ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 16, NO. 7 (2015)
PAGES 919-931

STUDY ON COLD-FORMED STEEL BUILT-UP SQUARE SECTIONS WITH INTERMEDIATE FLANGE AND WEB STIFFENERS

G. Aruna[1*], S. Sukumar[2] and V. Karthika[1]
[1]Department of Civil Engineering, K.S.R College of Engineering, Tamilnadu, India
[2]Department of Civil Engineering, Government College of Engineering, Tamilnadu, India

Received: 15 February 2015; **Accepted:** 22 May 2015

ABSTRACT

This paper describes a series of experiments conducted on cold-formed built-up square sections with intermediate flange and web stiffeners under axial compression with hinged end conditions. The specimens were formed using angle sections with edge, intermediate flange and web stiffeners connected by self- tapping screws. 27 columns were tested by varying the cross section dimensions of the specimen. The column lengths of the specimens varied from 840 mm to 2240 mm. Tensile coupon tests were conducted to find the material properties of the sections. Local buckling, distortional buckling, flexural buckling and interaction of these buckling were observed during the test. The column strengths obtained from the experiments were compared with the design strength calculated using direct strength method (DSM) in the North American Specification for cold-formed steel structures. The reliability of the DSM method was evaluated using reliability analysis. It is shown that, strengths calculated by using direct strength method are reliable and slightly unconservative. Finally, a design recommendation was proposed for DSM to calculate the ultimate strength of cold formed built-up square sections with intermediate flange and web stiffeners.

Keywords: Cold-formed steel; column; direct strength method; distortional buckling; flexural buckling; local buckling.

1. INTRODUCTION

Built-up closed sections formed by connecting the channel sections toe to toe are commonly used in cold-formed steel construction due to their relatively larger torsional stiffness and favourable radius of gyration [1] as compared with open sections. When the width to-thickness ratio of a stiffened compression element is relatively large, local buckling will

*E-mail address of the corresponding author: aarunasree@gmail.com (G. Aruna)

reduce the full strength of the member [2]. However, local buckling stress could be enhanced by adding intermediate web stiffeners [3]. In this study, the cold-formed steel built-up square sections with intermediate flange and web stiffeners are investigated.

Limited research is carried out on cold-formed built-up closed sections in the past years. Young and Ju Chen [3] carried out a series of column tests on cold-formed steel built-up closed sections with intermediate stiffeners. Jessica Whittle and Chris Ramseyer [4] investigated the buckling capacities of axially loaded, cold formed built-up C channels. The Evaluation of the slenderness ratio in built-up cold-formed box sections was investigated by Wilson Reyes and Andres Guzmanc [5]. Design of built-up cold-formed steel columns according to the direct strength method was presented by Georgieva et al. [6]. Experimental and Numerical investigation was carried out on built-up- Z members under bending and compression by Iveta Georgieva et al. [7]. There are not many test data reported on cold-formed steel square sections with intermediate flange and web stiffeners.

In this paper, explains a series of experiments conducted on cold-formed steel built-up square sections with intermediate flange and web stiffeners. The column strengths obtained from the experiments were compared with the design strength calculated using direct strength method in the North American Specification for cold-formed steel structures. The reliability analysis was carried out to assess the reliability of the DSM. And also a design recommendation was proposed to calculate the ultimate strength of cold-formed steel built-up square sections with intermediate flange and web stiffeners.

2. EXPERIMENTAL INVESTIGATION

2.1 Specimens

The built-up square sections (BSS) were formed by connecting two angle sections with edge, intermediate flange and web stiffeners using self- tapping screws. Typical cross-section of angle section and built-up section are shown in Fig.1 and Fig.2 respectively. The screws are placed at a nominal spacing of 200 mm and minimum edge distance of 20 mm, as shown in Fig. 3. The nominal dimensions of cross section and length of the specimens are presented in Table 1.

