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Numerical modeling and nonlinear analysis of semi-rigid jointed steel frames

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Abstract

This paper investigates the effect of semi-rigid connection, geometric nonlinearity and material nonlinearity in steel frame analysis. To study the independent and combined effects of different nonlinearities, elastic and inelastic analyses are carried out using general purpose finite element software SAP2000. Connections are modeled as rotational springs and frame as one dimensional beam element. Verification and application of the simplified numerical model developed in the present study is demonstrated by considering different examples and comparing the results of present study with those available in the published literature. Numerical alternatives, key features about modeling and necessary input parameters are discussed in detail. Rotational springs are characterized by linear, bilinear, multi-linear or nonlinear moment-rotation relationships of the connection. Results in terms of beam moment and nodal displacement are presented for both elastic and inelastic analyses. With the increase in connection flexibility, beam mid-span moments and displacements increase, but beam-end moments decrease. It is observed that the influence of connection nonlinearity dominates over material and geometric nonlinearities.

Keywords: Semi-rigid, Nonlinear analysis, Numerical modelling, Rotational springs, Steel frames

1. Introduction

In the analysis and design of large frames, beam-to-column connections are in general assumed as perfectly rigid or pinned. But in practice it is very difficult and expensive to attain such rigidity; making most of the frames as semi-rigid jointed i.e. between these two extremes. The current design codes [1-4] consider the effect of semi-rigid connections in the design of steel frame structures. AISC-LRFD [1] recommends the use of partially restrained (PR) and fully restrained (FR) connections whereas AISC-ASD [2] refers to type-1 (rigid framing), type-2 (simple framing) and type-3 (semi-rigid framing) connections. Eurocode3 [3] gives clear demarcation between rigid, semi-rigid and flexible connections. Indian steel design code [4] also includes design of steel structures with semi-rigid connections. Inclusion of the effect of semi-rigid connections, makes the analysis procedure nonlinear as the connection behaviour is nonlinear in the entire load domain [5]. In elastic analysis; geometric nonlinearity and in inelastic analysis; both geometric nonlinearity and material nonlinearity are considered. Analyses of frames, especially the large frames, with numerous nonlinearities require the use of sophisticated numerical tool. To reduce the exhaustive computational efforts of nonlinear analysis, linear analysis method is still popular in the engineering community [6]. But with the advent of high performance computers and sophisticated numerical analysis tools, the nonlinear analysis of large semi-rigid jointed frames can be done easily.

The behaviour of semi-rigid connection is expressed in terms of its moment-rotation relationship. In reality the relationship is always nonlinear but sometimes idealized as linear, bi-linear or multilinear [7]. Several experimental studies were carried out to observe the behaviour of semi-rigid connections. Data was stored in the form of initial stiffness, initial/ ultimate moment, and geometric properties of connections. Thus, different data banks say Goverdhan data bank, Nethercot data bank, Kishi and Chen data bank were created. Liew *et. al.* [8] conducted a benchmark study by physical testing of several semi-rigid jointed frames. The test data from this study is very useful in development and validation of these connection models.

Extensive studies in the field of analysis and design of semi-rigid jointed frames were done in last three decades. Researchers [9-12] focused their study on the behaviour of flexibly connected unbraced and braced frames. Both elastic and inelastic studies were done by these researchers. Methods of inelastic analysis may be categorized into two groups; firstly, distributed plasticity or plastic zone method and secondly, lumped plasticity or plastic hinge method. Kitipornchai *et. al.* [13] demonstrated that plastic zone analysis is only suitable for detailed study and for all practical purposes, lumped plasticity or plastic hinge method is suitable. King *et. al.* [14] developed a suitable lumped-plasticity model for inelastic analysis of flexibly jointed frames. Sekulovic and Nefovska [15] developed springs-in-series model, where plastic hinge was modeled to simulate

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both elastic-perfectly plastic behaviour and improved plasticity with gradual plastification effect. Stiffness matrix was developed and a computer program was prepared for the analysis of the frames. Liu *et. al.* [16] developed a compound element by combining these springs in series. Based upon these studies, few researchers developed their own computer program for the analysis of large frames. But all these programs are unique in nature and may not be easily available for wide use by design engineers.

Hence, objective of the present study is to develop a well validated numerical model and perform elastic and inelastic analyses of semi-rigid jointed steel frames. It may be a good filler between these analytical approaches and design office requirement.

2. Development of Numerical Model

The effect of semi-rigid connection may be considered in numerical analysis of steel frames by different ways: (i) modeling of connection as rotational spring and frame as one dimensional beam element [17], (ii) connection as component based macromodel, which is collection of springs and frame as one dimensional beam element [18], (iii) modeling of connections as three dimensional solid element and frame as one dimensional beam element [19] and, (iv) modeling of entire frame as three dimensional solid element. Numerical model with three dimensional solid elements is the most powerful and able to consider all local effects, but it is computationally very expensive and accuracy of these models is highly dependent upon the expertise of the user [20]. Macromodel approach is a viable option to 3D modeling but primary challenge with these model lies in careful calibration of the model [21-22]. Application of rotational springs for semi-rigid connections is widely accepted [5, 15 and 23] because of its simplicity and efficiency. Accuracy of this model may be less as compared to three dimensional solid element model, but it is very efficient and computationally less expensive [24].

