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LATERAL DRIFT OF SEMI-RIGID STEEL FRAMES - I

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ABSTRACT: It is widely appreciated that if the inherent stiffness of the commonly used beam-to-column connections could be included in the design practice, the resulting structure would be more economical compared to those designed using the conventional assumptions of 'simple' or 'rigid' frame. Yet, designers have not preferred such practice for multi-storied unbraced frames due to their scepticism regarding the behaviour of such frames in sway. Thorough investigation on the behaviour of such frames is very much warranted to gather adequate confidence for the use of semi-rigid connections. In this study, an existing finite element program has been used to study the behaviour of multi-storied semi-rigid sway steel frames. Medium-rise frames ranging from five to eight story height having a wide range of connection stiffness have been analysed for the behavioural study. The main focus in this study has been on the lateral drift and the level of connection-rotations. The prospect of using rigid and semi-rigid connections simultaneously at different locations of a frame has also been looked into. This has led to the conclusion that with judicious combination of both semi-rigid and rigid connections, frame drift can be brought within acceptable limit of serviceability.

KEYWORDS: Semi-rigid connection, Unbraced or Sway frame, Medium-rise or Multi-storied frame, Lateral drift or Sway, Connection rotation

INTRODUCTION

The connection of the constituent members of steel frames plays an important role in affecting the behaviour of the complete structure because the amount of moment-transfer is controlled by the connection characteristics. In the analysis and design of steel frames, it is customary to represent connection behaviour by an idealised model, either as a rigid connection or as a pinned connection. A number of experimental investigations have established that these two extreme assumptions are, strictly speaking, unattainable in practice. In reality most connections are semi-rigid in nature and possess some amount of rotational stiffness.

Although semi-rigid construction is recognised by the major building codes and is economical, it has not become a viable type of construction due to lack of confidence about its behaviour. This is particularly true for multi-storied sway steel frames. The research to explore the behaviour of flexible connections was started in early twentieth century when Wilson and Moore (1917) first investigated the

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response of riveted connections. To date, many researchers have contributed to a better understanding of connection restraint and its influence on the behaviour of beam and column frames. Compared to studies on non-sway semi-rigid steel frames very little work has been conducted on sway frames with semi-rigid connections.

In the present study, the sway behaviour of semi-rigid steel frames has been studied. A limited parametric study has been conducted using an existing finite element computer program (Ahmed, 1992), which has already been verified with test results using tri-linear M-φ curves. This parametric study attempted to determine the parameters affecting serviceability condition of semi-rigid frames, particularly the lateral drift. The reason of emphasising on the sway behaviour of semi-rigid frame is that a previous study (Anderson and Benterkia, 1991) concluded that the serviceability limit on sway, rather than the ultimate strength, is likely to control design. Therefore, it is quite important that a study is conducted to determine the moment-rotation relationships of connections that will provide enough rigidity to restrain the sway of the overall frame within the limit of 1/300 of the total height of the frame under working load.

PARAMETERS OF THE BEHAVIOURAL STUDY

A number of parameters have been selected to study the response of semi-rigid frames with the main focus on connection properties. The present study looks into the behaviour of medium rise buildings with semi-rigid connections subjected to lateral sway. The behaviour of 5 to 8 storied frames has been studied for different connection details. The study deals with 2-bay frames with bay width 500 cm and story height 350 cm. The 3-bay frames with varying bay width and story height are examined in the companion paper (Ahsan et al., 2003). Beam and column sections are W21x57 and W12x65 respectively. Member properties have not been varied along the width or height of the frame.

To examine the influence of semi-rigid connection on the sway of medium rise buildings, a wide spectrum of Moment-rotation (M-φ) relationship covering the whole range between rigid and pinned behaviour has been considered. To this end, different details of top- and seat-angle connection (with or without double web-angle) have been varied to obtain a wide variation of rigidity of such connection. Figures 1 (a) and 1(b) show typical sections of top- and seat-angle connections. The details of the connections studied are shown in Table 1 and Fig. 2. Since the actual test results of these connections used with the beam and column sections mentioned earlier were not available, a mathematical model called 3-parameter power model by Kishi and Chen (1990) has been used to obtain the non-linear moment-rotation relationship.

