Investigation on cold-formed steel lipped channel built-up I beam with intermediate web stiffener

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Received: 8 February 2018 / Accepted: 5 February 2019 / Published online: 13 February 2019
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Abstract
The aim of the present study is to examine the behaviour of cold-formed steel (CFS) lipped channel built-up I-section with edge and intermediate web stiffeners under bending. Initially, the section dimension of length, width of the flange and depth of the sections are optimized numerically and finally, it is validated with the test results. All the select cross-section dimensions have satisfied the pre-qualified beam dimensions. Numerical analysis is carried out using the software ABAQUS. Totally, four section geometries are tested experimentally. After validation, a total of 75 parametric studies are carried out using the verified finite element model. All the results are compared with the direct strength method specifications for CFS structures and the suitable design modifications are detailed.

Keywords Bending · ABAQUS · Edge stiffener · Intermediate stiffener · Two-point loading

List of symbols

| Symbol | Description |
|--------|-------------|
| b      | Breadth of flange |
| CFS    | Cold-formed steel |
| H      | Depth of the section |
| L      | Length of the section |
| d1     | Lip size |
| d2     | Size of return lip |
| S      | Size of intermediate stiffener |
| t      | Thickness of the section |
| P FEAS | Ultimate load from FEA |
| MEXP   | Ultimate moment from experiment |
| MFEA   | Ultimate moment from FEA |
| M DSM  | Ultimate moment from DSM |
| MYS    | Yield moment |

FEM   Finite element model
EXP   Experimental result

Introduction

Cold-formed steel (CFS) members have become ready for the action of building products in modern building construction due to their inherent constructive uniqueness over conventional hot-rolled steel members. The reason is that, the CFS members provide enormous advantages such as high strength-to-weight ratio, high structural efficiency and so on over hot-rolled members. The load capacity of CFS beam depends on buckling mode like local buckling (LB), distortional buckling (DB), lateral torsional buckling (LTB), flexural buckling (FB) or interactions among them.

Experimental and numerical investigations on CFS C-section flexural member were carried out by Wang and Zhang (2008). An experimental study on laser-welded CFS built-up beams was conducted by Landolfo et al. (2008). Paczos and Wasilewicz (2009) have investigated the buckling studies on lipped CFS I-shaped beam with anti-symmetrical bends, which increase the load capacity, and while designing, special attention needs to be paid to their size. Magnucka-Blandzi (2010) has studied the behaviour of CFS channel beams with double-box flange beams. Magnucka-Blandzi and Magnucki (2010) have investigated the global–local buckling behaviour of thin-walled channel beams. The LTB behaviour of CFS lipped channel beams under bending was examined by Kankanamge...
and Mahendran (2010). Anapayan and Mahendran (2010) have presented the behaviour and capacity of light steel flexural members subject to LTB. Numerical investigation of CFS members subjected to bending and compression of built-up double Z-members has been discussed by Georgieva et al. (2011).

Similarly, Madulia et al. (2012) have developed the new design rules for in-elastic bending capacity of CFS channel sections. Haidarali and Nethercot (2012a, b) have investigated the true buckling behaviour of beam with both edge and intermediate stiffeners in their compression flanges on the post-buckling of laterally restrained CFS Z-section beam. Manikan-
dan et al. (2014, 2015, 2016) have investigated the behaviour of thin-walled built-up I beams in pure bending. Experimental and numerical studies on the flexural behaviour of CFS built-up section were performed by Alex and Iyappan (2016), Yang et al. (2017) and Hassan et al. (2017).

There are only a minimal amount of studies available on the behaviour of the CFS built-up section under bending and it is observed that studies on built-up beam with intermediate stiffener are almost nil. Hence, in the current study, the lipped channel built-up sections with intermediate web stiffeners are chosen. Totally, four section geometries are tested and the results are validated numerically. A total of 75 parametric studies were carried out using finite element analysis (FEA) software ABAQUS. The aim of the study is to examine the behaviour of CFS built-up I-section with edge and intermediate stiffeners under bending. All the parametric results are compared with the DSM specifications for CFS structures and a suitable design modification is proposed.

**Experimental investigation**

Totally, four types of built-up cross-section are tested: first is the simple lipped channel (SLC), second is the simple lipped channel with intermediate web stiffener (SLC-I), third is the complex lipped channel (CLC) and fourth is the complex lipped channel with intermediate web stiffener (CLC-I). Material properties of the specimens are determined by conducting tensile tests on steel coupons as per the IS standard (IS 1608 -2006).

Totally, three coupons are tested and the average results of yield stress, Young’s modulus are presented in Table 1 and Fig. 1. The select cross-section profile with defined nomenclature is illustrated Fig. 2 and the corresponding dimensions are listed in Table 2.

