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LATERAL DRIFT OF SEMI-RIGID STEEL FRAMES - II

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ABSTRACT: Connections constitute a small part of the total weight of steel framing but they represent a substantial part of the total cost due to high labour content. Consideration of semi-rigid nature of connections in the design phase and allowance of semi-rigidity in construction may result in considerable saving without any change in construction practices. According to previous studies lateral drift has an overbearing importance in the design of semi-rigid sway frames. At present there exists is no simplified method to estimate the lateral drift of such frames. To this end, an appropriate representation of moment-rotation relationship of semi-rigid connections, used in sway frames, has been developed. It has been shown that the true moment-rotation relationship of connection can be replaced by an approximate secant connection stiffness, which can be used in simplified analysis technique of semi-rigid frame in sway mode. A simplified method to estimate the lateral drift of medium-rise multi-storied semi-rigid sway steel frames has been proposed.

KEYWORDS: Semi-rigid connections, Sway frame, Moment-rotation relationship, Connection stiffness, Lateral drift.

INTRODUCTION

In designing building frames it is generally assumed that connections behave either as perfectly pinned or as completely rigid. This simplification results in an inaccurate prediction of frame behaviour. The true behaviour of structural frames lies between these two extreme cases of connection response. Considerable research over the years has clearly shown that actual connections exhibit characteristics over a wide spectrum between these two extremes. Structural frames with such connection behaviour are classified under the heading of semi-rigid. Researchers (Steel Structure Research Committee 1934, Roberts 1981, Maxwell et al 1981, Bjorhovde 1984, Nethercot et al 1988) have shown that incorporation of semi-rigid design concept would result in economy in steel building construction. Despite this fact, incorporation of semi-rigid behaviour in design practice of multi-storied unbraced frames has not been preferred by designers.

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 ultimate strength,

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lateral drift is most likely to govern the design. Hence, the overall sway behaviour of multi-storied semi-rigid frames deserves attention by researchers in order to capitalise its inherent economy. In the companion paper it is shown that certain types of flexible connections can be used for medium-rise frames meeting the serviceability limit on lateral drift. But while designing, the designer must have the knowledge about the range of connections that will produce sway within the limit. This necessitates that the designer has a simple method of estimating the sway of semi-rigid frames at his disposal. One impediment to development of such a method is the non-linear nature of the connection M-φ relationship. Although this non-linearity can easily be taken into account using an incremental technique in a computer program, this is not suitable for routine practical design and therefore some simplified representation of the M-φ behaviour, which would provide results of acceptable accuracy, is very much warranted. The non-numeric representation of connection flexibility used in the companion paper fails to fit an appropriate scale to show the graduation of flexibility of different connections. In this study a numeric index for non-linear or multi-linear M-φ curves has been introduced. Finally a simplified method for determination of sway has been proposed in order to overcome the primary difficulty to the design and reliable use of semi-rigid connections in sway-frames.

DETERMINATION OF SECANT STIFFNESS

Different researchers took different approaches to quantify and represent the connection flexibility. The most commonly adopted approach is to take a linear approximation of the M-φ curves. This approach includes the initial tangent stiffness method and the secant stiffness methods. Eurocode 3 (1990) idealised connection behaviour in a tri-linearised form with a non-dimensional parameter '*a*'. Anderson and Benterkia (1991) introduced a parameter called 'degree of flexibility' in their study of sway steel frames. However, these measures of flexibility have neither been intended nor been developed to be used in a simplified method for determining sway of semi-rigid frames. Therefore a new approach has been sought in the present study. In this study, the cases analysed in the companion paper with tri-linearised M-φ curves have been analysed again with a set of linear moment-rotation relationship covering the whole range from almost pinned behaviour to rigid behaviour. A correlation has been sought between the tri-linearised and linear representations. The correlation would then provide the base for the development of a simplified and realistic measure of connection flexibility. While analysing frames with linear connection behaviour some interesting relations have been obtained which has eventually led towards developing the simplified method of determining sway.

Analysis of Semi-rigid Frames with Linear Connection Moment-rotation Relationship

The results of the analyses with linear connection response for 2-bay frames are shown in Fig. 1 where top lateral sway is plotted against linear connection stiffness. The frames studied in this section have the same configurations, member properties and loading as discussed in the companion paper. A linear relationship is found between top lateral sway and connection flexibility, as shown in Fig. 2.

