Design of I-Beam to Box-Column Connections Stiffened Externally

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ABSTRACT

This paper is concerned with I-beam to box-column connections stiffened externally. A design method to determine the dimensions of T-stiffeners is proposed. Connections of I-beams and box-columns for a wide range of dimensions were studied by the finite-element method and found to satisfy the basic design criteria for a moment connection. The Ramberg-Osgood function was used to curve-fit the moment-rotation curves based on the geometric parameters of the connections and the results are found to agree well with those from the finite-element analyses. Finally, the design procedure and the curve-fitting parameters were compared with the experimental results of a four-way connection tested to failure.

INTRODUCTION

It is a well known fact that the behavior of beams and columns at their connection is one of the most important factors considered in the analysis of steel frames. A vast number of different types of connections are used, and the rigidity of connections range from one that is extremely flexible, behaving more like a pin joint, to one that is almost rigid. Researchers have carried out studies on the effect of the semi-rigid connection on frame behavior. A state-of-the-art paper was presented by Jones, et al[1] on the analysis of frames with semi-rigid joints. A modified stiffness matrix method, incorporating the partial rigidity of joints to find the elastic buckling load of semi-rigid frames was presented by Yu and Shanmugam.[2] Gerstle[3] noted that the effect of the connection flexibility on frames can be two-fold: (a) connection rotation contributes to the overall frame stability and (b) it affects the distribution of internal forces and moments in the girders and columns. The effects of connections on columns was considered by Nethercot and Chen[4] and Jones, et al[5] while Kato, et al[6] carried out a study on the effect of joint flexibility due to joint-panel shear deformation on frames. Barakat and Chen[7] used idealized connection models in the analysis of frames and subsequently implemented the method on personal computer.

Analytical models incorporating semi-rigid connections will result in efficient design. In such design the frame members will be utilized more efficiently, resulting in a lower cost. Therefore, there is an important need to accurately determine the moment-rotation (M-ϕ) characteristics of various types of connections and to define them in a convenient way suitable for incorporating them in frame analyses. Many researchers have carried out both analytical and experimental investigations on the behavior of different types of connections. Various types of models defining the M-ϕ relationship, ranging from the simple linear model in the 1930s to the present day complicated cubic B-spline curve-fitting model have been reported by Jones, et al[1] The curve fitting technique was also used by Attiogbe and Morris.[8] Experimental data was fitted to the Richard-Abbott function while Ang and Morris[9] used the Ramberg-Osgood function for the curve fitting process. Due to the diversity of the behavior of the connections, researchers[10,11] have proposed a classification system in an attempt to present the behavior of connections consistently. An alternative approach was to build up a data base for the various types of connections[12,13] so that designers can obtain the necessary data for their specific use.

However, most of the past work was carried out on connections between I-beams and I-columns. Limited work is available on the behavior of I-beam to box-column connections.[14,15,16] The authors have carried out an investigation on such connections stiffened externally using the finite element method.[17] Experimental and analytical results from tests carried out on a series of specimens stiffened both internally as well as externally have been reported.[18] It has been found that the T-section provides an efficient external stiffener for the connection. In this paper, a simple design procedure to determine the dimension of external T-stiffeners is proposed. A curve fitting method using the Ramberg-Osgood function to define the M-ϕ characteristic of such connections is also discussed.

BASIC DESIGN PHILOSOPHY

The basic design criteria for rigid or moment connections are:[19]

1. sufficient strength

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2. sufficient rotation capacity
3. adequate stiffness
4. ease of erection and economical fabrication

Whether a particular connection satisfies the first three conditions can be determined by observing its moment-rotation curve. The last criterion is a matter of practical application which has to take into account both the material cost of the various components of the connection and the labor cost in fabricating it.

Figure 1 shows four moment-rotation curves exhibiting different characteristics of connections. Connection A is considered to be properly designed as it satisfies criteria (1) to (3), i.e., it can attain sufficient strength in excess of the plastic moment of the beam as well as having adequate stiffness and rotation capacity before failure. Connection B, however, has insufficient rotation capacity although it is adequate in terms of stiffness and strength. As for connection C, it only has rotation capacity but not stiffness and strength while connection D has neither sufficient strength nor rotation capacity. It is the objective of this paper to present a design method for I-beam to box-column connections stiffened externally with T-stiffeners (Figure 2) which can exhibit the property of the connection A in Figure 1.

CONNECTIONS WITH EXTERNAL T-STIFFENERS

When an I-beam frames into a box-column, the width of the beam flange is normally less than the column width, as a result the connection will be weak if it is not stiffened. In order to achieve the conditions of an acceptable moment connection (connection A in Figure 1), the traditional method is to stiffen the connection by welding internal continuity plates at the levels of the beam flanges inside the box-columns. This, however, is a difficult and expensive process. The authors have carried out a study[17,18] to investigate the possibility of using external stiffeners in place of internal continuity plates such that the basic design criteria are still satisfied.