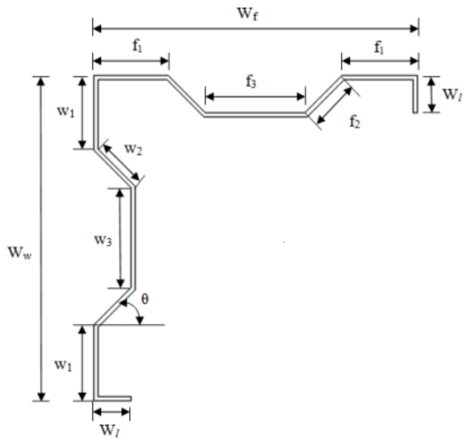

Figure 1. Definition for dimensions of angle section

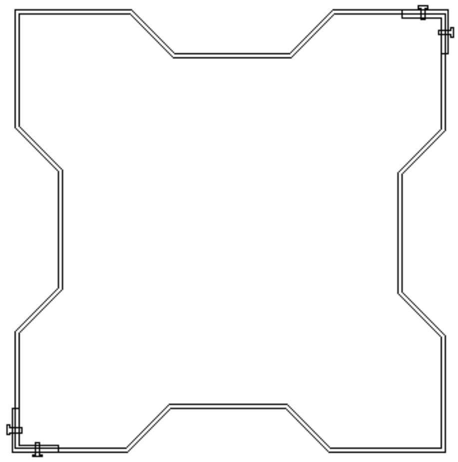

Figure 2. Cross section of built-up square section

Table 1: Nominal dimensions of cross section

Specimen ID	Flange				Web				Lip	Angle	Thickness	Length
	W_f (mm)	f_1 (mm)	f_2 (mm)	f_3 (mm)	W_w (mm)	w_1 (mm)	w_2 (mm)	w_3 (mm)	W_l (mm)	υ (deg)	T (mm)	L (mm)
TB30-IS40-840	130	30	21.2	40	130	30	21.2	40	15	45	1.6	840
TB30-IS40-1640	130	30	21.2	40	130	30	21.2	40	15	45	1.6	1640
TB30-IS40-2240	130	30	21.2	40	130	30	21.2	40	15	45	1.6	2240
TB30-IS50-840	140	30	21.2	50	140	30	21.2	50	15	45	1.6	840
TB30-IS50-1640	140	30	21.2	50	140	30	21.2	50	15	45	1.6	1640
TB30-IS50-2240	140	30	21.2	50	140	30	21.2	50	15	45	1.6	2240
TB30-IS60-840	150	30	21.2	60	150	30	21.2	60	15	45	1.6	840
TB30-IS60-1640	150	30	21.2	60	150	30	21.2	60	15	45	1.6	1640
TB30-IS60-2240	150	30	21.2	60	150	30	21.2	60	15	45	1.6	2240
TB40-IS40-840	150	40	21.2	40	150	40	21.2	40	15	45	1.6	840
TB40-IS40-1640	150	40	21.2	40	150	40	21.2	40	15	45	1.6	1640
TB40-IS40-2240	150	40	21.2	40	150	40	21.2	40	15	45	1.6	2240
TB40-IS50-840	160	40	21.2	50	160	40	21.2	50	15	45	1.6	840
TB40-IS50-1640	160	40	21.2	50	160	40	21.2	50	15	45	1.6	1640
TB40-IS50-2240	160	40	21.2	50	160	40	21.2	50	15	45	1.6	2240
TB40-IS60-840	170	40	21.2	60	170	40	21.2	60	15	45	1.6	840
TB40-IS60-1640	170	40	21.2	60	170	40	21.2	60	15	45	1.6	1640
TB40-IS60-2240	170	40	21.2	60	170	40	21.2	60	15	45	1.6	2240
TB50-IS40-840	170	50	21.2	40	170	50	21.2	40	15	45	1.6	840
TB50-IS40-1640	170	50	21.2	40	170	50	21.2	40	15	45	1.6	1640
TB50-IS40-2240	170	50	21.2	40	170	50	21.2	40	15	45	1.6	2240
TB50-IS50-840	180	50	21.2	50	180	50	21.2	50	15	45	1.6	840
TB50-IS50-1640	180	50	21.2	50	180	50	21.2	50	15	45	1.6	1640
TB50-IS50-2240	180	50	21.2	50	180	50	21.2	50	15	45	1.6	2240
TB50-IS60-840	190	50	21.2	60	190	50	21.2	60	15	45	1.6	840
TB50-IS60-1640	190	50	21.2	60	190	50	21.2	60	15	45	1.6	1640
TB50-IS60-2240	190	50	21.2	60	190	50	21.2	60	15	45	1.6	2240

