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

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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

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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

<table>
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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 1). The obtained material properties are presented in Table 2.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Coupon test results</th>
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<tr>
<td>Yield Stress (fy)</td>
<td>272 N/mm²</td>
</tr>
<tr>
<td>Ultimate Stress (fu)</td>
<td>349 N/mm²</td>
</tr>
<tr>
<td>Young’s Modulus (E)</td>
<td>2.04 x 10⁴ N/mm²</td>
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<tr>
<td>Poisson’s Ratio (µ)</td>
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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.

![Experimental set-up](image)

**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.

Figure 5. Failure modes for several specimens
Table 3: Comparison of experimental strengths with design strength

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Experiment</th>
<th>Design</th>
<th>( \frac{P_{\text{EXP}}}{P_{\text{DSM}}} )</th>
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<td>252.20</td>
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<td>264.45</td>
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<td>L+D</td>
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- **Mean**: 0.926
- **Coefficient of variation**: 0.032
- **Reliability index \( \beta \)**: 2.75

L=Local buckling, 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
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 $P_{ne}$, $P_{nd}$ and $P_{nel}$ as given below.

The nominal axial strength for flexural buckling is
Where, $\lambda c = \frac{P}{P_{c e}}$, $P_y = \text{yield stress}$ and $P_{c e} =$ 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

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

where, $\lambda_l = \frac{P_{ne}}{P_{cr l}}$, $P_{cr l} = A f_{ol}$, $P_{cr l} =$ 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

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

Where, $\lambda_d = \frac{P_y}{P_{cr d}}$, $P_{cr d} = A f_{od}$, $P_{cr d} =$ Critical elastic distortional column buckling load; $f_{od} =$ elastic distortional buckling stress of the cross section; $P_y$ is described in eqn. (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.
4. RELIABILITY ANALYSIS

The reliability of the design method for cold-formed built-up BSS was assessed using reliability analysis. A target reliability index ($\beta$) of 2.5 for cold-formed structural members is recommended by the AISI Specification [10]. The resistance factor ($\phi$) 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 $\beta$ 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 $P_{\text{EXP}}$ and $P_{\text{DSM}}$ is shown in Fig. 12. The relationship between the strength obtained from the experiment ($P_{\text{EXP}}$) and the strength calculated in accordance with the direct strength method ($P_{\text{DSM}}$) is $P_{\text{EXP}} = 0.729 (P_{\text{DSM}}) + 59.55$ 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. $P_{\text{EXP}}$ Versus $P_{\text{DSM}}$ curve](image)

$$y = 0.729x + 59.55$$

$R^2 = 0.954$

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.

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