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Comparative Study on Distortional Buckling Strength of Cold-Formed Steel Lipped Channel Sections

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Abstract

Usage of cold formed steel structural components for buildings and structures is gaining popularity in India for a decade. Hot rolled steel member behaviour and design are well developed, whereas the cold formed steel member behaviour and design is not developed fully compared to the rest of the world. The Indian code for cold-formed steel design, IS 801 was revised during 1975, which is in line with 1968 edition of AISI standard. Bureau of Indian standards is in the process of revision of IS 801 to catch up with the latest developments and design methods with the other codes of practices in the world. As a background for the development of codal provisions, the design provisions developed in the various codes of practices have been reviewed and a comparative study has been carried out on design flexural strength of cold formed steel lipped channel sections. For this purpose, experimental results are collected from the literature. Based on the comparative study, direct strength method (DSM), which gives flexural strength closer to experimental results has been chosen for further parametric studies. There are several failure modes among which distortional buckling is one such failure mode that affects the strength of the section. In order to assess the influence of distortional buckling, a parametric study has been conducted by varying the lip depth, which is the influencing factor for distortional buckling strength. This paper presents the details of the studies carried out and the conclusions arrived.

Keywords: Cold-formed steel, Lipped channel, Direct strength method, Distortional buckling.

Introduction

Two types of structural steel members are being used, namely hot rolled steel and cold formed steel. Use of cold formed steel for buildings and structures is gaining popularity in India for a decade. Hot rolled steel member design and behaviour are well developed, whereas the cold formed steel member behaviour and design is not developed fully compared to the rest of the world. Of the various CFS members and sections, lipped channel sections are used as purlins, beams and columns. Different buckling modes are occurring in the lipped channel beams and columns. The failure modes are local buckling, distortional buckling, overall buckling and their interactions. Distortional buckling is the highly influencing mode on the section strength. A review has been conducted on the latest works carried out on distortional buckling.

The elastic post-buckling behaviour of cold-formed steel lipped channel simply supported columns is generally affected by mode interaction phenomena involving distortional buckling, local/distortional buckling, distortional/global buckling and local/distortional/global mode interaction. A finite element investigation was carried out on the elastic post-buckling behaviour of simply supported cold-formed steel lipped channel columns. It was concluded that the columns analysed were affected by interaction between local, symmetric distortional and flexural-torsional-distortional modes[1]. A closed-form solution for distortional buckling mode of cold-formed channel sections subjected to combined compression and bi-axial bending was presented[2]. It was concluded that the numerical results from the closed form solution matched closely with the finite strip results. It was also concluded that by including shear and distortion effects of flange the accuracy of this solution can be improved.

The distortional buckling of castellated beams through testing the simply supported beam under central concentric load were discussed[3]. The test setup was prepared in such a way that lateral-distortional and restrained distortional modes of instability were expected to occur. It was reported that all the test beams underwent lateral buckling accompanied by web distortion. Web distortion was observed and demonstrated through experimentally obtained load-deflection and load-strain curves. As a result of which the occurrence of lateral distortional mode of bucking was confirmed. The application of the direct strength method to calculate the distortional buckling strength of cold-formed thin wall steel members with uniform and non-uniform elevated temperature distributions in the cross sections were assessed[4]. Based on the numerical analysis results, it was concluded that the direct strength method (DSM) equation in AISI standards[5] is directly applicable for uniform temperature applications. A new distortional buckling curve for cross-sections with non-uniform temperature distributions was proposed. A non-linear finite element model by using ABAQUS FEA software was developed and verified against the flexural tests conducted on cold-formed steel C-section beams[6]. It was reported that DSM gives a reasonable strength prediction for both distortional buckling and local buckling failures of C-section beams and was concluded that the DSM predicts the increased strength due to moment gradient in distortional buckling.

From the literature review, it is found that distortional buckling affects the flexural strength of the section by interaction of other modes of buckling. Though sufficient work and design methods have been reported in the literature, a study has been conducted to understand the distortional buckling and their influence. As a background for the development of codal provisions, the design provisions developed in the various codes of practices have been reviewed and a comparative study has been carried out on design strength of cold formed lipped channel beams. Experimental results are used as the bench mark for comparison.