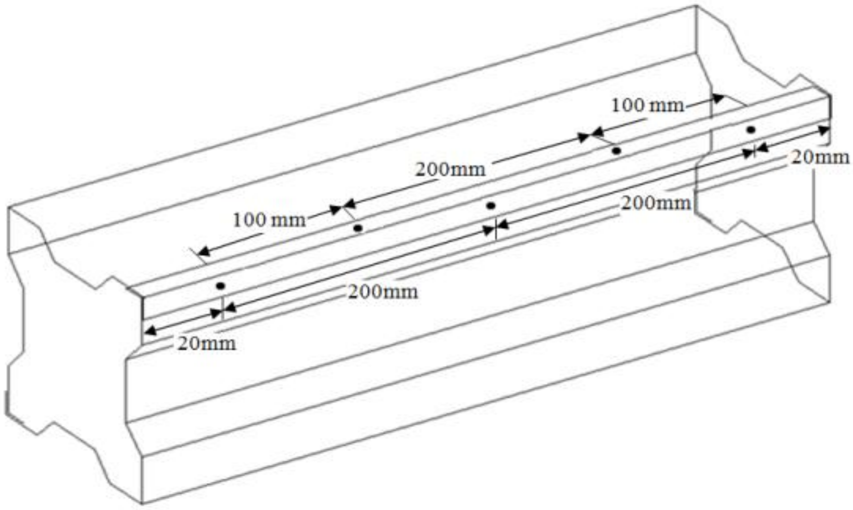

Figure 3. Arrangement of screw spacing for 440 mm length of the column

Nine series of cold-formed built-up box sections were tested. Nine series are labelled according to their width of top and bottom of the flange and web element, width of intermediate stiffener of the flange and web element and length of the specimen. For example, the label "TB30-IS40-440" defines the specimens as follows

- "TB30" indicates the top and bottom of flange and web element with the width of 30 mm.
- "IS40" indicates the intermediate stiffener of flange and web element with the width of 40 mm.
- "440" shows the length of the specimen.

2.2 Material properties

Material properties of the specimens were obtained by tensile coupon tests. The coupon specimens were prepared according to IS1608-2005 (Part I). The obtained material properties are presented in Table 2.

Table 2: Coupon test results

Material Properties	Coupon test results
Yield Stress (fy)	272 N/mm2
Ultimate Stress (fu)	349 N/mm2
Young's Modulus (E)	2.04 x 10 4 N/mm2
Poisson's Ratio (μ)	0.3

2.3 Experimental set-up

The column test was carried out in 100 tonne capacity of self - straining loading frame. Two thick steel end plates were welded to the ends of the specimen. Rubber gaskets were placed between the platens and the end plates of the specimen to simulate the hinged-end conditions at both supports [8,9]. Hydraulic jack was used to apply an axial load at the bottom end of the specimens. A load cell was mounted above the hydraulic jack to measure the load increments. Three LVDTs were located; one on the bottom end plate of the specimen to measure the axial shortening of the column, and the other two at the mid height on the web and flange of the specimen to measure the lateral deformation of the column. A data - acquisition system was used to trace the applied load and deformation. Fig.4 shows the experimental set-up of the column.

Figure 4. Experimental set-up

2.4 Column test results

The results of the experiment for cold-formed BSS are presented in Table 3. Local buckling, distortional buckling, flexural buckling and interaction of these buckling were observed during the test. Fig.5 shows the failure modes for several specimens. Axial load versus axial shortening curve and axial load versus lateral deformation curve for TB-30-IS40 series are shown in Fig.6 and Fig.7 respectively. A graph is drawn between the ultimate load (P_u) to yield load (P_y) ratio versus effective length of the column, as shown in Fig.8 – Fig.10. It is shown that, P_u/ P_y ratio decreases with the increase in the length of the column from 840 mm to 2240 mm for all series. The P_u/ P_y ratio of series TB30-IS40, TB30-IS50 and TB30-IS60 is 0.93, 0.90, 0.86 for column with 840 mm length, 0.90,0.87,0.84 for column with 1640 mm length and 0.89,0.86,0.83 for column with 2240 mm length.