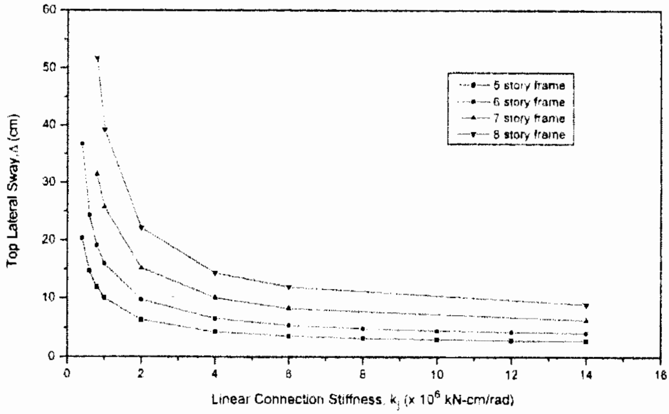


Fig. 1. Effect of linear connection stiffness of 2-bay frames

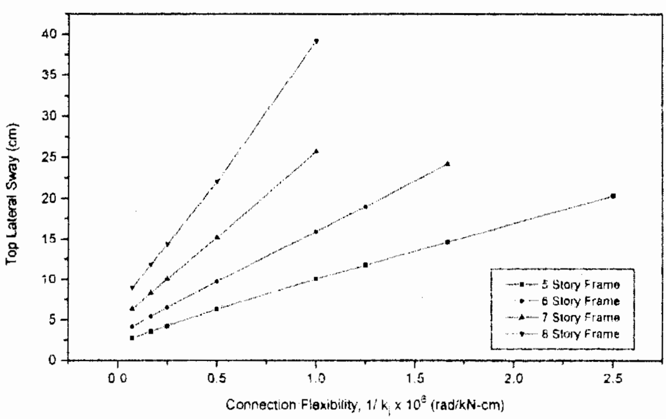
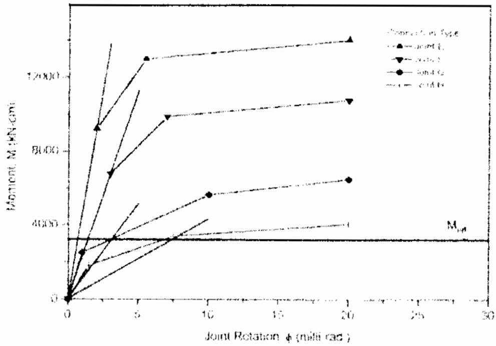


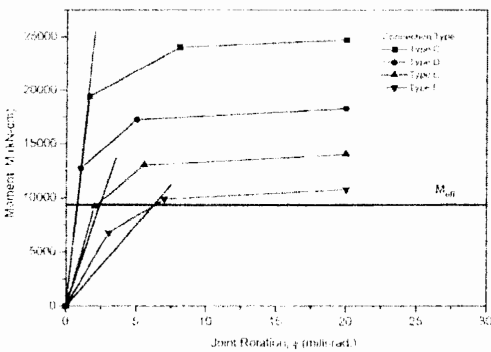
Fig. 2. Linear connection flexibility and top lateral sway

Correlation between tri-linear M-φ relationship and linear connection stiffness

The objective of analysing the semi-rigid frames with linear connection stiffness was to find out whether the linear stiffness produces the same sway as produced by the use of tri-linear form of M-φ relationship. A common relation between these two representations was sought. The linear connection stiffness, for which the same sway as for a tri-linearised M-φ representation is produced, is superposed on the corresponding tri-linear moment-rotation relationship and the point of intersection is noticed (Figs. 3 and 4).



(a) 5-storied frame



(b) 6-storied frame

Fig. 3. Stiffness correlation for 2-bay frame

The purpose of observing the point of intersection is to develop some relation so that a secant stiffness method may be established. From Figs. 3 and 4 it is evident that the points of intersection for any particular frame with specified loading lie along a common value of moment irrespective of connection type. This common value of moment may provide basis for a secant stiffness to quantify numerical indices to replace non-linear M-φ curves. From the study of the companion paper it can be concluded that no single rotation value can be assigned for sway frames to find out such secant stiffness of connections; since for the same frame and loading, the level of rotation varies with connection type, even though the pattern of distribution of rotation remains the same.