The investigations showed that by using external T-stiffeners, all the basic design criteria can be satisfied. Two series of experiments have been carried out[18] on connection specimens stiffened by internal continuity plates or by two different types of external stiffeners namely angle and T-stiffeners. In the first series, the specimens were subjected to a monotonically increasing load while in the second series, the specimens were subjected to cyclic loads. The specimens consisted of two 1.5 m long beams welded to opposite sides of a box-column of 1.0 m height. The dimensions of the external stiffeners were designed based on a preliminary design method by using finite element analysis. The length of the stiffeners were so chosen that the normal stress distribution is uniform across the stiffener. This would prevent any premature failure of the stiffeners due to stress concentration. However, it was found that this method gives rise to overdesign of the stiffeners and an alternative method of design for the T-stiffener is, therefore, presented in this paper.

Due to the complexity of the connection involved, the finite element method was used to analyze the connections. MSC/NASTRAN,[20] which can carry out both material and geometrical non-linear analyses was used to analyze all the connections. Due to the symmetry of both the model and loading, only a quarter of the model was analyzed and a typical finite-element mesh is shown in Figure 3. The results obtained are compared with those obtained from the experiments.

T-STIFFENER DESIGN

Minimum stiffener length for stiffness

From the finite-element analyses, it was observed that a minimum length for the T-stiffener is required to transfer the forces from the beam flanges to the column webs effectively. It was also found that for the stiffener to be effective, its web thickness must be at least equal to half that of the beam-flange

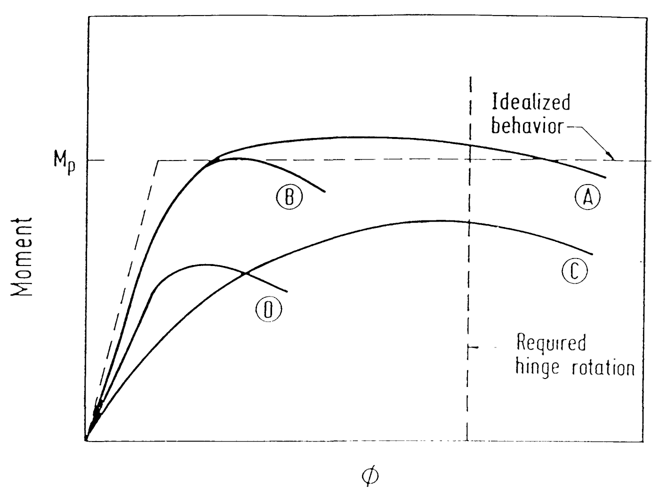

Fig. 1. Moment-rotation curves.

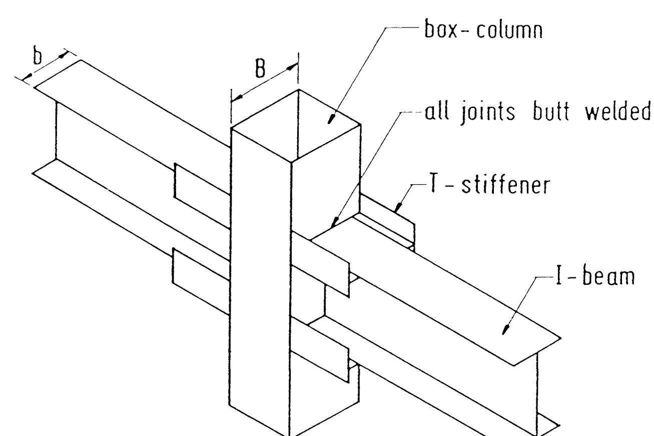

Fig. 2. Typical specimen with external T-stiffeners.

thickness. Otherwise, the stiffener web may yield prematurely, resulting in a weak connection.

Figure 4 shows the load-deflection curves of a typical connection with external T-stiffeners of various lengths. These curves were obtained by the elasto-plastic finite-element method using the MSC/NASTRAN package. The plastic capacity of the beam, P_p is also shown. The lengths were defined by the angle θ as shown in the figure. The curves corresponding to θ = 15° and 20° have sufficient stiffness and strength while the other two curves are more flexible. The curve corresponding to θ = 15° show marginal increase in ultimate strength capacity over the curve with θ = 20°. It was thus decided to adopt θ = 20° as the design criterion because this would result in a shorter stiffener length and hence more economical design. The stiffener length l can thus be written as

$$l = (B - b) / (2 \tan 20°)$$

where

B = column width
b = beam-flange width

The other factor affecting the stiffness of the connection is the stiffener-flange width which is connected to the edge of the column web. This stiffener flange serves two purposes: 1) it increases the moment of inertia of the beam cross-section at the connection significantly, thus increasing the stiffness of the connection, and 2) it transfers the stresses from the beam to the column web more evenly, minimizing the possibility of stress concentration.