2.1. Present Study

With this background in the present study, a simplified finite element based numerical model is developed to take care of all three types of nonlinearity, using general purpose software SAP2000 [25]. For elastic analysis, semi-rigid connection is modeled as rotational spring and frame as one dimensional elastic beam element [Fig. 1(a)]. In inelastic analysis, material nonlinearity may be considered through another rotational spring connected in series to the semi-rigid connection [Fig. 1(b)]. This, second rotational spring is usually referred as plastic hinge and the model as springs-in-series model. Apart from connection and material nonlinearities, effect of geometric nonlinearity may be considered through P-Delta analysis.

The connection moment-rotation relationship may be expressed as linear, bilinear, multi-linear, nonlinear [26]. Nonlinear moment rotation relation may be expressed by cubic B-spline, power model or polynomial model. Both, three-parameter and four-parameter power models may be used to define the semi-rigid connection.

Three-parameter power model of Kishi and Chen [27] is given by Eq. (1),

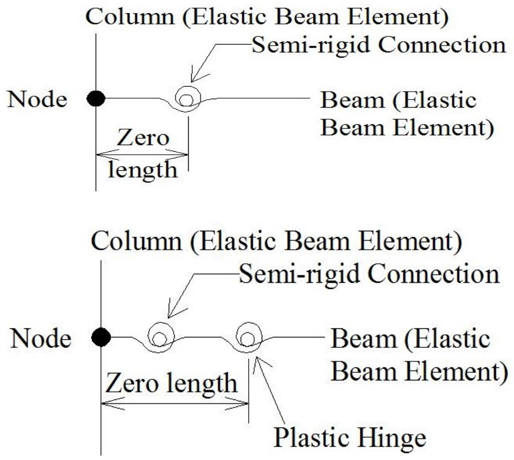


Fig. 1. Analytical model of semi-rigid jointed frames: (a) Elastic analysis; (b) Inelastic analysis

$$\theta_c = \frac{M}{R_{ki}(1-(M/M_u)^n)^{1/n}} \quad \text{or,} \quad M = \frac{R_{ki}\theta_c}{(1+(\theta_c/\theta_0)^n)^{1/n}} \tag{1}$$

Where, R_{ki} is the initial connection stiffness, M_u is the ultimate moment capacity of connection, n is the shape parameter and θ_0 is reference plastic rotation given by M_u/R_{ki}.

Four parameter power model of Richard and Abott [28] is given by Eq. (2),

$$M = \frac{(R_{ki}-R_{kp})\theta_c}{(1+(\theta_c/\theta_0)^n)^{1/n}} + R_{kp}\theta_c \tag{2}$$

Where, R_{kp} is strain hardening/softening stiffness and θ_0 is reference relative rotation given by, $M_0/(R_{ki}-R_{kp})$, M_0 being reference connection moment.

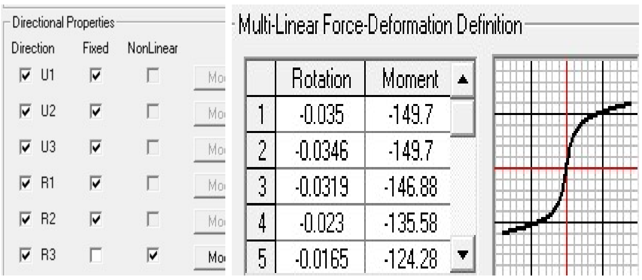
Four parameter power model reduces to three parameter power model, if strain hardening/softening stiffness R_{kp} *is* considered as zero. Using three parameter power model, connection rotation (θ_c) is obtained directly from the equation, whereas four parameter power model involves iterative procedure for finding θ_c. This is the reason why three-parameter power model is preferred over four-parameter power model.

Similarly, connection rotation (θ_c) may be obtained directly from the Frye and Morris [29] polynomial model. The moment-rotation (M-θ) relationship is expressed by Eq. (3),

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

Where, C_1, C_2 and C_3 are curve fitting constants and K is a standardization constant. Frye and Morris [29] standardized the equation for different semi-rigid connections.

In the numerical model of SAP2000, rotational spring is defined using 2-joint multi-linear elastic Link element. The in-plane moment-rotation curve of the connection forms the input for the applicable directional property (R3) of Link element and remaining directional properties are kept as fixed (Fig. 2). The second rotational spring, applicable for member inelasticity is defined by plastic hinges readily available in SAP2000. Plastic hinges defined in the study are flexural hinges (M3-type). Modeling parameters for the plastic hinges are entered as the value of B, C, D and E shown in the Fig. 3. Where, "B" refers to plastic moment capacity of the hinges.