(a) For 5-storied frames

(b) For 6-storied frames

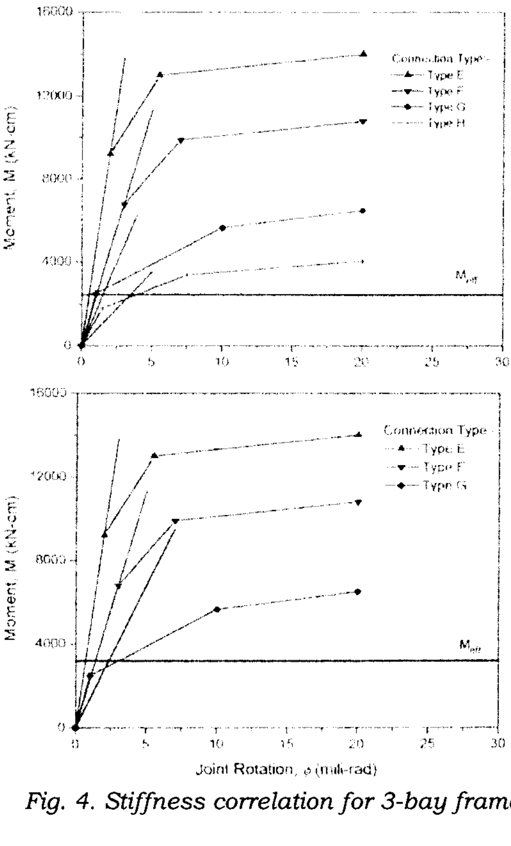
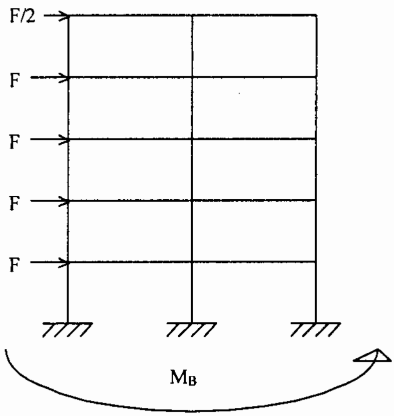


Fig. 4. Stiffness correlation for 3-bay frame

Figures 3 and 4 show that the value of the moment depends on the configuration of the frame. This moment may be thought of as an average moment carried by all the connections irrespective of connection types and, as such, may be a portion of the total moment carried by the frame; it is examined whether it is a portion of the base moment M_B, the moment developed at the base when the frame is conceived to act as a cantilever (Fig. 5). It is found that the level of moment for which secant stiffness can be derived is in-between 1.9% to 2.3% of the base moment (M_B) for 2-bay frames and 1.8% to 1.4% of M_B for 3-bay frames. On an average 2.1% and 1.6% of M_B for 2-bay and 3-bay frames respectively can be taken as effective moment (M_{eff}) for which secant stiffness can be obtained. The error associated with this averaging is negligible since the overall structural response is not very sensitive to a certain degree of variation in the M-φ behaviour of the connection. Nethercot et al (1988) showed that for a 10 per cent shift in M-φ curve, the response of beam was almost unchanged. It can be seen that the shift in load displacement response due to a 10 per cent shift in connection M-φ relationship is insignificant.

Fig.5. Base moment

Now taking the effect of bays i.e., the number of columns (Nc) the relation between M_{eff} and M_B can be written as:



$$M_{eff} = \frac{0.063}{N_c} M_B \qquad (1)$$

Equation 1 provides a basis to account for the effects of height and number of columns of frame and the effect of loading on M_{eff} have been taken care of. It is evident from Figs. 3 and 4 that the numerator of Eq. 1, i.e., the quantity 6.3% of M_B does not depend on the type of connection. It may depend on the frame configurations other than the height and number of bays of frame e.g. relative stiffness of beam and column. The fact is that every minute detail of frame may have some effect on M_{eff} but their effect can be anticipated not to be a significant one for any simplified method to take those into consideration. As is evident in case of an increase of a bay from 2 to 3 causes only a shift of 0.5% of M_B. Thus Eq. 1 may be applied to all moment-resisting medium-rise sway steel frames, having usual configuration.