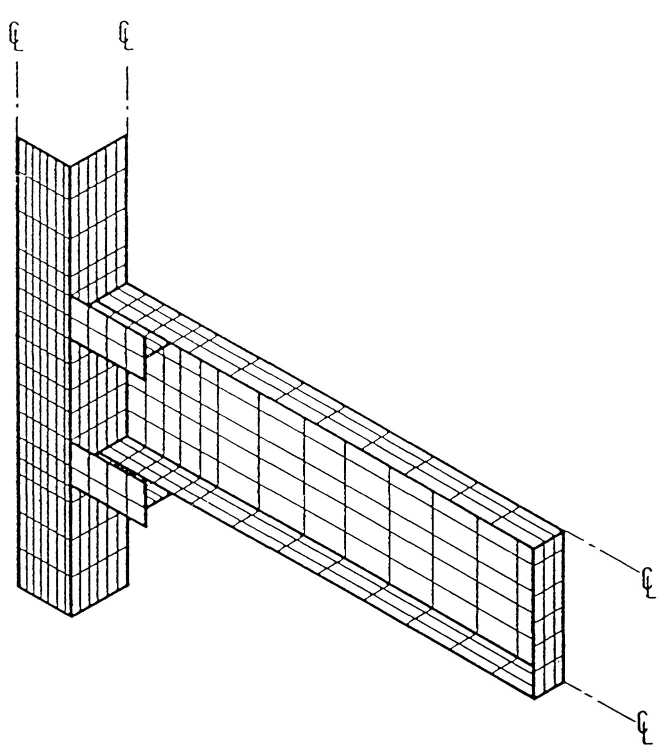

Fig. 3. Typical finite element mesh.

Minimum Stiffener Length for Strength

The length of the stiffener, therefore, depends upon the ratio of beam-flange width to column-flange width (b / B). When this ratio reaches a value close to one, the stiffener length will become so short that it will result in premature failure at the stiffener web. For such cases, a check has to be made on the minimum length based on the strength criteria of the stiffener web. To determine the minimum length based on this type of failure of the web, the following assumptions are made. The moment developed at the connection should be at least equal to the plastic moment capacity M_p of the beam and it is carried by the beam flanges such that $T_p = M_p / d_b$ (Figure 5); the stress distribution at failure on the beam flanges and stiffeners are as shown in Figure 6(a) with stiffener flanges and stiffener web between the flange and K-line reaching yield; the flange forces, T_p are transferred to the column webs through the stiffeners as shown in Figure 6(b). It can be seen from Figure 6(b) that

$$\frac{T_p}{2} = T_1 + T_2 \tag{1}$$

where

$T_1 = (A_f + A_w)$ (2)
$T_2 = l t_{sw} \tau_y$ (3)
A_f = stiffener flange area
A_w = area of stiffener web between the flange and K-line
l = stiffener length
t_{sw} = thickness of stiffener web

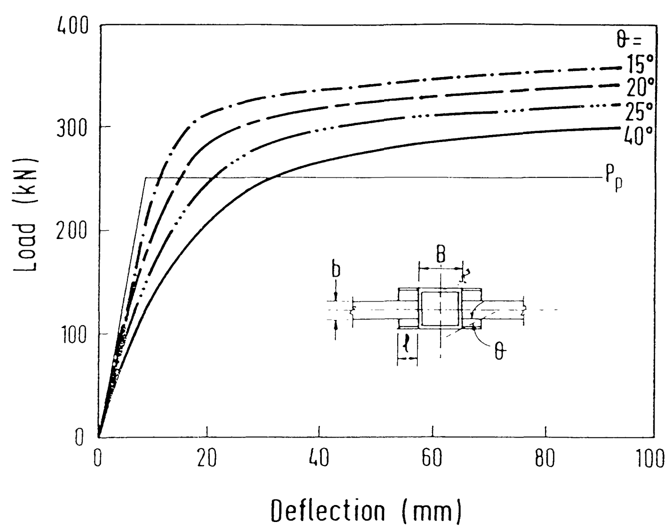

Fig. 4. Load-deflection curves of specimen with various stiffener lengths.

$\tau_y = \sigma_{yt}\sqrt{3}$

σ_{yt} = tensile strength

The stiffener length l can be calculated for Equations 1–3.

DESIGN PROCEDURE

Given the dimensions of a beam and a column, the following simple procedure can thus be adopted to determine the suitable size and length of the T-stiffener required. From the section table, an I-beam or T-section having web thickness equal to at least half the beam-flange thickness is chosen for the stiffener. Assuming $\theta = 20°$ (Figure 4), the stiffener length is determined; the stiffener length based on the strength criteria is calculated from Equations 1–3. The larger stiffener length is finally chosen. All welds between the various components at the connection are assumed to be full penetration welds. Two examples based on the above design procedures are shown in Appendix II.