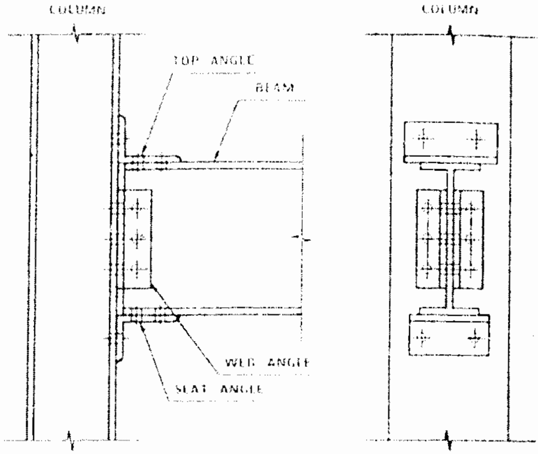

Fig 1(a). Top- and seat-angle connections with double web-angle

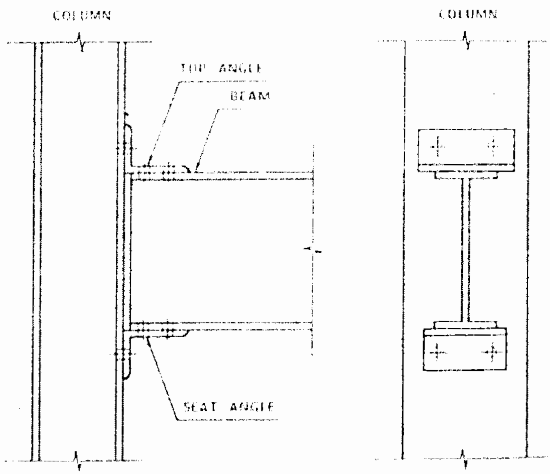

Fig 1(b). Top- and seat-angle connections without double web-angle

The M-φ curves, for the connections tabulated in Table 1, which were generated using this model, are presented in Fig. 3. Non-linear M-φ relationships obtained have been simplified with a tri-linearised form (Fig. 4) for use in the analysis.

Table 1. Description of joint types studied

Joint Type	Joint Category	Top and Seat Angles		Web Angles		Beam Depth
		Designation	Length	Designation	Length	
A	Top and Seat Angle Joint with Double Web-Angle	L130x130x20	15cm	L100x100x20	25cm	50cm
B		L130x130x20	15cm	L100x100x12	19cm	50cm
C		L130x130x20	15cm	L100x100x10	19cm	50cm
D		L100x100x12	15cm	L75x75x12	19cm	50cm
E		L100x100x12	15cm	L75x75x10	19cm	50cm
F		L100x100x12	15cm	L75x75x6	19cm	50cm
G		L130x130x20	15cm	X	X	50cm
H	Top and Seat Angle Joint without Double Web-Angle	L130x130x12	15cm	X	X	50cm

To understand the extent of rigidity being provided by the connections considered in this study, a line of demarcation is needed to identify connections as rigid or semi-rigid. For this purpose, the classification system proposed by the Eurocode, 1990 (EC3) is followed here. This EC3 boundary has been included in the M-φ relations of the connections considered and shown in Figure 4 which shows that the connections considered in the study cover a wide spectrum of semi-rigid connection with behaviour between nearly rigid and pinned.

The present study has been intended to examine the lateral drift of semi- rigid frames under working load. Frames have been analysed for gravity and wind loads at working level. Applied load intensities are mentioned in Table 2. The load intensity has been assumed to be applied uniformly on the frame.

An elastic-perfectly-plastic material behaviour is assumed in the analysis. The reason for considering plastic behaviour of material, is that for very flexible connections relatively tall frames undergo excessive drift which induce second order effects causing, in some cases, material to exceed its elastic limit even at the level of working load as shown by Ahsan (1995). The yield stress is taken as 250 N/mm2 and the modulus of elasticity is assumed to be 210 kN/mm^2.

Common details of the connections:

Yield stress of steel, s_y = 25 kN/cm^2
Nominal size of bolts, D = 20mm
Nominal size of nuts, W = 30mm
Distance between heel of web angleto the centre of fastener closest to web of beam, g_w = 45mm
Distance between heel of top- or seat angle to the centre of fastener closest to flange of beam, g_t = 65mm