The approach of deriving a basis for a linear representation of the connection behaviour in the form of secant stiffness, as put forward here, has been developed within the scope of the study. This method can yet be categorically used for more general cases. It has been developed comparing tri-linear representation of M-φ behaviour with linear connection stiffness. The method can still be applied to entirely non-linear M-φ relationship since the tri-linear representation, as previously discussed, gives almost identical results with non-linear connection behaviour. Although the study is completely based on top- and seat-angle connections with or without double web angle, the method may yet be applied to any type of connection e.g. extended end plate connection, flush end plate connection, header plate connection etc. as long as the designer has the connection moment-rotation relationship at his disposal. Because it has been shown (Ahmed, 1992) that it is not appropriate to judge a connection stiffness purely on the basis of a given connection type, rather it is the M-φ curve of the connection that provides the information relating to its performance in the structure. Now the new method of obtaining secant connection stiffness for sway frames may be summarised in the steps as stated below:

- The M-φ curve of the connection is to be obtained using any suitable analytical model or from experimental data.
- The base moment, M_B is to be calculated for the particular frame and loading.
- The line of effective moment, M_{eff}, calculated by Eq. 1, is to be drawn on the M-φ diagram.
- The point of intersection of the M_{eff} line and M-φ curve has to be connected with the origin.
- The slope of this secant line represents the stiffness of the connection to be used for the analysis of sway frames.

SECANT STIFFNESS AND SWAY

Once the appropriate stiffness value is assigned to a particular M-φ relationship, it is now possible to replace the non-numeric index used in the figures of the companion paper with a corresponding numeric index. Figure 6 shows the typical behaviour of the sway frames where non-numeric index is used for the connections. With the secant stiffness in the abscissa Fig. 7 shows the sway behaviour of frames where both flexible and rigid connections have been used. Figure 7 shows the appropriate graduation of connection stiffness. Therefore, with these figures the designer can be properly informed of the extent of freedom of his choices when he has to ensure limiting the sway within a specified limit. The advantage of using the secant stiffness approach discussed earlier becomes more evident while comparing these two figures particularly for connection type C. Though connection type C possesses greater moment capacity, as is seen in Fig. 8, its initial stiffness is slightly less than that of connection type D. Since the M_{eff} lines cuts below the initial linear part of M-φ curves of these two connections the initial stiffness coincides with the effective connection stiffness. That is why connection C produces slightly greater sway, which causes the slight unevenness in Fig. 6. Plotting sway values against the effective connection stiffness in Fig. 7 the unevenness of the former figure could be avoided altogether.