LOAD-DEFLECTION CURVES FOR TYPICAL SPECIMENS

Since there is no closed-form solution to define the behavior of connections, the finite-element method has been used to analyze these connections. This method has been shown to predict the load-deflection characteristic of specimens with reasonable accuracy. As such, it was decided to use this method to test the validity of the design procedure proposed. Two series of specimens were designed based on the above procedure. One series consisted of specimens with two beams framing into the box column on opposite sides while the other series consists of connections with four beams framing into the column on all four sides. The same design procedure was used for both series, resulting in the same stiffener size for connections between a particular beam and column dimensions. Both the beam and box-column sections were obtained from section tables.[22] Beams and column sizes were taken such that the whole range of sections in the table can be represented. The external T-stiffeners were then designed accordingly and the specimens were analyzed using MSC/NASTRAN.

Figure 7 shows some typical load-deflection curves of one of the specimens. For comparison, the results obtained using the simple elastic-plastic method are also plotted. It can be seen from the figure that the connections are able to develop strength well in excess of the plastic capacity of the beams. In addition, the initial stiffness of the connections satisfied the basic criteria for a moment connection. The slight difference in the initial stiffness between the two- and four-way connections is expected since the column web for the two-way connection is unrestrained in one direction while that of the four-way connection is restrained all round.

MOMENT-ROTATION PREDICTION BY CURVE-FITTING TECHNIQUE

It is commonly known that the behavior of connections between beams and columns is one of the most uncertain parameters in the design of frames at present. Analyses are carried out assuming the connections to be either fixed or pinned but in practice it is never the case. An accurate moment-rotation (M-ϕ) characteristic for different types of connection is therefore essential if any work is to be carried out to incorporate the semi-rigid nature of these connections. Many researchers have tried to standardize the M-ϕ relationships for various types of connections so that they can be incorporated into the computer programs during the analysis of frames. One of the most common method of standardizing the M-ϕ curves is by curve-fitting the available test data for the different types of connections.

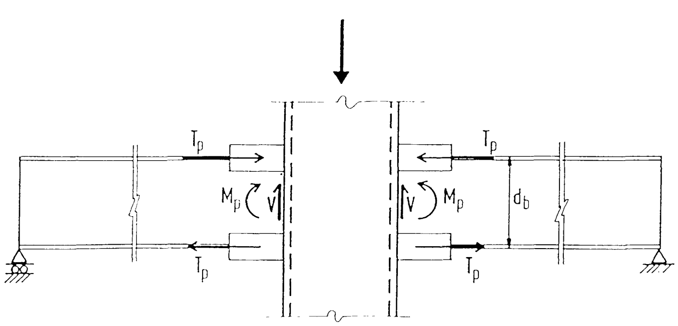

Fig. 5. Internal forces at connection under symmetrical load.

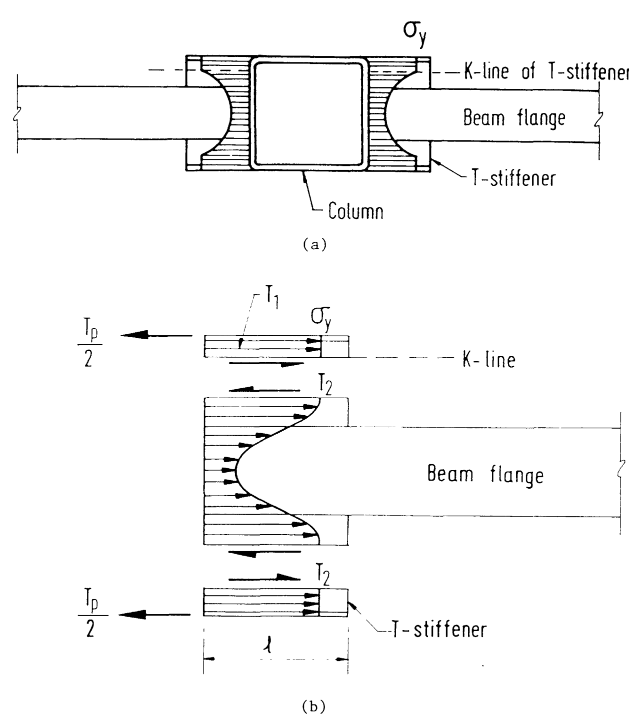

Fig. 6. Stress distribution at failure.

