length have not affected the behaviour of the connection to a large extent.

7.5 Effect of diameter of bolt on the behaviour

Three finite element models with bolt diameter 12 mm, 16 mm and 20 mm are developed to study the behaviour of the connection. Fig. 18 shows that the model with 20 mm diameter has higher moment carrying capacity than the other two with 12 mm and 16 mm diameter. The model with bolt diameter 16 mm experiences shear failure at the bolt shank; whereas in other two more stress concentration is observed in the bolt head as well as around the bolt hole and the ultimate failure by tearing of seat angle.

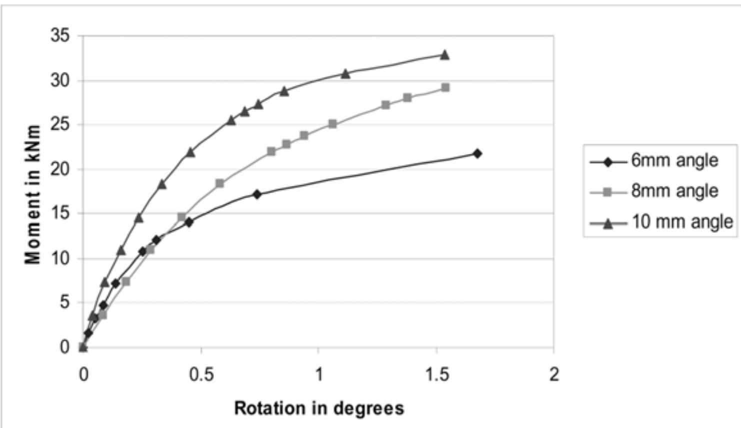


Fig. 16 Effect of angle thickness on the behaviour

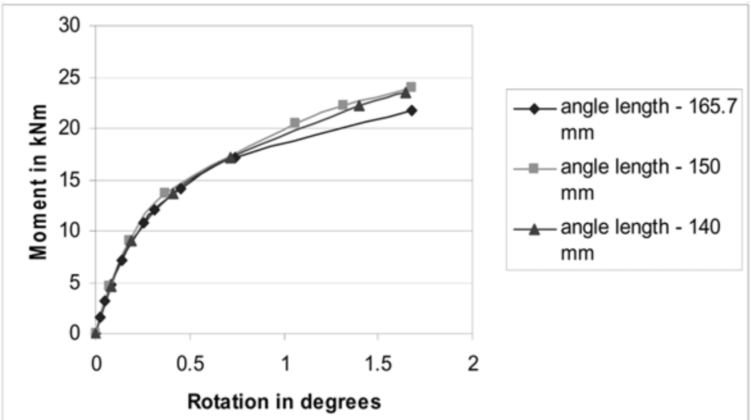


Fig. 17 Effect of angle length on the behaviour

7.6 Proposed modification to Frye-Morris (1975) model

A new polynomial model for the moment-rotation behaviour of top- and seat-angle connections is developed based on the Frye-Morris model procedure using the finite element studies. The procedure for standardization of moment-rotation curves is given by Frye-Morris *et al*. (1975). They have given the moment-rotation relationship as

$$\theta_r = 1.63 \times 10^3(KM) + 7.25 \times 10^{14}(KM)^3 + 3.31 \times 10^{23}(KM)^5 \tag{2}$$

Moment (M) is kN-m and the size parameters are in mm. The standardization constant for the top- and seat-angle connection is given as

$$K = d^{-1.5} t_a^{-0.5} l_a^{-0.7} d_b^{-1.1} \tag{3}$$

The parametric studies conducted by varying the air gap distance between beam and the column have