Review of Codal Provisions: The following codes of practices are studied to know how these limit states are handled: i. AISI Standard – North American specification for the design of cold formed steel structural members. ii. BS 5950-5:1998[7]. iii. IS 801 – Code of practice for use of cold formed light gauge steel structural members in general building construction[8]. iv. Eurocode 3 (EN 1993-1-3:2004)[9]. v. Direct Strength method of design AS/NZS 4600 – 2005 Australian/New Zealand standard[10]

North American Specification for the Design of Cold Formed Steel Structural Members, 2001 Edition: This code gives the following guidelines for evaluating the design strength of the flexural member. i. Maximum width to thickness of a stiffened compression element stiffened by simple lip is limited to 60. ii. Maximum depth to thickness of the web is limited to 200

Effective width of compression element with edge stiffener: Calculate $S = 1.28\sqrt{(\frac{E}{fy})}$ based on the assumption that initial yielding starts at compression flange, where E is the modulus of elasticity and fy is the yield strength of the material

Case 1: If w/t of the element is less than or equal to 0.328S, edge stiffener may not be required and effective width equals the flat width of the element, and also if edge stiffener is provided, the effective depth is calculated as follows:
$d'_s = d$, when $\lambda \le 0.673$
$d'_s = \rho\, d$, when $\lambda > 0.673$, where $\lambda = \sqrt{(\frac{fy}{fcr})}$ and $\rho = (1 - \frac{0.22}{\lambda})\lambda$

Case 2: If w/t of the compression element is greater than 0.328 S
Effective width of the edge stiffener side and $b2 = b - b1$
Effective depth of edge stiffener $ds = d's(\frac{Is}{Ia})$
where I_s - moment of inertia of the full section of the stiffener

$$I_a = 399t^4[\frac{\frac{w}{t}}{S} - 0.328]^3 \le t^4\left[115\frac{\frac{w}{t}}{S} + 5\right], I_s/I_a \le 1$$

K value has to be calculated as below based upon the ratio between depth of stiffener and flat width of compression element
If $\frac{D}{w} \le 0.25, k = 3.57(\frac{I_s}{I_a})^n + 0.43 \le 4$
If D/w is between 0.25 and 0.8 $k = \left(4.82 - \frac{5D}{w}\right)(\frac{I_s}{I_a})^n + 0.43 \le 4$
$n = [0.582 - \frac{\frac{w}{t}}{4S}] \ge \frac{1}{3}$

Effective width of web: The web is under stress gradient on which the k value depends and is given by the following expression. Figure-1 shows the section details and variables for the calculation of effective width of web.

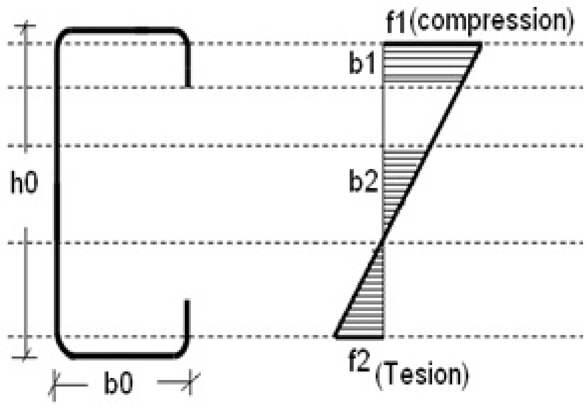

Figure-1
Effective width calculation of web

$k = 4 + 2(1+\psi)^3 + 2(1+\psi)$ where $\psi = \left|\frac{f_2}{f_1}\right|$
Case 1: for $\frac{h_0}{b_0} \le 4$
$b1 = \frac{b_e}{3+\psi}$; $b2 = \frac{b_e}{2}$ when $\psi > 0.236$ and $b2 = b_e - b1$,when ψ is less than or equal to 0.236

Case 2: for $\frac{h_0}{b_0} > 4$
$b1 = \frac{b_e}{3+\psi}$; $b2 = \frac{b_e}{1+\psi} - b1$, where h_0 and b_0 is the overall depth and width of the channel

BS 5950-Part5:1998: The moment capacity of the cross-section is,
$M_c = P_0 \times Z_c$
where,
P_0 = Maximum compressive stress on the section
$= \left\{1.13 - 0.0019\frac{D}{t}\left(\frac{Y_s}{280}\right)^{0.5}\right\}p_y$
D = Depth/width of the element

Py = Yield stress
Z_c = Compression section modulus of the effective cross-section

The effective width calculation is a power law in the BS: 5950. The code provides curves for determining the value of buckling coefficient 'k' using the value of "$h=b_f/b_w$".