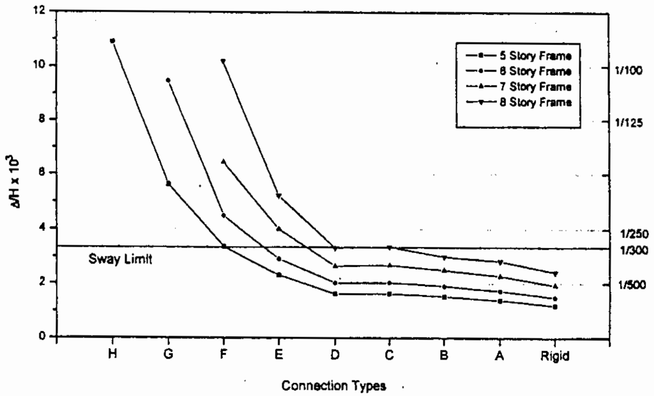


Fig. 6. Sway for different connection types of 2-bay frames

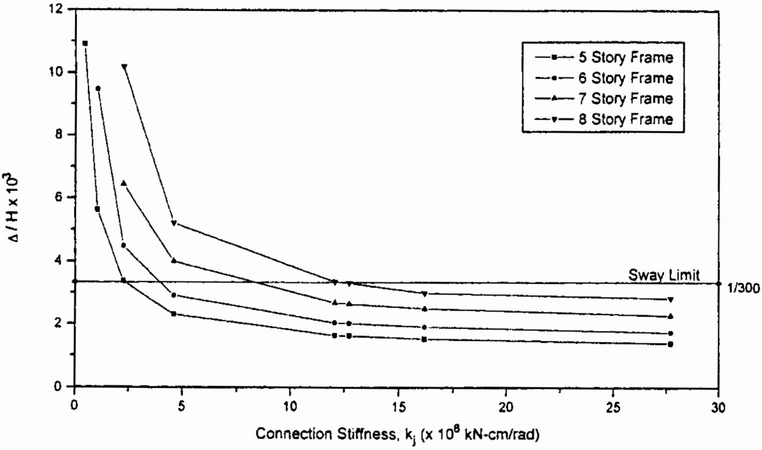


Fig. 7. Sway with respect to numerical index of connection stiffness

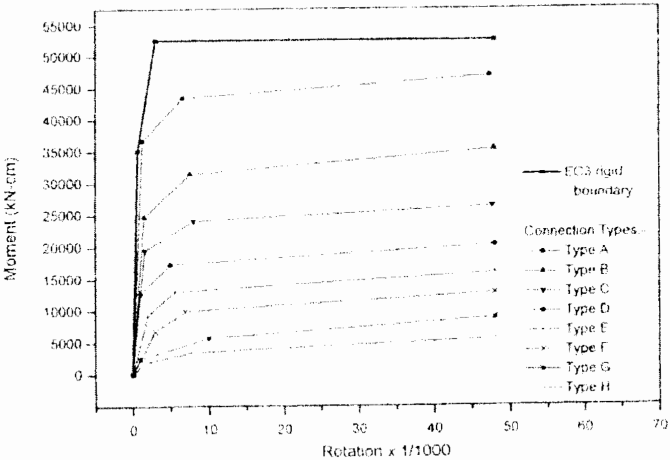


Fig. 8.Tri-linearised moment-rotation relationship

One interesting point is to be noted here that the connections for which the M_{eff} line intersects the M-φ curve well above the initial linear portion, produce lateral sway much in excess of the sway limit of 1/300 of the total height of the frame. Therefore, for semi-rigid frames under working load, initial tangent stiffness of connection makes a valid representation of the connection behaviour so far as connection has sufficient stiffness to hold the lateral sway within acceptable limit.

NOMOGRAPH FOR DETERMINATION OF SWAY

Although some behavioural study has already been conducted in the companion paper but that study has mainly been focused on the variation of sway with the change in connection stiffness. In this section the effect of beam and column stiffness is also studied. To derive any simplified method of estimating sway some non-dimensional parameters must be set to address generalised set of conditions. The ratio of beam stiffness to connection stiffness is varied while sway of semi-rigid frames is also normalised by sway of rigid frames. To accommodate column stiffness in this approach, two frames having different configurations but possessing almost the same ratio of beam stiffness to column stiffness have been studied. The configurations of the frames are shown in Table 1. The results of the study when plotted with $\frac{EI_b}{L_b K_j}$ as abscissa and $\frac{\Delta}{\Delta_{rig}}$ as ordinate, lie on a single straight line up to a certain range of the ratio of beam to connection stiffness (Fig. 9). Therefore it can be concluded that a characteristic straight line can be derived for all frames having the same ratio of beam to column stiffness when plotted as mentioned above. The error induced with such conclusion may become significant for very flexible connections for which the sway exceeds the recommended limit with a large margin. For most of the practical cases the value of remains much below 0.5. Now for a practical range of ratio of beam to column stiffness, as shown in Table 2, similar parametric study has been conducted. Figure 10 presents the results of this study. This figure may actually be used as a nomograph to estimate the sway of a semi-rigid frame. To estimate sway of a semi-rigid frame with this chart one has to determine the sway of a rigid frame having the same configuration as the semi-rigid one, except that the connections are rigid using any suitable software.

Table 1. Configuration of Frames 1 and 2 of Fig. 9

	Beam Section	Beam Length	Column Section	Column Length	k_B / k_C
Frame1	W 21 x 62	500 cm	W 16 x 40	300cm	1.54
Frame2	W 21 x 57	500 cm	W 12 x 65	350 cm	1.537

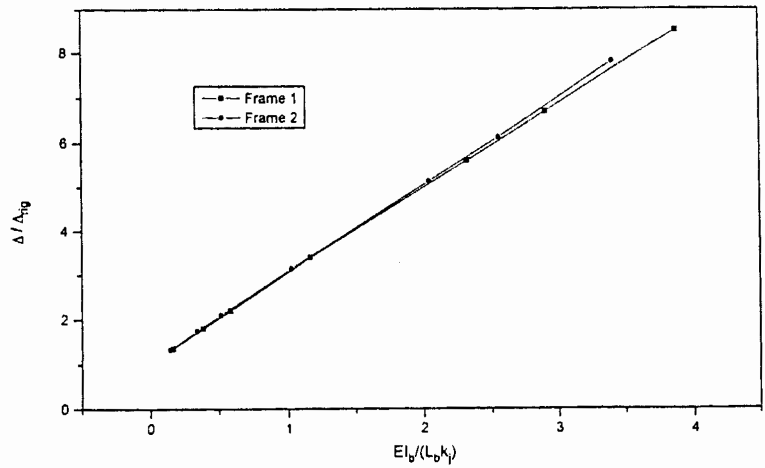


Fig. 9. Sway behaviour with same ratio of beam to column stiffness

Table 2. Member properties used for Fig. 10

Beam Section	Column Section	k_B / k_C
	UC 305X305(198)	0.56
UB 533x165(73)	UC 305X305(118)	1.02
	UC 254X254(89)	1.98
	UC 203X203(86)	2.99