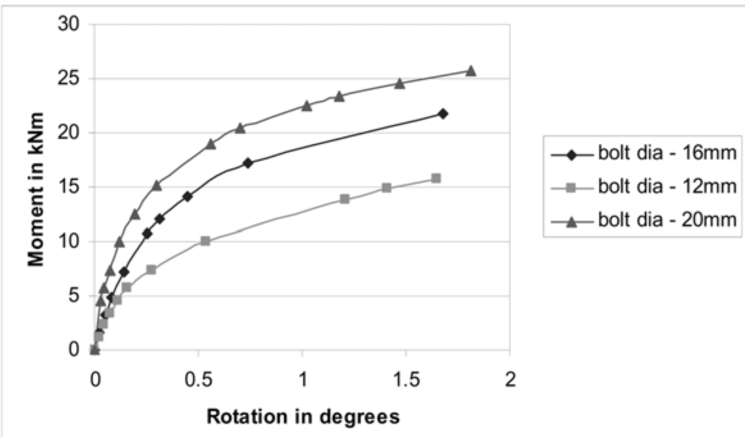


Fig. 18 Effect of diameter of bolt on the connection behaviour

influence on the moment-rotation behaviour. So, it is proposed to incorporate a new size parameter, air gap 'a_g' in Eq. (3). First, the standardization constant is determined. The modified K can be written as

$$K = d^{a1} t^{a2} l_a^{a3} d_b^{a4} d_g^{a5} \tag{4}$$

The new moment-rotation characteristics for TSA connection can be generated by substituting its revised size parameters into the standardized relationship. The revised values of $a1$, $a2$, $a3$, $a4$ and $a5$ obtained from the parametric studies are −1.70, −0.84, 0.48, −1.21 and 0.07 respectively. Therefore the proposed standardization constant K (Eq. 3) becomes

$$K = d^{-1.7} t_a^{-0.84} l_a^{-0.48} d_b^{-1.21} a_g^{0.07} \tag{5}$$

After finding all size parameter exponents 'aj', standardized moment-rotation (KM *versus* θ_r) diagram is plotted for all studies. Finally, the constants C_1, C_2, C_3 of standardized moment-rotation relationship are derived by using the least squares curve fitting procedure. The curve fitting constants C_1, C_2, C_3 of the model for each study are given in Table 3.

With the average values of $C_1 = 2.76 \times 10^3$, $C_2 = 1.80 \times 10^{11}$, $C_3 = 1.70 \times 10^{19}$, Eq. (2) become

$$\theta_r = 2.76 \times 10^3 (KM) + 1.80 \times 10^{11} (KM)^3 + 1.70 \times 10^{19} (KM)^5 \tag{6}$$

Where, θ_r is relative rotation in degrees, M connection moment in kNm, and all other parameters are in mm.

This proposed model is checked with the present experimental result and also with Frye-Morris (1975) model. The comparison (Fig. 19) shows that the proposed model with displacement modification predicts a more flexible behaviour than the Frye-Morris model. The proposed model also incorporates a new size parameter, air gap distance, between the beam and the column. Also, the proposed model presents a best fit with the experimental results than the Frye-Morris model. From the literature covered, it is seen that no model has been developed with air gap as a size parameter for top- seat-angle connection.

The experimental result presented by Hechtmann et al. (1947) (Test id No: 16) is used to evaluate the Frye-Morris model and the proposed model. The comparison (Fig. 20) shows the underestimation of connection stiffness by Frye-Morris model and the proposed model compares better with the experimental result (1947) (Id No: 16). Hence the proposed moment rotation model is found to be more representative.