For stiffened element: $\frac{b_{eff}}{b} = [1 + 14(\sqrt[4]{\frac{f}{p_{cr}} - 0.35}\ ]^{-0.2}$

p_{cr} =185000 k (t / b)^2 (critical buckling stress of the plate element)

f = Compressive stress in the plate element

For unstiffened element: Determine the effective width, b_{eff}, as for a stiffened element but using the buckling co-efficient applicable to the unstiffened element. This is then converted to an enhanced effective width for an unstiffened element using the following equation

$b_{eu} = 0.89b_{eff}+0.11b$

IS 801 Code of practice for use of cold formed light gauge steel structural members in general building construction: Effective width calculation of compression elements

Flange is fully effective if $\frac{w}{t} \le (\frac{w}{t})_{lim}$

If $\frac{w}{t} > (\frac{w}{t})_{lim}$, effective width can be calculated from

$$\frac{b}{t} = \frac{2120}{\sqrt{f}}\ (1 - \frac{465}{\frac{w}{t}\sqrt{f}})$$

Where, w – flat width of the compression element, t – Thickness of the element, b – Effective width of the element, f – Basic design stress,

$$(\frac{w}{t})_{lim} = \frac{1435}{\sqrt{f}}$$

The required minimum depth of the lip should be

$$d_{min} = 2.8t\sqrt{(\frac{w}{t})^2 - \frac{281200}{fy}} > 4.8t$$

Direct Strength Method (AS/NZS 4600:2005): In this method of design, provisions are given only for nominal strength of axial compression and moment capacity only for prequalified sections

Moment capacity of channel sections: This does not require effective width calculation; instead it considers the buckling interactions such as lateral torsional buckling, local buckling and distortional buckling. Minimum of the moment values for the above buckling mode governs the member strength

Nominal moment capacity by lateral torsional buckling (M_{be})

$M_{be} = M_0$ for $M_0<0.56M_y$

$M_{be} = \frac{10}{9}\ M_y\ (1 - \frac{10M_y}{36M_0})$ for $2.78M_y \ge\ M_0 \ge 0.56M_y$

$M_{be} = M_y$ for $M_0>2.78M_y$

Where: M_0 = elastic lateral torsional buckling moment, Refer Figure-2 for the sectional details.

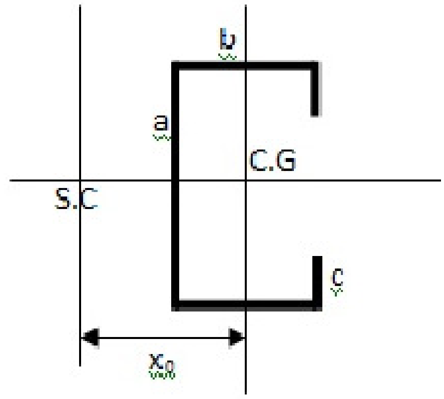

Figure-2
2 Torsional Buckling moment (Sectional details)

$M_0 =\ C_b A r_{01}\sqrt{f_{oy} f_{oz}}$

A – Area of full cross section

$r_{01} =\ \sqrt{r_x^2 + r_y^2 + x_0^2 + y_0^2}$

r_x, r_y - radius of gyration with respect to x and y axes of the cross section

x_0,y_0 – coordinates of shear centre

$x_0 = \frac{bt(b+2c)}{A} + \frac{bt}{12I_x}(6ca^2 + 3ab^2 - 8c^3), y_0 = 0$

$f_{oy} =\ \pi^2 E/(\frac{l_{ey}}{r_y})^2;\ f_{oz} = GJ/Ar_{01}^2(1 + \frac{\pi^2 E i_w}{GJ l_{ez}^2})$

l_{ey}, l_{ez} = effective lengths about y axis and for torsion
G = Shear modulus
J = Torsion constant

I_w = Warping constant
$= \frac{b^2 t}{6}\ (4c^3 + 6ac^2 + 3a^2c + a^2b)m^2 I_x;\qquad m = \frac{a^2b^2t}{I_x}(\frac{1}{4} + \frac{c}{2b}\frac{2c^3}{3a^2b})$

Local buckling (M_{bl})