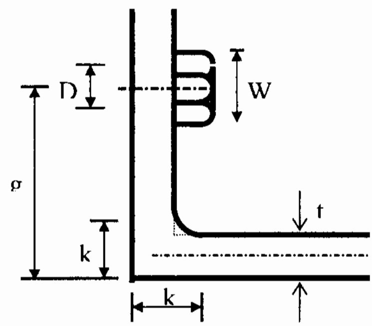

Fig. 2. Main parameters of an angle

STUDY ON LATERAL DRIFT

To inspect the influence of connection flexibility on frames the whole array of frames from 5 to 8 story height and possessing connections as described in the preceding section have been analysed using the finite element program. In this section any particular frame is assumed to have same type of connection at all the connections. The typical sway behaviour of semi-rigid frames at different floors has been plotted against the height of the respective floors in Fig. 5. The purpose of such presentation is to verify the shape of the frames they assume under the influence of lateral loading. It has been found that semi-rigid frames have deformation behaviour exhibiting two distinct features i.e. the lower part of predominant flexural deformation and the upper part of predominant shear deformation. An interesting observation here is that the point of inflection shifts its position along the height of the frame from first storey or below for rigid frame to second storey or above for frames having very flexible connections within the limit of medium-rise frames studied here. Another important point is that storey drift due to added flexibility is more pronounced at the middle part of the frame i.e. at the transition from flexural deformation part to shear deformation part; whereas at the upper portion of the frame, the storey drift is almost parallel for different flexibility of connections except for extremely flexible connections. The most evident and obvious information that can be affirmed from these figures include that frames having more flexible connections experience greater sway at all levels along the height and frames of higher number of stories experience greater sway for any particular type of connection.

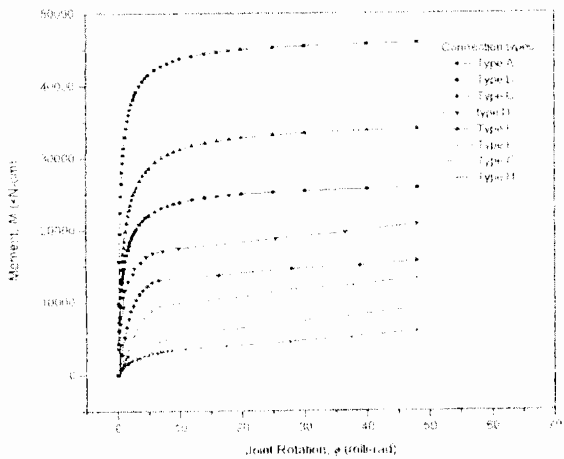

Fig. 3. M-φ curves derived by 3-parameter power model

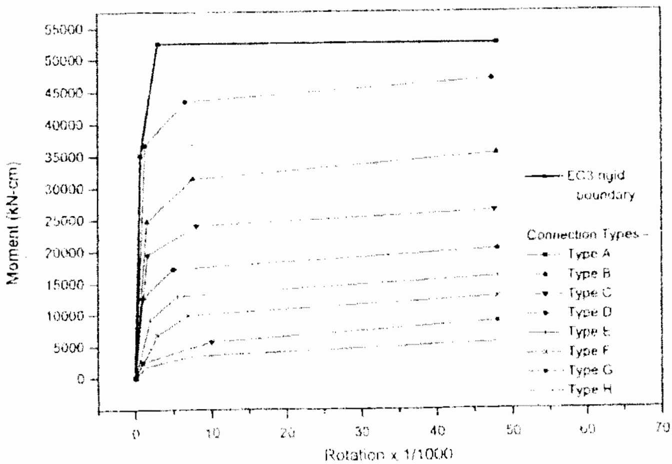

Fig 4.Tri-linearised moment-rotation relationship

Table 2. Applied load intensities

Gravity Load (kN/m²)		Wind Load (kN/m²)			
Dead Load	Live Load	5 Story	6 Story	7 Story	8 Story
3.25	2	2	2	2.16	2.27