The P_u/ P_y ratio of series TB40-IS40, TB40-IS50 and TB40-IS60 is 0.94, 0.92, 0.89 for column with 840 mm length, 0.93,0.90,0.87 for column with 1640 mm length and

0.92,0.89,0.85 for column with 2240 mm length. The P_u /P_y ratio of series TB50-IS40, TB50-IS50 and TB50-IS60 is 0.92, 0.89, 0.85 for column with 840 mm length, 0.89,0.86,0.83 for column with 1640 mm length and 0.88,0.85,0.82 for column with 2240 mm length. It is observed that, the dimensionless ratio decreases with the increase in the width of the element from 40 to 60 for all series. It is also indicates that, series TB40-IS40 have the highest values of P_u /P_y ratio compare than other series. So, series TB40-IS40 is the optimum series of BSS.

a.TB50-IS50-840 b.TB30-IS40-840

c.Tb30-IS40-1640 d.TB30-IS60-1640 e.TB30-IS40-2240

Figure 5. Failure modes for several specimens

Table 3: Comparison of experimental strengths with design strength

Specimen ID	Experiment		Design	P_{EXP}/P_{DSM}
	P_{EXP} (kN)	Failure modes	P_{DSM} (kN)	
TB30-IS40-840	252.20	L+D+F	264.45	0.954
TB30-IS40-1640	242.90	L+D+F	250.80	0.969
TB30-IS40-2240	232.50	L+D+F	235.67	0.987
TB30-IS50-840	259.20	L+D+F	282.39	0.918
TB30-IS50-1640	250.20	L+D	269.88	0.927
TB30-IS50-2240	242.40	L+D+F	255.91	0.947
TB30-IS60-840	272.60	L+D	300.25	0.908
TB30-IS60-1640	262.80	L+D	288.74	0.910
TB30-IS60-2240	253.19	L+D	275.79	0.918
TB40-IS40-840	286.30	D	300.35	0.953
TB40-IS40-1640	279.20	D	289.18	0.965
TB40-IS40-2240	270.00	L+D+F	276.60	0.976
TB40-IS50-840	298.20	L	318.13	0.937
TB40-IS50-1640	288.30	L+D	307.76	0.937
TB40-IS50-2240	281.11	L	296.02	0.950
TB40-IS60-840	310.88	L	335.86	0.926
TB40-IS60-1640	300.93	L+F	326.20	0.923
TB40-IS60-2240	288.38	L	315.21	0.915
TB50-IS40-840	313.50	L+D	335.92	0.933
TB50-IS40-1640	301.30	D	326.49	0.923
TB50-IS40-2240	289.30	D	315.76	0.916
TB50-IS50-840	318.50	L	353.61	0.901
TB50-IS50-1640	308.25	D	344.76	0.894
TB50-IS50-2240	296.48	D	334.67	0.886
TB50-IS60-840	330.55	L	371.26	0.890
TB50-IS60-1640	318.24	L	362.95	0.877
TB50-IS60-2240	308.31	L	353.43	0.872
Mean				0.926
Coefficient of variation				0.032
Reliability index β				2.75
L=Local bucklin, D=Distortional buckling, F=Flexural buckling				