STANDARDIZED MOMENT-ROTATION FUNCTIONS

In the present study, a series of 15 M-ϕ curves has been generated for each of the two cases, namely, two-way and four-way connections using the finite-element method. These specimens cover the combination of full range of beams and box columns available in the section table.[22] The Ramberg-Osgood function was used to curve-fit the data. This function can be expressed in terms of moment, M, and rotation, ϕ, as follows:

$$\frac{\phi}{\phi_o} = \frac{M}{M_o}\left[1 + \left\{\frac{M}{M_o}\right\}^{(n-1)}\right] \tag{4}$$

where M_o, ϕ_o, and n are the independent parameters of the function. M_o and ϕ_o are the reference moment and rotation respectively, while n defines the sharpness of the curve. These independent parameters can be expressed in terms of the geometric properties of the connection as follows:

$$M_o = \prod_{i=1}^{m} p_i^{a_i} \tag{5}$$

$$\phi_o = \prod_{i=1}^{m} p_i^{b_i} \tag{6}$$

$$n = \prod_{i=1}^{m} p_i^{c_i} \tag{7}$$

where p_i represents the ith geometric parameter of the connection and a_i, b_i, and c_i are the exponents that indicate the effect of the ith geometric parameter; m is the number of geometric parameters considered. Taking the logarithms of both sides of the above equations, the Ramberg-Osgood parameters can be expressed as:

$$\log M_o = a_1 \log p_1 + a_2 \log p_2 + ... + a_m \log p_m \tag{8}$$

$$\log \phi_o = b_1 \log p_1 + b_2 \log p_2 + ... + b_m \log p_m \tag{9}$$

$$\log n = c_1 \log p_1 + c_2 \log p_2 + ... + c_m \log p_m \tag{10}$$

Multiple linear regression analysis was then carried out to determine the coefficients a, b, and c.

A total of six terms, representing the various geometries of the connection, has been used to determine the coefficients, and the relationships thus obtained are given as follows:

$$M_o = \alpha_M \left[\frac{B}{t_c}\right]^{-0.484} \left[\frac{b}{B}\right]^{-0.484} \left[\frac{h}{B}\right]^{1.085} [d_b]^{2.738} \left[\frac{t_{sf}}{t_c}\right]^{-0.640} \left[\frac{t_{sw}}{t_{bf}}\right]^{-0.899} \tag{11}$$

$$\phi_o = \alpha_\phi \left[\frac{B}{t_c}\right]^{0.928} \left[\frac{b}{B}\right]^{1.658} \left[\frac{h}{B}\right]^{-1.377} [d_b]^{-0.887} \left[\frac{t_{sf}}{t_c}\right]^{-0.236} \left[\frac{t_{sw}}{t_{bf}}\right]^{0.388} \tag{12}$$

$$n = \alpha_n \left[\frac{B}{t_c}\right]^{1.905} \left[\frac{b}{B}\right]^{-0.467} \left[\frac{h}{B}\right]^{-0.899} [d_b]^{0.222} \left[\frac{t_{sf}}{t_c}\right]^{-1.136} \left[\frac{t_{sw}}{t_{bf}}\right]^{0.254} \tag{13}$$

where

B = column width
b = beam flange width
t_c = column thickness
h = stiffener flange width
d_b = beam depth
t_{sf} = stiffener flange thickness
t_{sw} = stiffener web thickness
t_{bf} = beam flange thickness

$\alpha_M = 5.395 \times 10^{-6}$ and 5.935×10^{-6}, $\alpha_\phi = 0.0324$ and 0.0308 and $\alpha_n = 0.019$ and 0.0285 for the two-way and four-way connections respectively. All dimensions are in millimeters. Units for M and M_o are in kNm, ϕ and ϕ_o are in radians ,while the geometrical parameters were measured in millimeters.

Figure 8 shows the comparison between results obtained from the Ramberg-Osgood function by using the standardized connection parameters and the corresponding results from the finite element analysis. Curves for typical specimens (Example 1 in Appendix II) are shown for both the two-way and four-way connections. It can be seen that the correlation between the curves is very good. Similar observation has been made for all the other specimens.

Figures 9(a) and (b) show plots of normalized moment-rotation relationships for all the 15 specimens of two-way and four-way connections, respectively. It can be seen that almost all the curves in each case lie very close, except for two specimens. These two specimens, which are the same for both cases, consist of specimens with beam and column of extreme sizes obtained from the section table i.e., one specimen consists of the smallest column and very small beams while the other specimen consists of the largest column size with very large beams. It is suggested that a single curve, as shown in

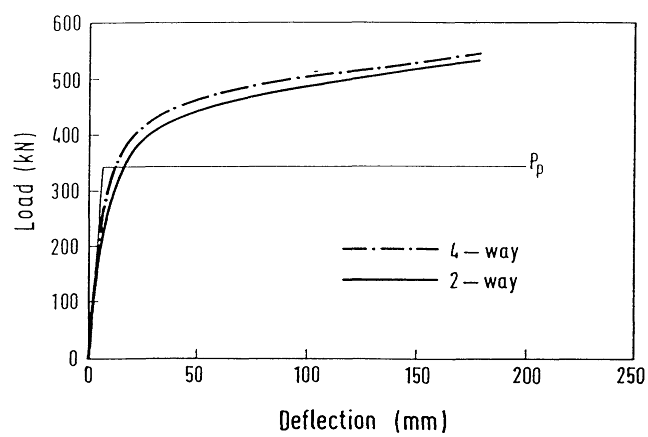

Fig. 7. Typical load-deflection curves for three-way and four-way connections.

the respective figures, can be used for the prediction of the moment-rotation characteristic of the connections between all beams and columns of practical dimensions.