8. Conclusions

This study focuses mainly on the numerical prediction of moment-rotation behaviour of top- and seat-

Table 3 Curve fitting constants

Size parameters	C_1	C_2	C_3
Depth of the beam (d)	2.47E + 03	1.59E + 11	1.64E + 19
Thickness of the top angle (t_a)	4.04E + 03	−8.17E + 08	2.12E + 19
Length of the top angle (l_a)	2.53E + 03	2.73E + 11	1.18E + 19
Diameter of the bolt (d_b)	2.21E + 03	2.58E + 11	2.22E + 19
Air gap distance (a_g)	2.57E + 03	2.10E + 11	1.32E + 19

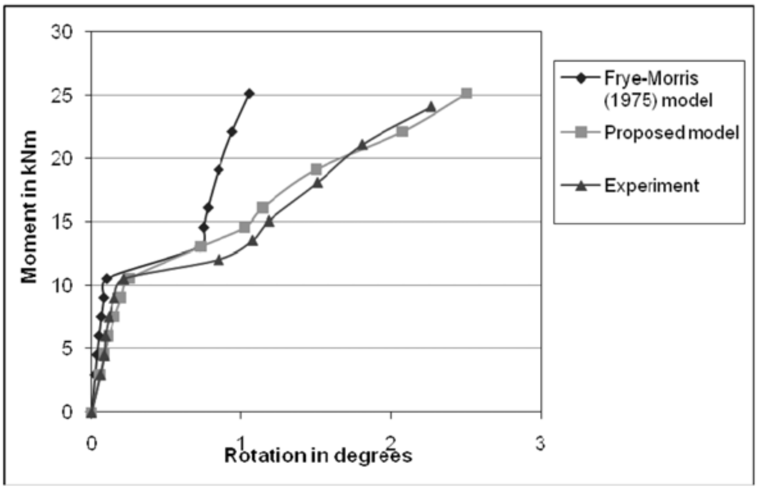


Fig. 19 Comparison of proposed model with present experiment and Frye-Morris model

angle connection. A systematic finite element parametric study was carried out using ABAQUS software on top and seat-angle connection. The finite element model is validated against experiments. The applicability of the polynomial model to predict the behaviour of top and seat-angle connection is investigated. Based on the numerical analysis, the following conclusions are made.

· The discrepancy in ultimate moment capacity between FE analysis and experimental results is about 0.2% for TSA connection. As the failure load and the mode of failure matches reasonably well, this model is used for further parametric studies.

· The parametric studies conducted by varying the air gap distance between beam and the column showed that the FE model with air gaps is flexible than the model without air gap distance. A new model has been proposed for the moment-rotation behaviour of the top- and seat-angle connection

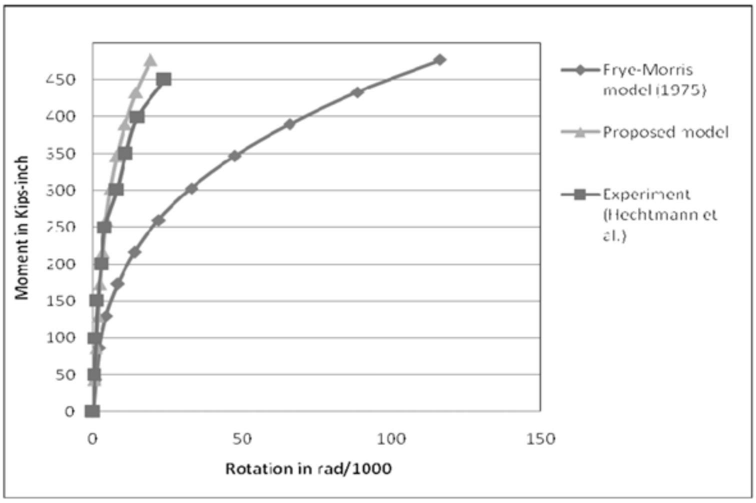


Fig. 20 Comparison of proposed model with experiment (1947) and Frye-Morris model

including a new size parameter, the air gap.

· The developed model is compared with the existing Frye-Morris model (sometimes overestimates and underestimates) which does not consider the air gap distance between beam and the column and the present experimental result. Also the experiment work of Hechtmann *et al.* (1947) is used to evaluate the developed model. In both the cases, the proposed equation presents a best fit with the experiment values. Hence the proposed model may be suitable for studies where air gap distance is also taken into account.

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