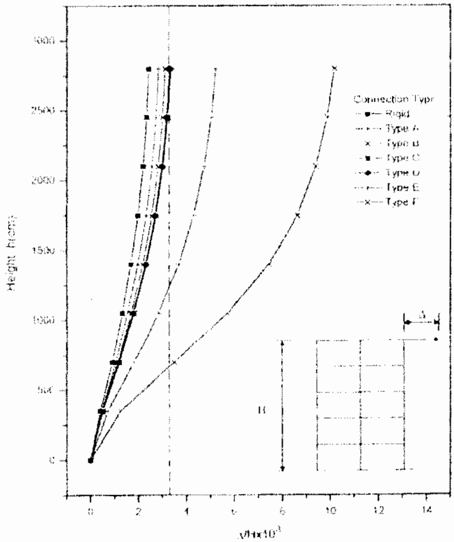

Fig. 5. Sway of a 8 storied 2 bay frame

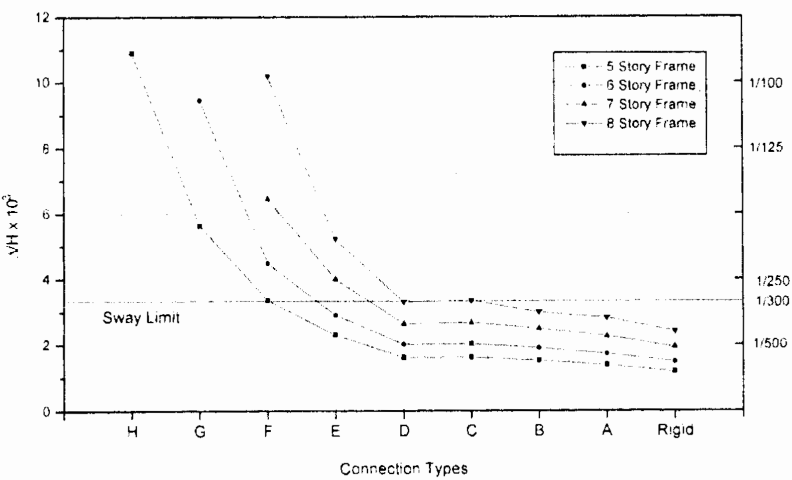

Fig. 6. Sway of 2-bay frames for different connection types

To have a definitive idea regarding whether frames with flexible connections would be able to meet serviceability limit of sway and if so what extent of flexibility may be allowed for different medium-rise frames, top lateral drift normalised by total height is plotted against semi-rigid connection types in Fig. 6. The serviceability limit of 1/300 of total height is also indicated in the figure. The figure shows that frames with semi-rigid connections may yield top lateral drift satisfying serviceability limit. The important role of the connection rigidity becomes apparent with the increase of frame height. Frames with very flexible connections and greater number of stories have collapsed even under the working load in this analysis. Five-storied frames with the most flexible type of connection considered, i.e. connection type H, has withstood the working load. However, frames having type H connections but with number of stories greater than five collapsed under similar loading. Seven and eight storied frames having type G connections have failed to withstand the working load.

STUDY ON ROTATION

The main feature of semi-rigid connection is that it undergoes some amount of rotation when subjected to moment. To gain insight into the behaviour of connections, the distribution of connection rotation at different locations of a frame has been studied in this section. A typical plot of rotation along the height of a 2-bay 8-story frame is shown (Fig. 7) at the four lines of connections i.e. connections at the right column, connections at the right side of the middle column, connections on the left side of the middle column and connections at the left column. The pattern of this behaviour may be explained by the argument that connection rotation depends on the restraints the connection is subjected to and the lateral shear at the level of the connection. For the first floor connections, the lower column is fixed with the base and the upper column is flexibly connected with other members. For the second floor connections, columns on both sides are flexibly connected with other members. Second floor connections being subjected to less restraint undergo greater amount of rotation. Since the lateral shear on the frame gradually decreases with the elevation of the connections, the upper stories experience smaller amount of rotation. Connections at the top most storeys on the other hand go through maximum rotation because these connections are subjected to the least restraint.

As for the level of rotation, the maximum rotations for connections D, E and F are 3 milli-rad, 5.5 milli-rad and 12 milli-rad respectively. From Figure 4 it is found that these level of rotations lie on the second linear portion of the M-φ curve for connections D and E. For the most flexible connection F, the level of maximum rotation lies in the last linear portion but in the vicinity of the transition of the middle and last linear portions of the M-φ curve. This suggests that under working load, maximum level of rotations of medium-rise semi-rigid frames will seldom exceed the initial and middle linear portions of the M-φ curves. This justifies the tri-linearisation of M-φ curves so that the first two linear portions adhere the non-linear curves as closely as possible.

COMBINED USE OF RIGID AND SEMI-RIGID CONNECTIONS

The level of rotation of connections of a particular story was found to depend on the shear at that story and the restraints imposed on the connections. Now with the objective to control the sway that the semi-rigid frames are otherwise likely to experience, the behaviour of frames with mixed use of semi-rigid and rigid connections has been examined. Two cases have been studied in this respect: one with rigid connections at the first floor and the other with rigid connections at the second floor. The reason of taking the first floor connections as rigid in the first case is due to the steeper slope of the deflected shape of the semi-rigid frames at that level. The idea of the second case with rigid connections at the second floor level has arisen while studying the pattern of the distribution of connection rotations in semi-rigid frames. It is apparent from Fig. 7 that the level of connection rotations is greater at the second floor level than at the first floor level. Hence it is expected that by restraining the connections at the second floor level with rigid connections would help to control the total sway of the frames. Although maximum connection rotations occur at the top most floors, the slope of the deflected shape of frames is very small at that level indicating a restraining effect of this connection on the total sway of semi-rigid frames.