EXPERIMENTAL VERIFICATION

An experimental investigation was carried out to study the behavior of a connection in which four I-beams frame into a box column. This is the typical connection which could occur at an interior column of a building. The connection was tested to failure, and strain and displacement measurements were made to obtain the stress distribution and moment-rotation characteristics. Details of the experimental program together with the results have been reported elsewhere.[23] For comparison, results from one of the specimens are shown here.

Figure 10 is typical specimen which was designed in accordance with the proposed method. It was supported at the ends of the four beams and subjected to a load applied vertically on the column until failure. Figures 11 and 12 show the load-deflection and the dimensionless moment-rotation curves, respectively. It can be seen that the initial stiffness of the connection is good and the ultimate strength capacity exceeds the plastic capacity of the beam. The large rotation capacity of the specimen also indicates that the connection is ductile. Good correlation is observed between the results from the experiment and the finite element method. Also, it can be seen that the fitted Ramberg-Osgood curve using the standardized moment-rotation function agrees with the experimental results.

CONCLUSIONS

A simple design procedure has been proposed to determine the size of the T-section to be used as the external stiffener for

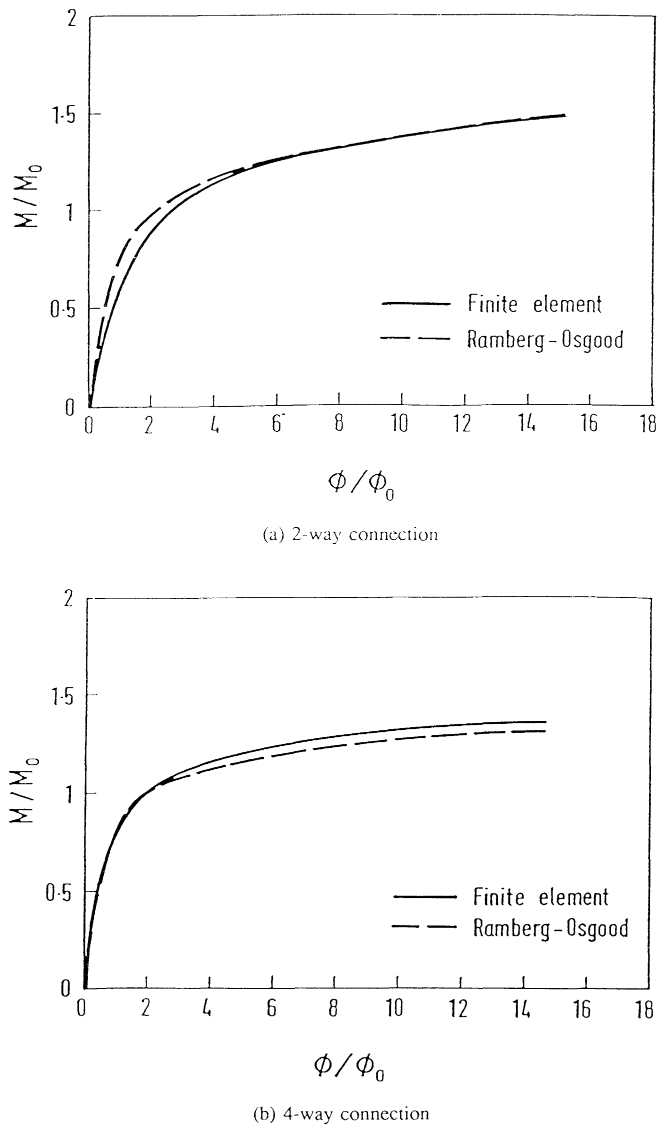

Fig. 8. Normalized moment-rotation curves for typical speciments.