Directional Properties

Direction	Fixed	NonLinear
☑ U1	☑	☐
☑ U2	☑	☐
☑ U3	☑	☐
☑ R1	☑	☐
☑ R2	☑	☐
☑ R3	☐	☑

Multi-Linear Force-Deformation Definition

	Rotation	Moment
1	-0.035	-149.7
2	-0.0346	-149.7
3	-0.0319	-146.88
4	-0.023	-135.58
5	-0.0165	-124.28

Fig. 2. Definition of Link element in SAP2000

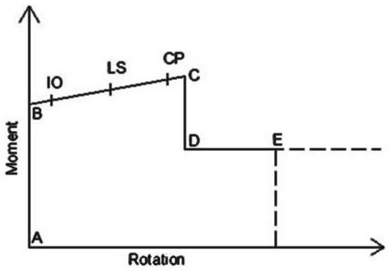


Fig. 3. Generalized moment-rotation curve for hinge definition in SAP2000

2.2. Numerical Alternatives

Inelastic analysis may also be carried out by replacing the springs-in-series at each beam ends with a compound element [30-31], which takes care of combined effect of semi-rigid connection and material nonlinearity.

3. Validation of the Model

For validation of the numerical model developed in the present study, three different benchmark studies are considered from published literature. These studies cover the different aspects of analyses of semi-rigid jointed frames; (i) elastic first order analysis, (ii) elastic second order analysis and, (iii) inelastic analysis.

3.1. Elastic linear or first order analysis

Elastic analysis of one-bay and one-story semi-rigid jointed steel portal frame done by Chan and Chui [33] is considered for validation of present study. This was also referred by Ihaddoudene *et. al.* [34] and Bandyopadhyay and Banik [32] for validation of their studies. Ihaddoudene *et. al.* [34] developed a mechanical model and established modified stiffness matrix considering flexible connections, where member end flexibility is considered using rotational springs. Modulus of elasticity (E) and Poison's ratio (μ) for steel are taken as 2x10^5 MPa and 0.3, respectively.

Geometry of the frame [length of beam (l_b) and columns (l_c)] and member properties [cross sectional area of beam (A_b) and columns (A_c); moment of inertia of beam (I_b) and columns (I_c)] are as shown in Fig. 4(a). In SAP2000, a zero length link element is used to simulate the semi-rigid connections at beam ends and column bases. Nodes 1 and 2 are disjointed to create two coincident nodes at these locations [Fig. 4(b)]. Link elements are inserted between these two coincident nodes and at column bases (nodes 4 and 5). Rotational stiffness of these connections are, $k_b = 4EI_b/l_b$ = 10.75 x 10^3 kN-m/rad and $k_c = EI_c/l_c$ = 3.1533 x 10^3 kN-m/rad. Results of the analysis are provided in Table 1. It is shown that the results are in agreement with those reported in referred literature.

3.2. Elastic nonlinear or second order analysis

The second order elastic analysis is an extension to the first order analysis considering the effect of geometric nonlinearity. Material nonlinearity is not considered as yielding effects are ignored in this analysis. P-Delta analysis is done to consider geometric nonlinearity. A two dimensional three-bay one-story steel portal frame earlier analysed by Ihaddoudene *et. al.* [34] is considered for validation of present study. Geometry and loading of the

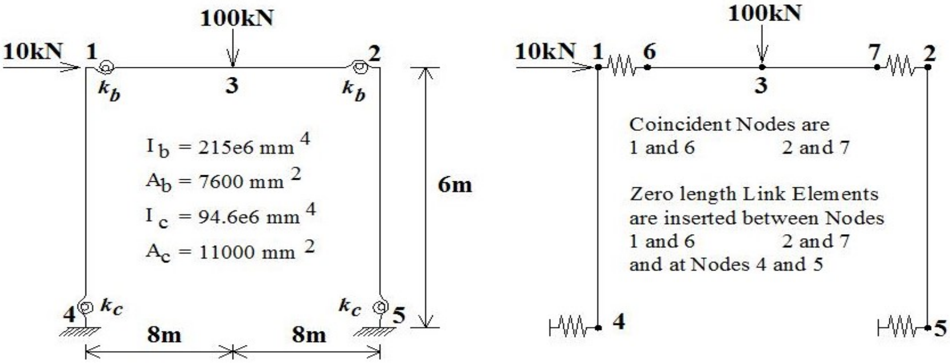


Fig. 4. (a) Geometry and loading of the frame [34]; (b) Modeling of link elements

Table 1 Results of elastic linear analysis

Bending Moment (kN-m)	**Semi-rigid connections at beam ends and at column bases $k_b = 4EI_b/l_b$, $k_c = EI_c/l_c$**			**Semi-rigid connections at beam ends $k_b = 4EI_b/l_b$, $k_c = 0$**		
	Chan and Chui [33]	Ihaddoudene *et. al.* [34]	Present Study	Chan and Chui [33]	Ihaddoudene *et. al.* [34]	Present Study
M_{41}	0.3	0.3392	0.32	31.7	31.9	31.68
M_{14}	80.3	80.27	80.26	93.6	93.7	93.65
M_{52}	24.2	24.1813	24.17	71.5	71.8	71.53
M_{25}	116.4	116.4294	116.42	113.8	113.9	113.8
M_{32}	301.7	301.6495	301.66	296.3	296.4	296.3