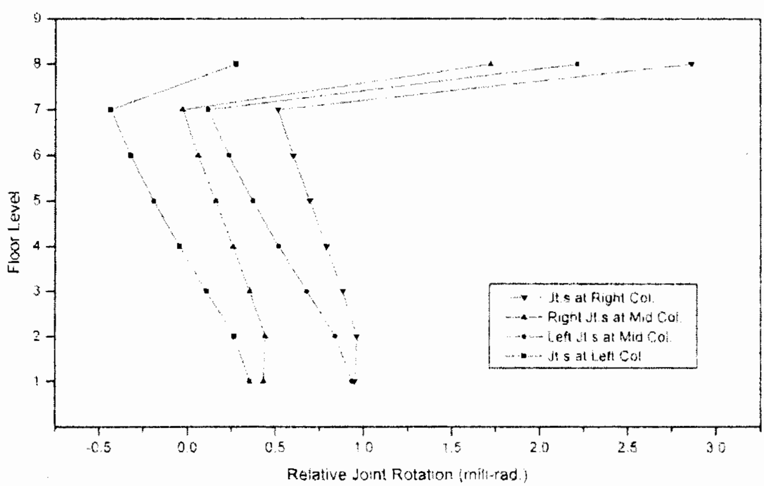

Fig 7. Relative rotation of connection type D of 2 bay 8 storey frame

A typical result of the first case is shown in Fig. 8. The most notable feature of these figures is the influence of connection restraint on the deflected shape of semi-rigid frame. This is evident in the deformation at the first floor level of frames with rigid connections in that floor. In these figures it is noticed that irrespective of the stiffness of connections at other stories, the drifts at first floor remains the same for a particular frame. Restraining the sway at the first floor resulted in reduction in the total sway of the frame, which has been shown in Fig. 9.

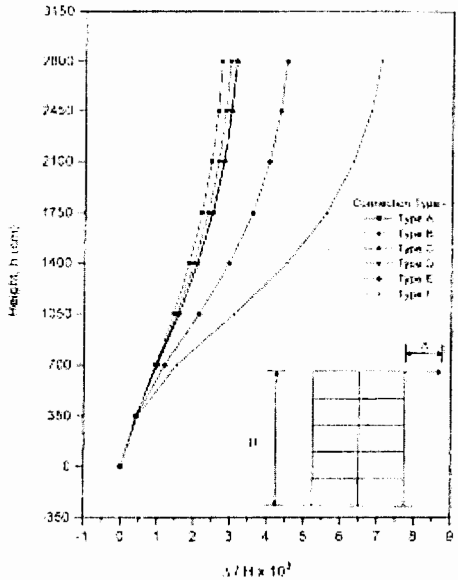

Fig. 8. Sway of a 8 storied 2 bay frame with rigid joint at story 1

Study of the second case has produced more interesting results, which have been plotted in Fig. 10. Using rigid connections at the second floor instead of at the first floor has reduced the sway further. Figure 10 shows that use of rigid connections at the second floor level has enabled 5-storied frames having type-H connections (the most flexible one being considered) to produce sway within the recommended limit. 6-storied and 7-storied frames with type-H connections have withstood the working load in the case when the second story connections are rigidly fixed; whereas these frames otherwise collapse under working load. For the 6-storied frames with type-F connections can now be used without exceeding the sway limit.