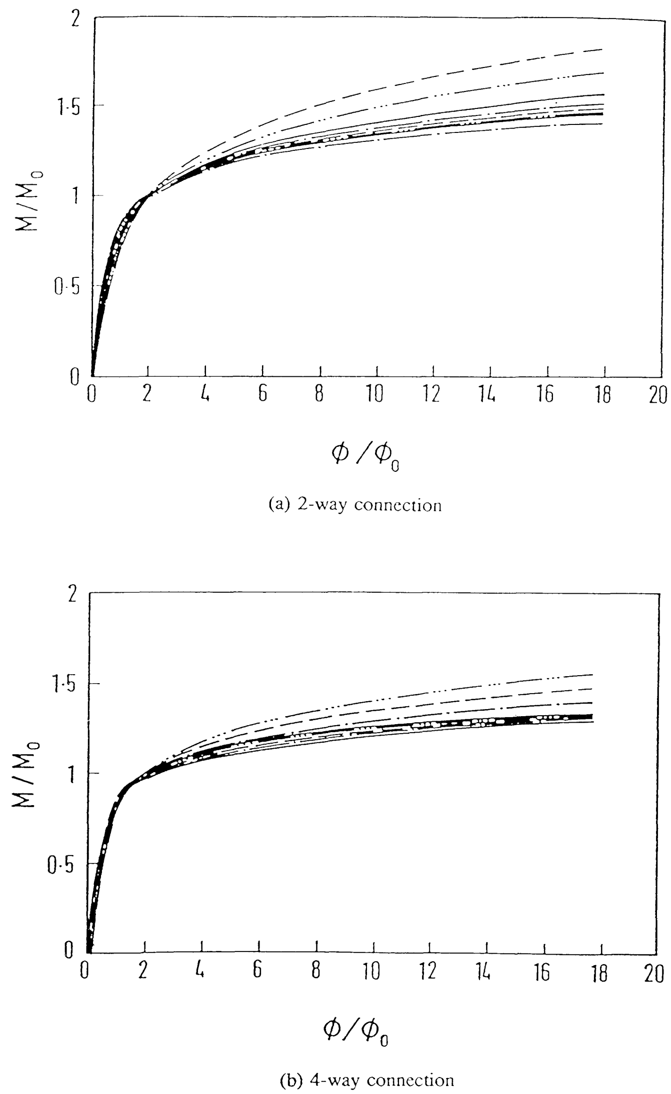

Fig. 9. Normalized moment-rotation curves for 15 specimens.

an I-beam to box-column connection. The design method is applicable for both the two-way and four-way connections. Results from connections, formed by a wide range of I-beams and box columns obtained from section tables, show the accuracy of the proposed design method.

It is common practice in modern design codes to propose a capacity reduction factor ϕ for ultimate-strength design. A similar factor may be adopted for the calculation of T_1 and T_2 to account for various uncertainties in the connection design and performance. A value of 0.9 given in the AISC-LRFD Specification for both shear and tension yield limit states may be used in this case also.

A curve-fitting procedure using the Ramberg-Osgood function has been used to obtain the moment rotation relationship for the connections. The independent parameters of the function was expressed in terms of the geometrical property of the connection. The curves obtained by using the fitted parameters compare well with those obtained from the finite-element analysis for all the specimens considered. Results indicate that a single moment-rotation curve can be used for the design of connections formed by a wide range of beam and column sections. Finally, both the design procedure and the Ramberg-Osgood function obtained have been found to agree well with experimental results. The results presented are with reference to two-way and four-way connections. Further research is in progress to study other types of configurations and to investigate the suitability of this connection for seismic design.

NOTATION

B	column width
M	moment imposed on the connection
M_o	reference moment
M_p	plastic moment of beam
T_p	beam-flange force corresponding to plastic moment of beam
a_i, b_i, c_i	exponents indicating effect of ith geometric parameter
b	beam flange width
d_b	beam depth
h	stiffener flange width
l	stiffener length
m	number of geometric parameters considered
n	"sharpness" of Ramberg-Osgood curve
p_i	ith geometric parameter of connection
t_{bf}	beam flange thickness
t_c	column wall thickness
t_{sf}	stiffener flange thickness
t_{sw}	stiffener web thickness
ϕ	rotation at the connection
ϕ_o	reference rotation

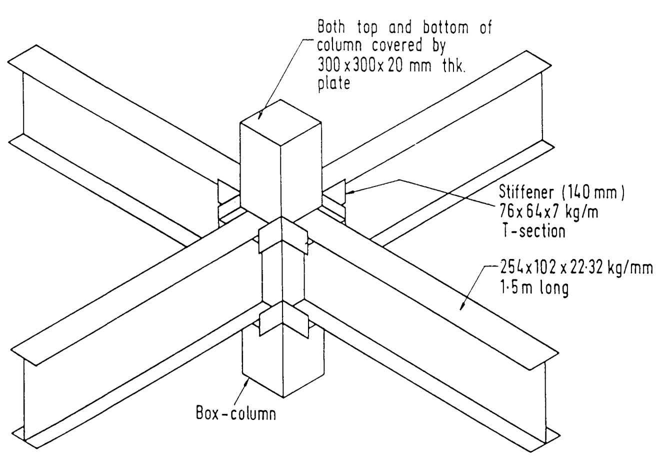

Fig. 10. 4-way connection test specimen.