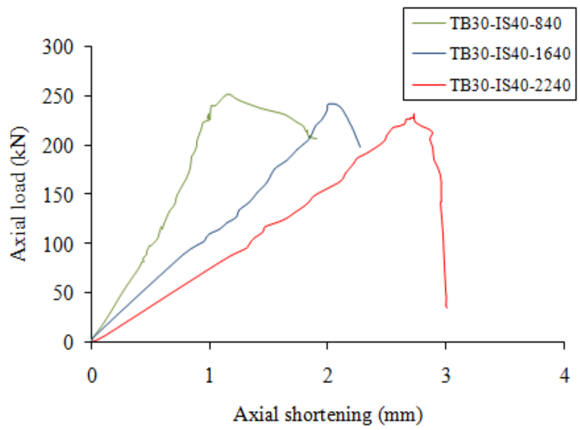

Figure 6. Axial load vs. axial shortening curves for TB30-IS40 series

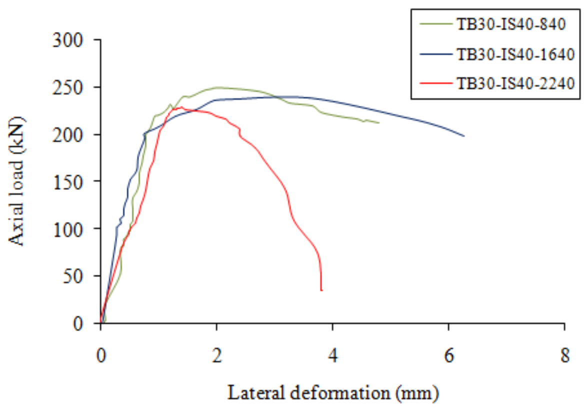

Figure 7. Axial load vs. lateral deformation curves for TB30-IS40 series

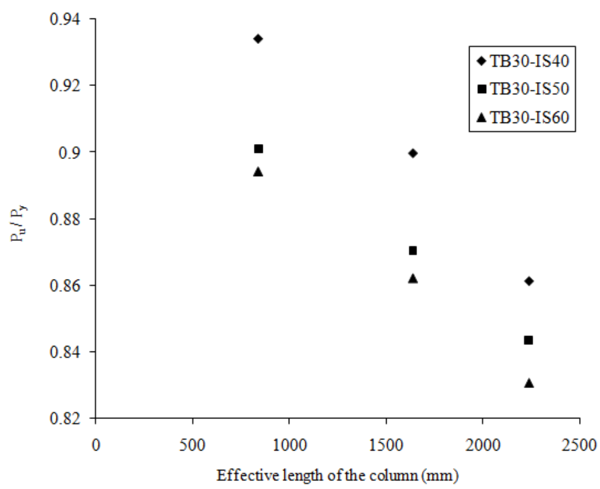

Figure 8. P_u/P_y vs. Effective length for TB30 series

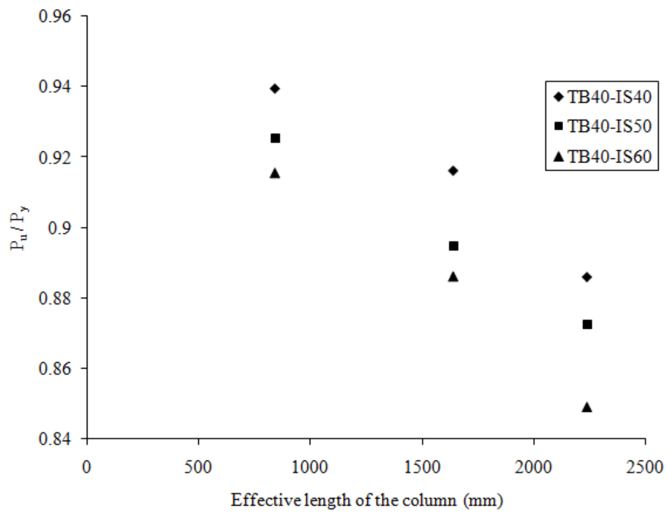

Figure 9. P_u/P_y vs. Effective length for TB40 series

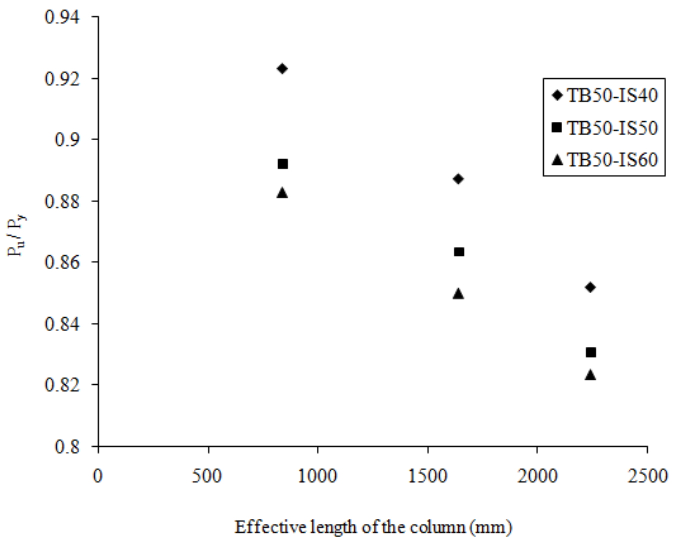

Figure 10. P_u/P_y vs. Effective length for TB50 series

3. DESIGN RULES

The unfactored design strength is calculated from the following design formula for the compression member using the direct strength method in the North American specification for cold formed steel structures[10].The nominal axial strength, P_n, is the minimum of P_{ne}, P_{nl} and P_{nd} as given below