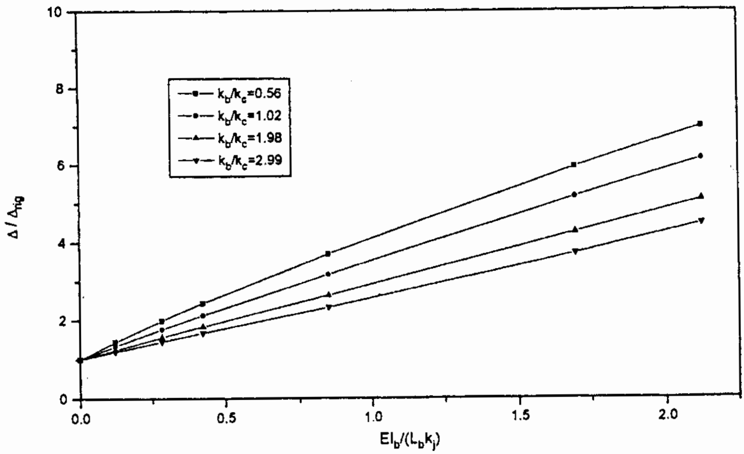


Fig. 10. Nomograph to determine sway

SIMPLIFIED METHOD OF ESTIMATING SWAY

Now from the parametric study as discussed in the previous section, a simplified method to estimate lateral sway of semi-rigid frames may be outlined by the following steps:

- The configuration of the frame has to be defined and the loading evaluated
- Any connection type with proper detailing should be selected
- The M-φ relationship of the connection is to be determined with the help of any analytical model or experimental data.
- The M_{eff} line is to be drawn on the M-φ diagram
- The secant stiffness, calculated by joining the origin and the intersection of the M_{eff} line and the M-φ diagram, can be taken as k_j.
- The quantities $\frac{EI_b}{L_b k_j}$ and $\frac{k_b}{k_c}$ have to be evaluated from the member properties of beams and columns.
- With the quantities evaluated in the previous step $\frac{\Delta}{\Delta_{rig}}$ can be determined from Fig. 10.
- Δ_{rig} is to be evaluated with the help of a computer program.
- Sway can then be calculated by multiplying Δ_{rig} with the value read from Fig. 10. If the value of sway exceeds the limit, a stiffer connection has to be chosen and this method has to be repeated. Otherwise the connection chosen can be considered satisfactory.

CONCLUSIONS

A simplified method of estimating lateral drift of medium-rise semi-rigid sway steel frames has been proposed in the present study. An appropriate simplified representation of moment-rotation relationship of sway frames has been developed for use. The present study has offered important conclusions regarding the selection of semi-rigid connections suitable for use in sway frames and the consequent behaviour of the semi-rigid frame, particularly the ways of controlling excessive lateral drift. Methods concerning simplified representation of moment-rotation relationship and estimation of lateral drift of sway frames as proposed in the study are expected to enhance the reliability of semi-rigid construction and facilitate the selection of appropriate connection type. The simplified representation of connection moment-rotation relationship has two fold merits: firstly it provides guidance about the connections that may be used in semi-rigid frames satisfying the serviceability limit and secondly it renders appropriate gradation for connection flexibility.

The important conclusions derived from the observations made during the development of the proposed method are now summarised below.

- For unbraced frame under lateral loads, a common value of moment (M_{eff}) irrespective of the type of connection may provide the basis of a secant stiffness of connections for a particular frame configuration and loading. The value of M_{eff} may be determined with Equation 1.
- The connections for which the M_{eff} line intersects their M-φ curves well above the initial linear portion, would produce sway much higher than the recommended limit. This criterion may be used to identify whether a connection is suitable for its use in unbraced frame.
- For connections, which under working load are likely to produce sway within the recommended limit, the initial tangent stiffness appears to be the most realistic representation of the connection behaviour.
- The ratio of rigid frame sway and semi-rigid frame sway when plotted against the ratio of beam stiffness and connection stiffness provides a characteristic plot for a particular value of the ratio of beam stiffness and column stiffness. Such plots for a practical range of ratios of beam and column stiffness may be used as a nomograph for estimating sway of semi-rigid frames.

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