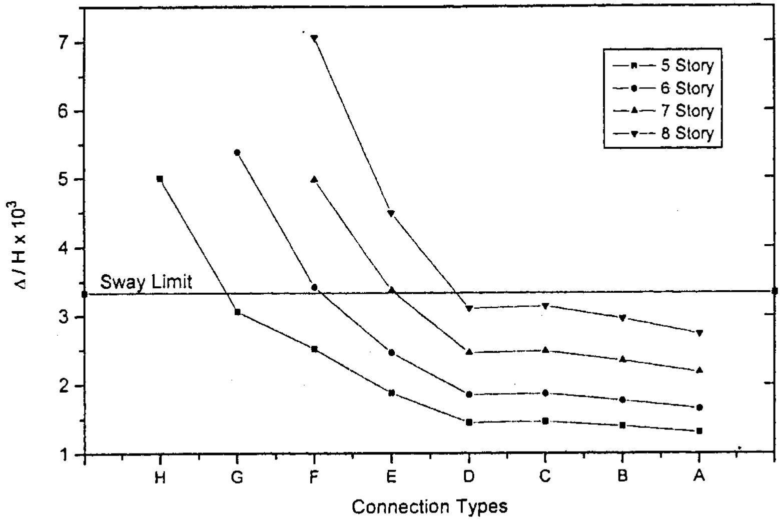

Fig 9. Top lateral sway of semi-rigid frames with rigid joints at story 1

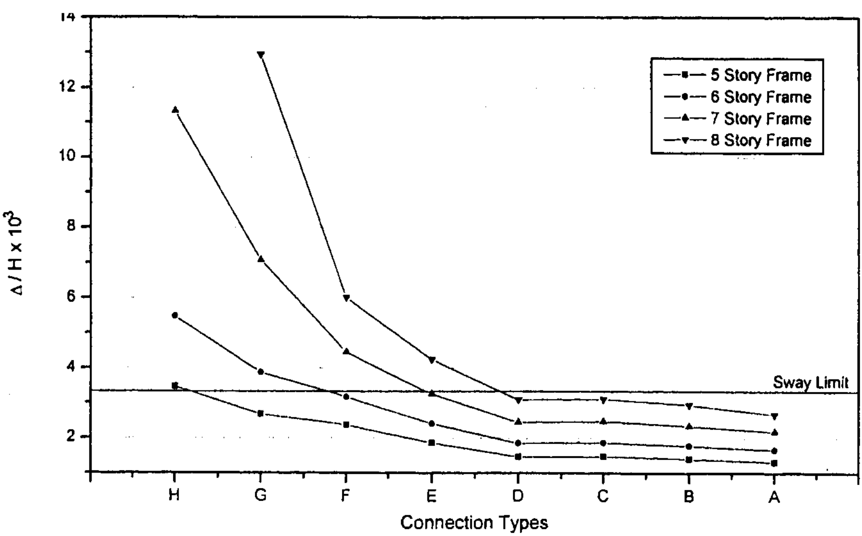

Fig 10. Top lateral sway of semi-rigid frames with rigid joints at story 2

The 7-storied and 8-storied frames with type-G connection do not fail under working load when the connections at the second story are restrained rigidly. Moreover 7-story 2-bay frames with type-E of connections can only be used maintaining the recommended sway limit when rigid connections are used at the second floor level. In fact restraining the second floor connections have produced better effects in the sway behaviour of semi-rigid frames than using rigid connections at the first floor level. Therefore, to capitalise the economy of semi-rigid construction it can be recommended that it is always beneficial to use rigid connections at the floor level where the level of rotation is the greatest except the top most floor.

CONCLUSIONS

It is expected that incorporation of semi-rigid design concept would result in economy in the construction of steel building. Compared to low-rise or non-sway frames, the economy offered by the semi-rigid construction is more significant in the case of multi-storied sway frames because such frames consist of greater number of connections. Again the overall behaviour of multi-storied sway frames is much dependent on the connection characteristics. The foremost reason for the reservations against using semi-rigid connections in sway frames is the absence of any guidance on the extent of lateral drift that will occur with the use of flexible connections. Moreover, research on semi-rigid sway frames (Anderson and Benterkia, 1991) indicated that instead of the ultimate strength, serviceability limit on lateral drift is most likely to govern the design. The present study has examined the behavioural aspect of multi-storied semi-rigid sway steel frames subjected to service loads - both wind and gravity load. It has been found that semi-rigid frames with appropriately selected connections can meet the sway limit of 1/300 times the height of the frame. Connection rotation depends on the restraints the connection is subjected to and the lateral shear on frame at the level of the connection. Under working load, the maximum level of connection rotations of medium-rise semi-rigid frames will seldom exceed the initial and middle portions of the tri-linearised moment-rotation curves.

The use of rigid connections at the first floor of a semi-rigid frame reduces the total sway of the frame. However, fixing the second story connections, which is near to the point of contra-flexure on the deflected shape of the frame, instead of first story connections reduces the sway further. Therefore, it can be concluded that in an attempt to control excessive sway that would otherwise result due to the use of semi-rigid connections, it is always beneficial to use rigid connections near to the point of contra-flexure of the deflected shape of a frame where the level of rotation is high.

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