The nominal axial strength for flexural buckling is

$$P_{ne} = \begin{cases} \left(0.658^{\lambda_c^2}\right) P_y \text{ for } \lambda c \leq 1.5 \\ \left(\frac{0.877}{\lambda c^2}\right) P_y \text{ for } \lambda c > 1.5 \end{cases} \quad (1)$$

Where, $\lambda c = \sqrt{\frac{P_y}{P_{cre}}}$; $P_y = A\ f_y$; A= gross area of the specimen; f_y = yield stress and P_{cre} = Minimum of the critical elastic column buckling load in flexural, torsional,or torsional-flexural buckling can be calculated in accordance with Section C4 of the NAS Specification (2007) using the elastic flexural buckling stress multiplied by the gross Cross-sectional area. The modified slenderness approach in Section D 1.2 of the AISI specification was used to calculate the elastic flexural buckling stress for the built-up Compression members.

The nominal axial strength for local buckling is

$$P_{nl} = \begin{cases} P_{ne} & \text{for } \lambda_l \leq 0.776 \\ \left[1\text{-}0.15\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4} P_{ne} & \text{for } \lambda_l > 0.776 \end{cases} \quad (2)$$

where, $\lambda_l = \sqrt{\frac{P_{ne}}{P_{crl}}}$; P_{crl}= A f_{ol} ; P_{crl} = Critical elastic local column buckling load; f_{ol}= elastic local buckling stress of the cross section and P_{ne} is described in using eq.(1)

The nominal axial strength for distortional buckling is

$$P_{nd} = \begin{cases} P_y & \text{for } \lambda_d \leq 0.561 \\ \left[1 - 0.25\left(\frac{P_{crd}}{P_y}\right)^{0.6}\right]\left(\frac{P_{crd}}{P_y}\right)^{0.6} P_y & \text{for } \lambda_d > 0.561 \end{cases} \quad (3)$$

Where, $\lambda_d = \sqrt{\frac{P_y}{P_{crd}}}$; P_{crd}= A f_{od}, P_{crd} = Critical elastic distortional column buckling load; f_{od} = elastic distortional buckling stress of the cross section; P_y is described in equ. (1). Elastic local buckling stress and distortional buckling stress were obtained from a rational elastic finite strip buckling analysis [3].

An analytical model was proposed to obtain the local buckling stresses and distortional buckling stresses of the specimen, which is used to find out the critical local column buckling load and distortional column buckling load respectively. In this analytical model, the connections between the two angle sections are modelled as rigid constraints at the screw locations [6,11] using CUFSM software, as shown in Fig.11.