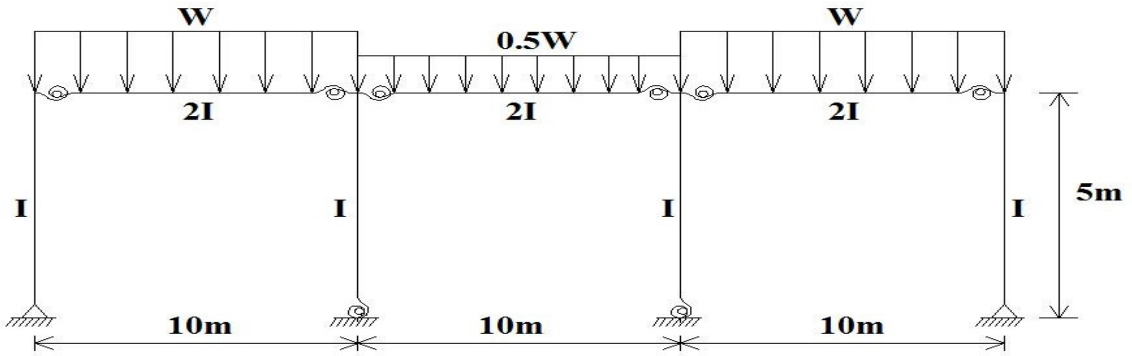


Fig. 5. Geometry and loading of the frame [34]

Table 2 Results of elastic nonlinear analysis

Bending Moment (kN-m)	Rigid Connections		Semi-rigid connections (Linear)		Semi-rigid connections (Bi-linear)	
	Ihaddoudene *et. al.* [34]	Present Study	Ihaddoudene *et. al.* [34]	Present Study	Ihaddoudene *et. al.* [34]	Present Study
M_A	148.84	146.05	118.44	118.46	121.68	121.61
M_B	118.75	219.07	296.06	296.28	304.19	304.31
M_C	296.65	290.8	164.36	163.98	144.85	144.76
M_D	194.25	194.15	107.38	107.26	102.33	102.25
M_E	48.61	48.33	14.21	14.28	10.60	10.77
M_F	25.10	24.60	111.37	111.49	116.41	116.50

frame is shown in Fig. 5. Magnitude of uniformly distributed load W is 35 kN/m. Flexural rigidity per unit length for beams and columns are taken as 15067 kN-m. Thus, moment of inertia for columns and beams are calculated as 3.767 x 10^{-4} m^4 and 7.533 x 10^{-4} m^4 respectively. Linear and bi-linear moment-rotation relationships (Fig. 6) of the rotational springs are used to simulate semi-rigid connections shown in Fig. 5. Typical bending moment diagram is shown in Fig. 7 and corresponding results of the analysis are given in Table 2.

Results reported in Table 2 for present study are very close to that obtained by Ihaddoudene *et. al.* [34]. While comparing the results of present study, a variation is seen in respect of M_B for rigid connection. The value of M_B is obtained as 219.07 kN-m as against 118.75 kN-m reported by Ihaddoudene *et. al.* [34]. As compared to rigid frame, for semi-rigid jointed frames beam mid span moments (M_B and M_F) increase and beam-end moments (M_A, M_C and M_D) decrease.

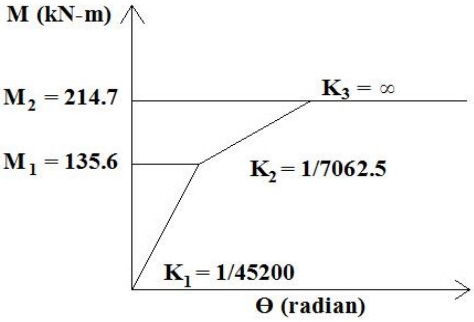


Fig. 6. Linear and Bilinear moment-rotation

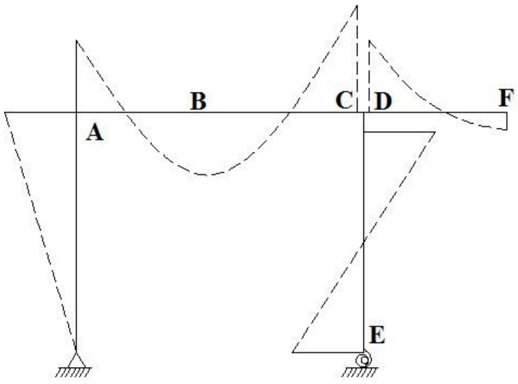


Fig. 7. Typical bending moment diagram

3.3. Inelastic analysis

To demonstrate the performance of present SAP2000 model in inelastic analysis, a one-bay and one-story steel portal frame earlier analysed by Ihaddoudene *et. al.* [34] is considered. This was referred by Bandyopadhyay *et. al.* [31] for validation of their studies. Modulus of elasticity (E) and Poison's ratio (μ) for steel are taken as 2 x 10^5 MPa and 0.3, respectively. Geometry of the frame is shown in Fig. 8.