$M_{bl} = M_{be}$ for $\lambda_l \le 0.776$

$M_{b1} = \left[1 - 0.15\left(\frac{Mol}{Mbe}\right)^{0.4}\right](\frac{Mol}{Mbe})^{0.4}M_{be}$ for $\lambda_l > 0.776$

λ_1 = Non dimensional slenderness
$= \sqrt{(\frac{M_{be}}{M_{ol}})}$

M_{ol} = Elastic local buckling moment
$= Z_f\ f_{ol}$

f_{ol} = local buckling stress which is obtained from CUFSM software for each cross section

Distortional buckling moment (Mbd)

Mbd = My for $\lambda_d \leq 0.673$

$M_{bd} = \left[1 - 0.22\left(\frac{Mod}{My}\right)^{0.5}\right]\left(\frac{Mod}{My}\right)^{0.5} My$ for $\lambda_d > 0.673$

λ_d = Non dimensional slenderness

$= \sqrt{\left(\frac{My}{Mod}\right)}$

M_{od} = Elastic local buckling moment

$= Z_f f_{od}$

f_{od} = distortional buckling stress which is obtained from CUFSM software for each cross section

Euro code 3 (EN 1993-1-3:2006): Effective width of compression flange

Stress ratio Ψ=1

The buckling factor, K_σ corresponding to the stress ratio and boundary condition is given in EN 1993-1-5:2006, Table 4.1 or Table 4.2 as appropriate;

The plate slenderness $\overline{\lambda_p}$ is given by:

$\overline{\lambda_p} = \frac{b_p/t}{28.4\epsilon\sqrt{K_\sigma}}$; Where $\epsilon = \sqrt{\frac{235}{f_y}}$

The reduction factor for plate buckling in internal compression elements is given by:

$\rho = 1$ for $\overline{\lambda_p} \leq 0.673$

$\rho = \frac{\bar{\lambda}_p - 0.055(3+\psi)}{\bar{\lambda}_p{}^2}$ for $\overline{\lambda_p} > 0.673$

Effective width of flange = $b_{eff} = \rho w$

Effective width of lip: Width of flange = b_p

Lip depth = $b_{p,c}$

The buckling factor k_σ is obtained from Cl 5.5.3.2 of EN 1993-1-3: 2006

If $\frac{b_{p,c}}{b_p} \leq 0.35$ then k_σ= 0.5

If $0.35 < \frac{b_{p,c}}{b_p} \leq 0.6$ then k_σ= 0.5 + $0.83\sqrt[3]{(b_{p,c}/b_p - 0.35)^2}$

The plate slenderness $\overline{\lambda_p}$ is given by: $\overline{\lambda_p} = \frac{b_{p,c}/t}{28.4\epsilon\sqrt{K_\sigma}}$

The reduction factor for plate buckling in outstand compression elements is given by:

$\rho = 1$ for $\overline{\lambda_p} \leq 0.748$; $\rho = \frac{\bar{\lambda}_p - 0.188}{\bar{\lambda}_p{}^2}$ for $\overline{\lambda_p} > 0.748$

∴ Effective width of lip = $\rho b_{p,c}$ from Cl 5.5.3.2 of EN 1993-1-3: 2006

Effective width of web: The effective width of web has to be determined with number of iterations

Stress ratio $\psi = \frac{h_c}{hp - hc}$

The buckling factor, K_σ is obtained from EN 1993-1-5:2006, Table 4.1 as appropriate;

K_σ=23.9 for $\psi = -1$

$\overline{\lambda_p} = \frac{d/t}{28.4\epsilon\sqrt{K_\sigma}}$

The reduction factor for plate buckling in internal compression elements is given by:

$\rho = 1$ for $\overline{\lambda_p} \leq 0.673$

$\rho = \frac{\bar{\lambda}_p - 0.055(3+\psi)}{\bar{\lambda}_p{}^2}$ for $\overline{\lambda_p} > 0.673$

From table 4.1 for internal compression elements and $\psi = -1$

$b_{eff} = \rho\, d/(1-\psi)$

Reduction factor for distortional buckling: Elastic critical buckling stress of the stiffener, $\sigma_{cr,s} = \frac{2\sqrt{KEI_s}}{A_s}$ from Cl 5.5.3 EN 1993-1-3:2006