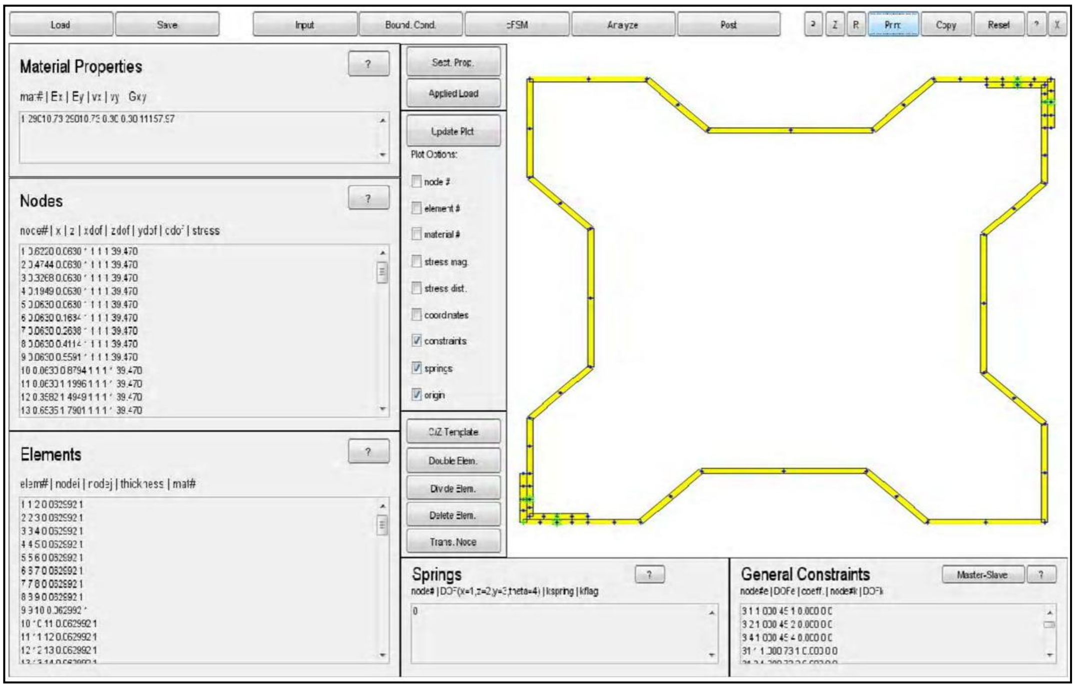

Figure 11. Connection details of built-up section

4. RELIABILITY ANALYSIS

The reliability of the design method for cold-formed built-up BSS was assessed using reliability analysis. A target reliability index (β) of 2.5 for cold-formed structural members is recommended by the AlSI Specification [10] .The resistance factor (ϕ) of 0.8 was used in the analysis as specified in the AISI Specification [10] and AS/NZS Standard [12]. A load combination of 1.2 DL+1.6 LL as specified in the American Society of Civil Engineers Standard [13] was used in the reliability analysis, where DL is the dead load and LL is the live load. The statistical parameters M_m, F_m, V_M and V_F are the mean values and coefficients of variation for material properties and fabrication variables. These values are obtained from Table Fl of the AISI Specification [10] for concentrically loaded compression members, where M_m = 1.10, F_m = 1.00, V_M = 0.10 and V_F =0.05. The statistical parameters P_m and V_P are the mean value and coefficient of variation of tested to design strength ratio, as shown in Table 3. The correction factor C_p is used to account for the influence due to a small number of specimens.

5. RESULTS AND DISCUSSION

The strength obtained from the experiment are compared with the unfactored design strength calculated by using DSM in the North American specification for cold formed steel structures are shown in Table 3 .The mean value P_{EXP} / P_{DSM} is 0.926 with the coefficient of variation of 0.032 and the corresponding values of reliability index β is 2.75 . It is shown that the reliability index is higher than the target value 2.5 of AISI [10]. So it is indicates that design strengths calculated by using DSM are slightly unconservative but reliable.

6. DESIGN RECOMMENDATION

The strength obtained from DSM was slightly unconservative. So the regression linear analysis is carried out between P_{EXP} and P_{DSM} is shown in Fig.12. The relationship between the strength obtained from the experiment (P_{EXP}) and the strength calculated in accordance with the direct strength method (P_{DSM}) is $P_{EXP} = 0.729\ (P_{DSM}) + 59.55$ with R-squared value of 0.954. From this analysis, a new design equation is proposed to calculate the compressive strength of BSS.