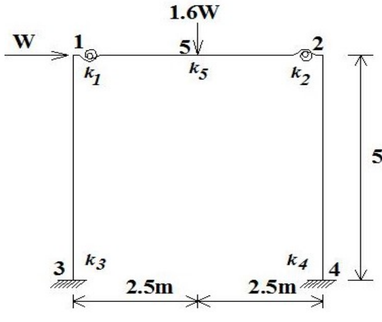


Fig. 8. Frame geometry

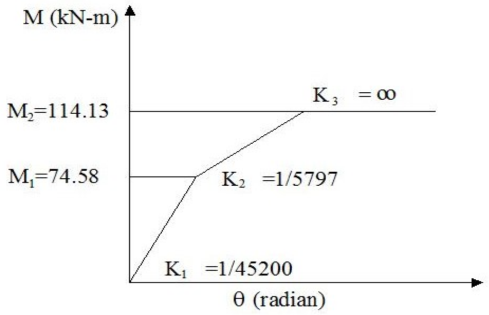


Fig. 9. Semi-rigid connection: *M-θ* relationship

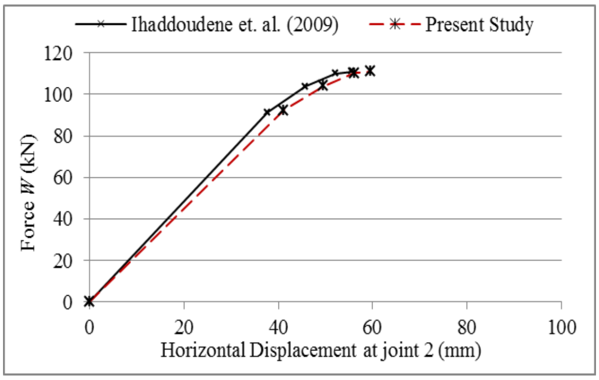


Fig. 10. Force displacement curve

Steel sections of beams and columns are IPE330. "M3" type plastic hinges are assigned at centre and ends of beam and at column bases to take care of member inelasticity. Moment-rotation relationship of semi-rigid connections at beam ends, are as shown in Fig. 9. Plastic moments of the joints and members are 114.13 kN-m and 192.96 kN-m respectively. The failure load (*W*) and horizontal displacement at joint 2 of the frame just before failure are reported in the literature as 111.122 kN and as 55.6mm, respectively. In the present study, these values are obtained as 111.13 kN and 59.6 mm, respectively. Failure load estimated in SAP2000 matches with that reported in the literature; whereas, displacement obtained in the present study is on little higher side as compared to that given in the literature (Fig. 10). Moreover, plastic hinge formation is observed sequentially at joints 2, 4, 5 and 3, which is similar to that reported in the literature.

4. Analysis of rigid and semi-rigid jointed steel frames

For further study, a two dimensional two-bay three-story frame (Fig. 11) is considered from published literature [35]. Degertekin and Hayalioglu [35] obtained the optimum design of the frame with different semi-rigid connections and semi-rigid column bases. Geometry and loading of the frame is shown in Fig. 11. Elastic and inelastic nonlinear analyses are done to observe the effect of geometric nonlinearity, material nonlinearity and semi-rigid connections on the behaviour of steel frame. Loading is enhanced by a factor of 1.6 as the frame was designed as per the allowable stresses design method of AISC-ASD.

Material Grade of steel used is A36 with modulus of elasticity (E) of 2 x 10^5 MPa and yield stress of 248 MPa. Semi-rigid connections are modeled at joints 4, 6, 8, 9, 11, 13, 14, 16 and 18. Frame is analysed for rigid and four types of semi-rigid connections i.e. double web angles (DWA), top and seat angles with double web angles (TSD), end plate with column stiffeners (EPCS) and T-Stub (TSTUB) connections to consider the wide range of semi-rigidity (Fig. 12). The moment-rotation relationships of these connections are developed using Frye and Morris [29] polynomial model given by Eq. (3). Curve fitting constants, standardisation constants and adopted connection size parameters are given in Table 3. The moment-rotation curve of these connections are generated for two applicable beam sizes W 12x65 and W 12x53 and these are shown in Fig. 13.