Spring stiffness, K = $\frac{Et^3}{4(1-\nu^2)} \times \frac{1}{b_1{}^2 h_p + b_1{}^3 + 0.5 b_1 b_2 h_p k_f}$

$k_f = 0$, for bending about z-z axis

Effective second moment of Inertia, I_s

$I_s = \frac{b_{e2}t^3}{12} + \frac{C_{eff}t^3}{12} + b_{e2}t\left(C_{eff} - X_{aa}\right)^2 + C_{eff}t\left(X_{aa} - 0.5Ceff2\right.$

where $b_1 = b_p - Y_{bb}$

X_{aa} , Y_{bb} is the centroid of flange-lip assembly

Effective area of effective flange-lip assembly

$A_s = t\left(b_{e2} + C_{eff}\right)$

$\sigma_{cr,s} = \frac{2\sqrt{KEI_s}}{A_s}$

$\bar{\lambda}_d = \sqrt{f_y/\sigma_{cr,s}}$ from Cl 5.5.3.1(7) of EN 1993-1-3:2006

The Reduction factor, χ_d for the distortional buckling is obtained from the relative slenderness, $\bar{\lambda}_d$

$\chi_d = 1$ if $\bar{\lambda}_d \leq 0.65$

$\chi_d = 1.47 - 0.723\bar{\lambda}_d$ if $0.65 < \bar{\lambda}_d < 1.38$

$\chi_d = \frac{0.66}{\bar{\lambda}_d}$ if $\bar{\lambda}_d \geq 1.38$

Reduced thickness, $t_{red} = \chi_d t$

Discussion on Codal Provisions: From the review of codal provisions, it is found that all the codes use effective width method as the main criteria. However, direct strength method of design utilizes the full section properties. The distortional mode of buckling is incorporated in DSM and Eurocode only. With the existence of differences in codes of practices, a comparative study has been conducted on the flexural strength of the lipped channel section calculated by using different codes of practices and compared with respective experimental results[11].

Experimental Results: A series of tests were conducted at Cornell University on lipped channel flexural members[11]. To obtain pure flexure, tests were conducted on identical specimens. All specimen dimensions were nearly identical except for the lip length. The yield strength of specimen is taken based on the tensile coupon results. Tests were carried out in a vacuum chamber which allows uniform loading on two beams at once.

Table-1
Specimen details

No	H, in	B, in	t, in	R, in	D,in	Fy, ksi	E, ksi	M, kip-in
Specimen 1	8.547	2.415	0.071	0.188	1.222	57.600	29500	124
Specimen 2	8.550	2.450	0.071	0.188	1.124	56.900	29500	106
Specimen 3	8.633	2.462	0.071	0.188	1.130	63.500	29500	127
Specimen 4	8.538	2.473	0.071	0.188	0.981	57.500	29500	117
Specimen 5	8.549	2.479	0.071	0.188	0.982	58.700	29500	104
Specimen 6	8.641	2.488	0.071	0.188	0.950	61.600	29500	124
Specimen 7	8.558	2.450	0.069	0.188	0.879	59.900	29500	138
Specimen 8	8.554	2.445	0.073	0.188	0.867	57.800	29500	116
Specimen 9	8.613	2.472	0.071	0.188	0.878	62.700	29500	133

Table-2
Design strength of beams for various codes

Details		Moment capacity predictions, Kip-in				
	AISI	IS 801	DSM	British	Eurocode	Test Result
Specimen 1	139.51	155.44	125.07	131.81	136.91	123.76
Specimen 2	142.17	153.02	123.59	129.79	134.30	105.75
Specimen 3	156.33	173.68	134.29	143.68	152.27	127.38
Specimen 4	145.53	152.26	123.16	128.68	133.91	117.13
Specimen 5	146.8	155.95	124.54	131.20	137.06	103.77
Specimen 6	148.86	165.69	129.73	137.51	145.73	123.94
Specimen 7	132.57	151.79	117.74	125.72	133.75	138.02
Specimen 8	139.89	153.97	123.01	131.24	136.50	116.00
Specimen 9	142.33	165.54	127.51	137.02	145.95	132.64

All the specimens were tested under uniformly distributed load. The web was restrained at the ends and lateral bracings are provided for compression flange at sufficient intervals. At the top of flange-web intersection from a stationary point outside the vacuum box the vertical deflections were measured and at the bottom web-flange interaction horizontal deflections were measured. From the mid-height of the web rotations were measured. The details of the specimens are given in table-1.