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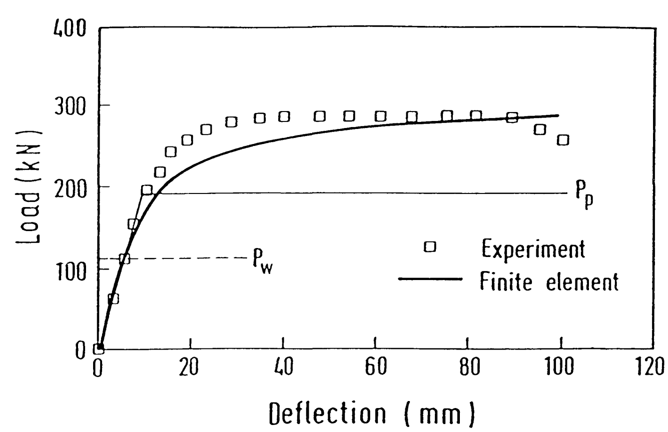

Fig. 11. Load-deflection curve for 4-way test specimen.

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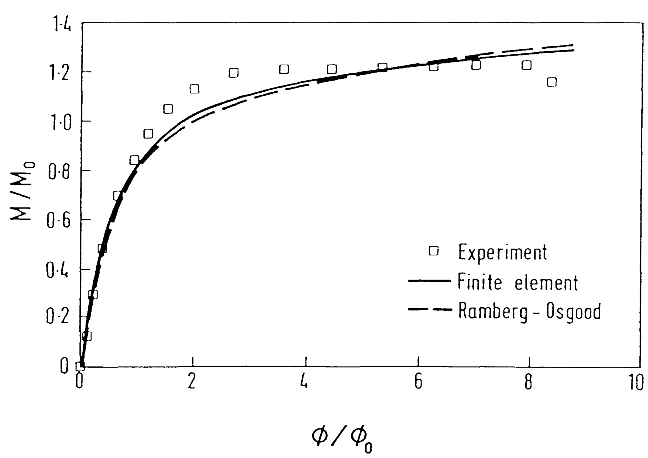

Fig. 12. Moment-rotation curve for four-way test specimen.

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APPENDIX II—DESIGN EXAMPLES

Design examples to determine the size of the T-section which can be used as the external stiffener for I-beam to box-column connections. Example 1 illustrates the case when the stiffener length is governed by the angle $\theta = 2°$ while Example 2 illustrates the case when the length is governed by the shear capacity of the stiffener web.

Example 1

Column size: 200×200×16 mm

Beam size: 305×165×40 kg/m

Grade 43 steel is assumed for column, beam, and stiffeners.

1. Choose a T- or I-section with a web thickness of at least half the beam-flange thickness.

Try T-section 102×102×12 kg/m

2. For $\theta = 20°$, stiffener length $l = (200 - 165) / (2 \times \tan 20°) = 50$ mm (2 in.)
3. Check minimum stiffener length based on strength criteria.

   Plastic moment capacity of the beam,

M_p = 275 × 624,000 Nmm
= 172 kNm (126.9 kip-ft)
T_p = 172 / 0.304 = 584 kN (131.3 kips)
T_1 = (101.6 × 9.3 + 7.6 × 5.2)0.275 = 281 kN (63.2 kips)
T_2 = $0.5T_p - T_1$ = 11 kN (2.47 kips)

The allowable shear stress according to von Mises yield criteria,

τ_y = 275 / 1.732 = 159 N/mm^2 (23.1 ksi)

From Equation 1

$T_p / 2 = T_1 + T_2$

Therefore, the minimum length is

l = 11,000 / (159 × 5.2) = 14 mm (0.55 in.)

4. From Steps 2 and 3, the longer length is chosen.

Therefore, use section 102×102×12 kg/m of length 50 mm (2 in.) as the external stiffener.

Example 2

Column size: 250×250×16 mm

Beam size: 457×191×67 kg/m

Grade 43 steel is assumed for column, beam, and stiffeners.

1. Choose a T- or I-section with a web thickness of at least half the beam-flange thickness. Try T-section 102×127×14 kg/m
2. For θ = 20°, stiffener length l = (250 − 191) / (2 × tan 20°) = 83 mm (3.27 in.)
3. Check minimum stiffener length based on strength criteria. Plastic moment capacity of the beam,

M_p = 275 × 1,470,000 Nmm
= 404 kNm (298 kip-ft)
T_p = 404 / 0.441 = 916 kN (205.9 kips)
T_1 = (102.1 × 10 + 7.6 × 6.4) = 294 kN (66.1 kips)
T_2 = $0.5T_p - T_1$ = 164 kN (36.9 kips)

The allowable shear stress according to von Mises yield criteria,

τ_y = 275 / 1.732 = 159 N/mm^2 (23.1 ksi)

Therefore, the minimum length

l = 164,000 / (159 × 6.4) = 161 mm (6.34 in.)

4. From Steps 2 and 3, the longer length is chosen.

Therefore, use section 102×127×14 kg/m of length 161 mm (6.34 in.) as the external stiffener.