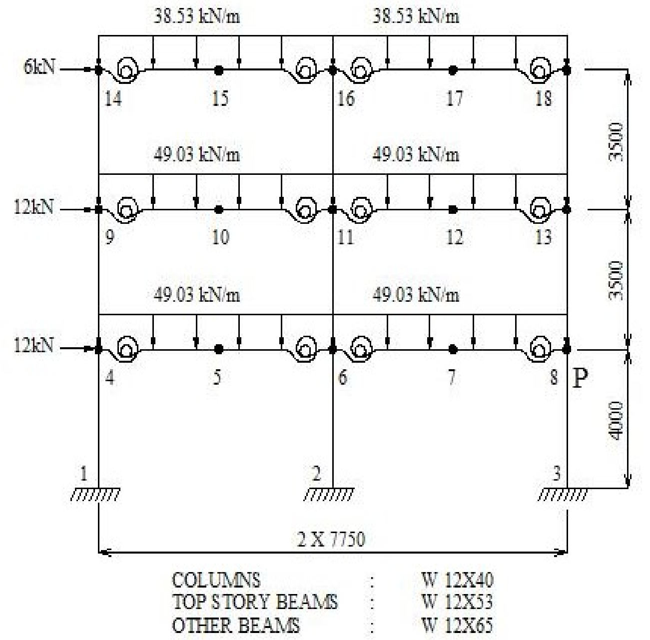
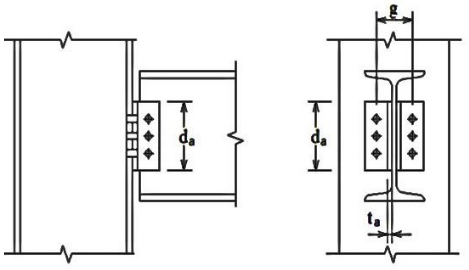
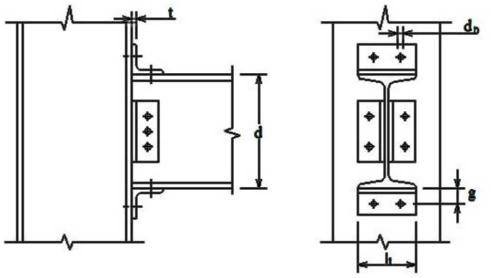


Fig. 11. Member properties, geometry and loading of the frame [35]

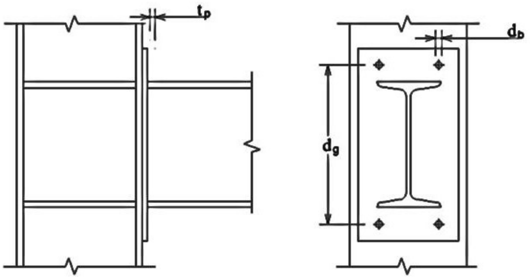
Results of elastic analysis are shown in Table 4 in terms of bending moments and displacements at different locations. As the rotational stiffness of connections gradually reduces from rigid to DWA type connection (Fig. 13), beam mid-span moments (M_5 and M_{15}) increase and beam end moments ($M_{6\text{-}5}$, $M_{16\text{-}15}$, $M_{13\text{-}12}$, M_{18}) decreases. Both vertical displacements (V_{12} and V_{17}) and horizontal displacement (U_{18}) increase gradually with decrease in rigidity at connections. Effect of geometric nonlinearity (GNL) on vertical responses (beam moments and vertical displacements) is not significant. Whereas, it affects the moment at column base (M_3) and horizontal displacement (Fig. 14). For frame with semi-rigid connections having lower moment carrying capacity (EPCS, TSD and DWA), significant influence of geometric nonlinearity is observed. Gaps between load displacement curves (Fig. 14) of linear and nonlinear (with geometric nonlinearity) analyses go on increasing with decrease in connection rigidity. Maximum moment capacities for different connections (TSTUB, EPCS, TSD and DWA) at ends of W 12X65 beams are 588 kN-m, 254 kN-m, 206 kN-m and 150 kN-m, respectively. For connections at ends of W 12X53 beams the capacities are 537 kN-m, 254 kN-m, 185 kN-m and 150 kN-m, respectively. Plastic moment of W 12x65 and W 12x53