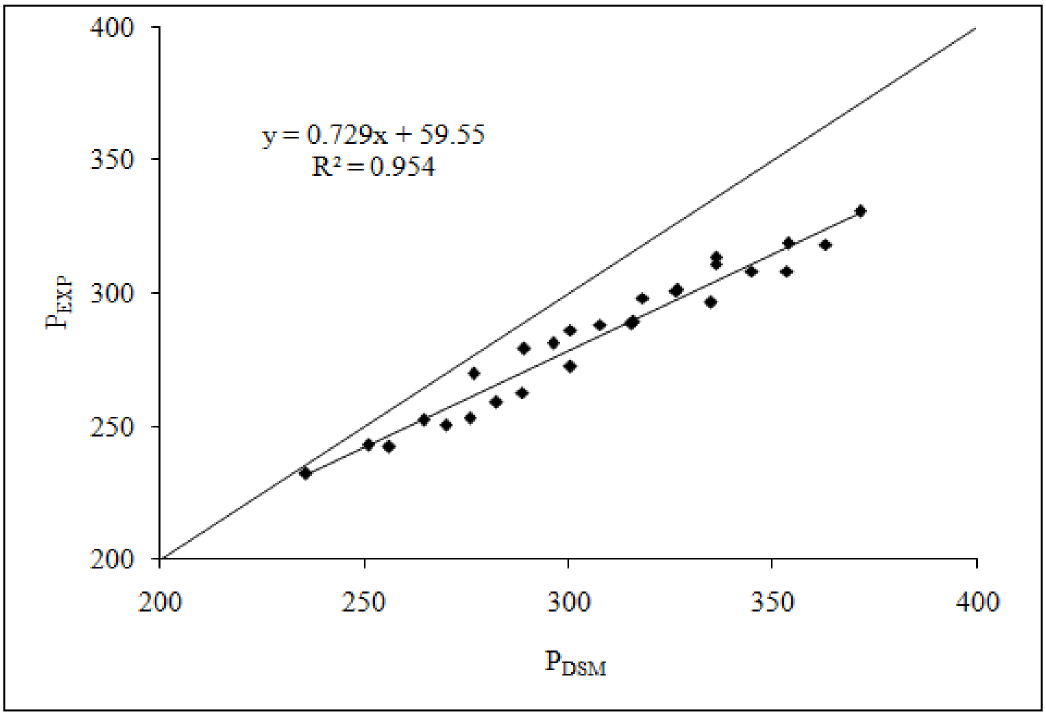

Figure 12. P_{EXP} Versus P_{DSM} curve

7. CONCLUSION

An experimental investigation of cold-formed built-up square sections with intermediate flange and web stiffeners has been described. Nine series of BSS were tested under the hinged support conditions. Tensile coupon test were conducted to obtain the material properties of the specimen, which is used to calculate the design strength. Local buckling, distortional buckling, flexural buckling and interaction of these buckling were observed during the experiment. The graph was drawn between the ultimate load to yield load ratio vs. effective length of the column. From the results it is concluded that the TB40-IS40 series is stronger than other series. The strengths obtained from the experiment were compared with the design strengths calculated using direct strength method in the North American specifications for cold-formed steel structures. The appropriateness of the direct strength method on BSS has been assessed by reliability analysis. It is shown that the reliability of DSM is reliable and slightly unconservative. So, a new design equation was proposed to calculate the ultimate compressive strength of BSS.

REFERENCES

1. Yu WW. *Cold-Formed Steel Design*, 3rd Ed, Wiley, New York, 2000.
2. Hancock GJ. *Design of Cold-Formed Steel Structures*, 3rd Ed, Australian Institute of Steel Construction, Sydney, Australia, 1998.
3. Young B, Chen J. Design of cold-formed steel built-up closed sections with intermediate stiffeners, *Journal of Structural Engineering, ASCE*, **134**(2008) 727-37.
4. Whittle J, Ramseyer C. Buckling capacities of axially loaded, cold-formed, built-up C-channels, *Thin Walled Structures*, **47**(2009) 190-201.
5. Reyes W, Guzmanc A. Evaluation of the slenderness ratio in built-up cold-formed box sections, *Journal of Constructional Steel Research*, **67**(2011) 929-35.
6. Georgieva L, Schueremans L, Vandewalle L, Pyl L. Design of built-up cold-formed steel columns according to the direct strength method, *Steel Structures and Bridges*, **40**(2012) 119-24.
7. Georgieva I, Schueremans L, Pyl L. Experimental investigation of built-up double –Z members in bending and compression, *Thin Walled Structures*, **53**(2012) 48-57.
8. Sukumar S, Parameswaran P, Jayagopal LS. Local distortional and euler-buckling of thin walled built-up open sections under compression, *Journal of Structural Engineering*, SERC India, **32**(2006) 447-54.
9. Anbarasu M, Sukumar S. Effect of connectors interaction in behaviour and ultimate strength of intermediate length cold formed steel open columns, *Asian Journal of Civil Engineering*, **14**(2013) 305-17.
10. AISI-S100. *North American Specification for the Design of Cold-Formed Steel Structural Members Specifications*, 2007.
11. Schafer B. *Design Manual for Direct Strength Method of Cold-Formed Steel Design*, 2002.
12. AS/NZS. *Cold-formed Steel Structures*, Sydney, Australia, New Zealand Standard, AS/NZS 4600, Standards Australia, 2005.
13. ASCE. *Minimum Design Loads for Buildings and Other Structures*, ASCE/SEI 7-05, American Society of Civil Engineers Standard, 2006.