Results and Discussion

Design strength of each cross section is calculated by using the provisions given in all codes. The strength predictions are presented in Table-2 and the results are compared with the corresponding experimental results.

For easy comparison the values predicted by various codes are normalized with experimental values and plotted in graph as shown in Figure-3. From the graph it is found that, IS 801 over predicts the strength by about 30% due to the neglection of distortional mode of buckling and DSM closely matches with the experimental results. The DSM variation is about 4%. British code also has good correlation with experimental values. With this it can be concluded that Direct Strength Method of Design may be considered for possible incorporation in the IS 801 revision.

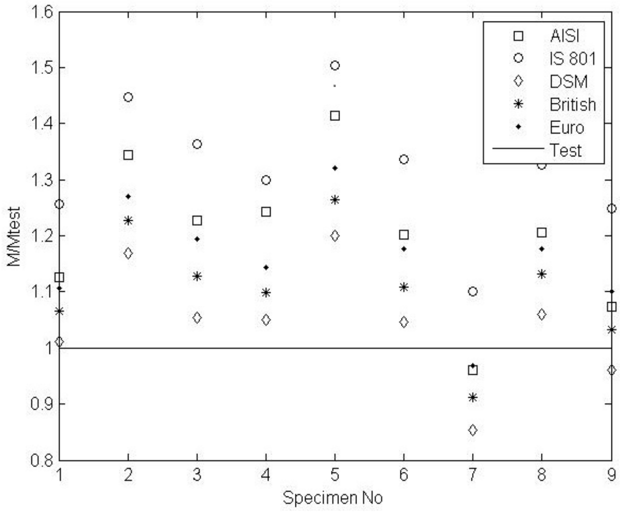

Figure-3
Comparison of code results with experimental results

As the DSM, which uses the load factors corresponding to different buckling modes and their interactions, predicts the flexural strength of the lipped channel section closer to the experimental results, parametric study has been conducted on distortional buckling strength of the cross-section by varying the lip depth for selected specimens. Each sections has been analysed by using CUFSM software, which is freely available software and used to get the strength of the cross-sections in different buckling modes. In the present investigation, influence of lip-depth has been studied for better understanding of the behaviour[12].

From the figure-4, it is found that the load factor for distortional buckling is increasing when the ratio of lip depth to flange width increases. However, the distortional buckling load factor starts to decrease when the ratio 0.7 and above.

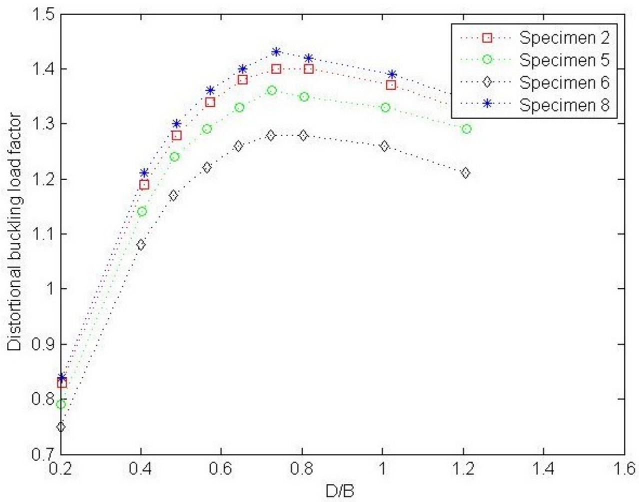

Figure-4
Distortional buckling load factor for the specimens

Conclusion

Review of codal provisions on flexural strength of lipped channel section has been carried out. A comparative study has been conducted on the flexural strength of lipped channel sections based on different code provisions and the values are compared with respective experimental values. With the comparative study, parametric study has been conducted by varying the lip depth for selected sections through CUFSM analysis, which is the background analysis for DSM. The load factor corresponds to distortional buckling for each cross-sectional shape has been calculated. Based on the studies, the following conclusions are arrived. i. All codes adopt effective width method of design as the main provision. ii. IS: 801 provisions are not accounting for distortional buckling and hence it over predicts the strength. iii. Direct strength method predicts the section strength closer to the experimental results. iv. Load factor corresponds to distortional buckling increases up-to the ratio of lip depth to flange width and later it decreases.

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