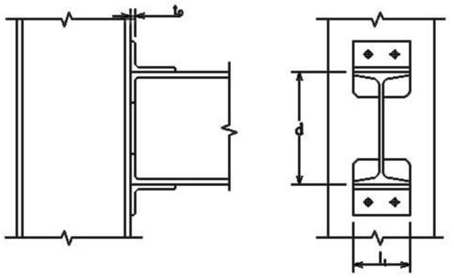
DWA



TSD



EPCS

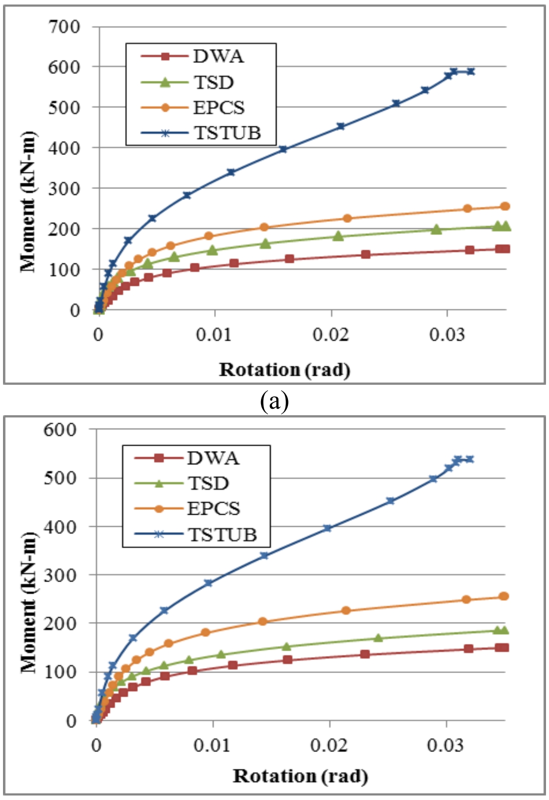


TSTUB

Fig. 12. Semi-rigid connections

beams are 393.3 kN-m and 316.7 kN-m. Beam end moments are limited to maximum moment capacities of the respective semi-rigid connection. But as the effect of material yielding is not considered in elastic analysis, there is no limitation in beam mid-span moment. Hence, beam mid-span moment goes on increasing with reduction in connection rigidity at beam ends. Thus, in elastic analysis of the frame under given loading condition no connection hinge formation is observed. Though, it may be noted that moments M_{6-5} and M_{13-12} are very close to connection capacities (150 kN-m) for frame with DWA connections. It is expected that further increase in load may cause connection hinge formation at beam ends of the frame with DWA connections. Hence, a parametric study is done by gradually increasing the applied loads through load factors (*F*) up to 2.0 from the present loading (*F*= 1.6). For *F*=1.7, no connection hinges are formed when geometric nonlinearity is not considered. With geometric nonlinearity, connection hinges are formed at joints 6, 11 and 13. For *F*=1.8, in linear and nonlinear analyses, connection hinges are formed at joints 11, 13 and 6, 8, 11, 13, respectively. For *F*=1.9, in linear and nonlinear analyses, connection hinges are formed at joints 6, 8, 11, 13 and 6, 8, 11, 13, 16, 18, respectively. For *F*=2.0, in linear and nonlinear analyses, connection hinges are formed at joints 6, 8, 11, 13, 16 and 6, 8, 11, 13, 16, 18, respectively. As connection reaches very close to its maximum capacities, influence of geometric nonlinearity becomes significant and displacements become significantly higher. Horizontal displacement (U_{18}) in linear analysis is observed as 61mm, 66.81mm, 72.84 mm, 81.23mm and 91.58 mm for *F*=1.6, 1.7, 1.8, 1.9 and 2.0, respectively. Whereas, for nonlinear analysis the corresponding values are 90.6mm, 106.61mm, 133.78mm, 171 mm and 210.18mm. The ratios of displacements (U_{18}) at nonlinear and linear analysis increases from nearly 1.5 to 2.3 for *F*=1.6 and *F*=2.0.

Results of the inelastic analysis are presented in Table 5. In this case also, as the rotational stiffness of connections gradually reduces from rigid to DWA type connections (Fig. 13), beam mid-span moments (M_5 and M_{15}) increase and beam end moments (M_{6-5}, M_{16-15}, M_{13-12}, M_{18}) decreases. Both vertical displacements (V_{12} and V_{17}) and horizontal displacement (U_{18}) increase gradually with decrease in rigidity at connections (Fig. 15 and Table 5). Plastic hinges



(a)

(b)

Fig. 13. Moment-rotation relationship of semi-rigid connections: (a) At beams W 12x65; (b) At beams W 12x53

Table 3 Semi-rigid connection parameters

Connection type	**Curve fitting constants**	**Standardisation constant**	**Connection size parameters (mm)**
DWA	$C_1 = 3.66 \times 10^{-4}$ $C_2 = 1.15 \times 10^{-6}$ $C_3 = 4.57 \times 10^{-8}$	$K = d_a^{-2.4} t_a^{-1.81} g^{0.15}$	$t_a = 25.4$ and $g = 228.6$
TSD	$C_1 = 2.23 \times 10^{-5}$ $C_2 = 1.85 \times 10^{-8}$ $C_3 = 3.19 \times 10^{-12}$	$K = d^{-1.287} t^{-1.128}\, {}^{4}t_c^{-0.415} l_a^{-0.694}\, g^{1.35}$	$t = 25.4$, $t_c = 25.4$ and $g = 114.3$
EPCS	$C_1 = 1.79 \times 10^{-3}$ $C_2 = 1.76 \times 10^{-4}$ $C_3 = 2.04 \times 10^{-4}$	$K = d_g^{-2.4} t_p^{-0.6}$	$t_p = 25.4$
T-STUB	$C_1 = 2.10 \times 10^{-4}$ $C_2 = 6.20 \times 10^{-6}$ $C_3 = -7.6 \times 10^{-9}$	$K = d^{-1.5} t^{-0.5} l_t^{-0.7} d_b^{-1.1}$	$t = 22.23$ and $d_b = 25.4$

Table 4 Results of elastic analysis

Quantity	Unit	Without geometric nonlinearity					With geometric nonlinearity				
		Rigid	Semi-rigid Connections				Rigid	Semi-rigid Connections			
			TSTUB	EPCS	TSD	DWA		TSTUB	EPCS	TSD	DWA
U_{18}	mm	11.3	20.1	39.2	49	61	12	22.6	50.3	66.8	90.6
V_{12}	mm	28.5	43.4	57.5	63	70	28.5	43.4	57.5	63.1	70.2
V_{17}	mm	31.6	43.4	52.2	60.2	65	31.7	43.7	52.5	60.7	65.6
M_3	kN-m	93	95	97	97	97	96	100	110	114	122
M_5	kN-m	232	318	397	428	468	232	318	397	429	469
M_{15}	kN-m	188	245	287	324	346	189	246	290	327	351
M_{6-5}	kN-m	471	327	223	188	143	473	329	226	191	146
M_{16-15}	kN-m	361	263	207	163	138	362	264	209	166	142
M_{13-12}	kN-m	351	296	218	186	143	352	298	222	190	147
M_{18}	kN-m	221	210	188	155	134	221	211	192	159	138

are formed in frame with all types of connections except TSTUB and thus frame with TSTUB connection remain elastic in the entire load domain. In frame with rigid connections, plastic hinges are formed at beam end (M_{6-5}) and in frame with semi-rigid connection (Except TSTUB) plastic hinges are formed at beam mid-span. Strength of the TSTUB connections is also very high as compared to other semi-rigid connections; but formation of plastic hinges is avoided as some rotation is allowed at connection. In beam with lower connection stiffness (TSD and DWA) connection hinges (M_{6-5} and M_{13-12}) are also formed and hence the frames with these connections fail to carry 100% load due to combined effect of material and connection nonlinearities. The effects of different nonlinearities are quite visible in the response of the frame with DWA connection. It sustains 100% loading under linear elastic analysis. In elastic nonlinear analysis also it sustains 100% loading but with increased moment and displacement (Table 4). In inelastic linear analysis it fails at 90% loading due to combined effect of connection and material nonlinearities. And finally during inelastic nonlinear analysis, the frame fails at 87% loading due to combined effects of all three types of nonlinearities (Table 5).

Comparison of horizontal displacements at node 18 (U_{18}) for different types of connections and different analysis procedures is presented in Fig. 16. It is observed that among all types of nonlinearities, effect of connection nonlinearity is predominant in behavior of steel frame. Frames with all types of connections (except TSTUB) are affected by material nonlinearity. Increase in displacement (U_{18}) from elastic to inelastic analysis is observed as much as 60% (from 49 mm to 79.9 mm) for TSD connection. In elastic analysis, maximum increase in displacement for DWA connection due to effect of geometric nonlinearity is nearly 50% (61 mm to 90.6 mm). In Fig. 16, it seems that there is some decrease in displacement while considering effect of geometric nonlinearity in inelastic analysis. But, it may be noted that the values of deflection shown in Fig. 16 for inelastic analysis corresponds to lower load levels (87%), as the frame fails due to plastic hinge formation (Table 5). Hence, Fig. 16 shall be read in conjunction with Figs. 14 to 15 Table 5 for interpretation of results. Similarly, in elastic analysis ratio of displacements (U_{18}) for frame with DWA connection and rigid connection goes up to nearly 5.5 (from 11.3 mm to 61 mm). If effect of geometric nonlinearity is included, the ratio goes up to 7.5 (12 mm to 90.6 mm) due to combined effect of connection and geometric nonlinearities.

5. Conclusions

A numerical model is developed for static elastic and inelastic analyses of semi-rigid jointed 2D frame using SAP2000. Effect of connection nonlinearity, geometric nonlinearity and material nonlinearity are considered in the analysis. Connections are modeled as rotational springs using Link element in SAP2000. Step-by-step numerical modeling including input requirement is discussed with examples for different analyses procedures. The model is validated against the analytical results available in published literatures. Observations noted in the present study are related to the frame in the paper with the given loading conditions and may not be generalised. From the numerical analysis done in the present study, it may be concluded that different types of nonlinearities i.e. material nonlinearity, geometric nonlinearity and connections nonlinearity influence the behaviour of the frame but the frame is most influenced by connection nonlinearity. Significant differences are observed between elastic and inelastic analyses results of the frame for all types of connections except TSTUB. Influence of geometric nonlinearity is observed to be more for frames with relatively less connection stiffness (EPCS, TSD and DWA). Numerical model developed in the present study, is very useful for both elastic and inelastic analysis of semi-rigid jointed frame. It is believed that development of numerical model discussed in the paper shall be useful for practicing engineers and researchers. In the present study, analysis of semi-rigid jointed 2D frames is only considered under static loading condition. The study may be easily extended for 3D frames under both static and dynamic loading conditions.

Disclosures

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