The entire cross-section dimensions satisfy the limitations of pre-qualified sections in DSM. Based on the literature support (Kankanamge and Mahendran 2012) and fabrication requirements, the sizes of lips and intermediate stiffeners are limited to 20 mm. Built-up I-section consists of two identical C-channel sections connected back-to-back using self-tapping screws with a spacing of 100 mm. Specimens are tested in a loading frame with a capacity of 250 kN under the simply supported boundary condition subject to two-point loading. Loads are applied using screw jack with a capacity of 100 kN. Lateral restraints are provided at the support as shown in Fig. 2. During the tests, a proving ring and dial gauges are used to measure the applied load and deformations, respectively. A typical experimental test

![Stress-strain curve](image)

**Table 1** Average results of coupon test

| Yield stress (Mpa) | Young’s modulus (Mpa) | Ultimate stress (Mpa) | Elongation |
|-------------------|----------------------|----------------------|------------|
| 276               | 2.05 × 10^5          | 350                  | 13%        |

![Table 2](image)

**Table 2** Dimension of the section

| S.No | Specimen ID | Dimension of the section (mm) |
|------|-------------|-------------------------------|
|      |             | $H$  $b$  $d_1$  $d_2$  $S$  $t$  $L$ |
| 1    | SLC         | 140  50  20  –  –  1.6  1200 |
| 2    | SLC-I       | 140  45  20  –  20  1.6  1200 |
| 3    | CLC         | 140  50  20  20  –  1.6  1200 |
| 4    | CLC-I       | 140  45  20  20  20  1.6  1200 |
set-up is illustrated in Fig. 3. All the specimens are tested up to the failure.

**Finite element modelling**

The finite element model (FEM) is developed using the numerical analysis software ABAQUS. In this study, material and geometric non-linearities are incorporated, whereas residual stress and cold-forming process are not incorporated (Xu et al. 2009). For defining the material non-linearity, multi-linear stress–strain behaviour is adopted. The numerical investigation involves two types of analysis. One is linear and the other one is non-linear. In the linear analysis, the sections are considered to have a perfect geometry to determine the probable buckling behaviour. In the non-linear analysis, both geometric and material non-linearities are incorporated (Manikandan et al. 2014; Manikandan and Sukumar 2015, 2016, Kankanamge and Mahendran 2012).

The numerical models are discretized using shell element (S4R) with a mesh size of 10 mm × 10 mm (Manikandan and Sukumar 2015). All the beams are analysed under simply supported boundary condition with two-point loading condition. The lateral restraints are provided at the supports as shown in Fig. 4. To make a built-up section numerically, the fastener option is used (Kankanamge and Mahendran 2012). The detailed FEM model is shown in Fig. 3. In this study, initial imperfection is not measured; however, a magnitude of L/1000 is incorporated (Manikandan et al. 2014; Manikandan and Sukumar 2015, 2016; Kankanamge and Mahendran 2012, GB 2002).
Selection of section dimensions

For arriving at the section dimensions, initially, 33 FEMs are analysed. To minimize the LB, in the entire study, the dimension of the lips ($d_1$), flange width of the section ($b$), depth of the section ($H$), length of the member ($L$), bolt spacing and thickness of the section are taken as 20, 40, 75, and 1200 mm, respectively, and the variations of these dimensions are specified in the appropriate places.

Basic properties of the cross-sections and buckling plots are obtained from the software CUFSM as shown in Fig. 5. Length ($L$), depth ($H$), flange width ($b$), size of the lips ($d_1$) and bolt spacing ($S$) are identified from the specimen labelling. For example, in “L900”, the first letter $L$ defines
The length and the second value defines the corresponding dimensions in millimeter. The effect of variation of section dimensions of the dimension of the lips ($d_1$), flange width of the section ($b$), depth of the section ($H$), length of the member ($L$), bolt spacing is displayed in Fig. 6 and Table 3. From Fig. 5, it is observed that the optimal length, depth, width, bolt spacing and lip size are 1200, 75, 40, 50 and 20 mm, respectively. From this parametric study, it is observed that length, depth, width, bolt spacing and lip size significantly affect the strength of the section.

| S. no | Specimen ID | Section dimensions (mm) | Ultimate load $P_{FEA}$ (kN) | Failure mode |
|-------|-------------|--------------------------|-----------------------------|--------------|
| 1     | L900        | 75 40 20 1.6 900 100     | 21.14                       | LT           |
| 2     | L1200       | 75 40 20 1.6 1200 100    | 24.93                       | LD           |
| 3     | L1500       | 75 40 20 1.6 1500 100    | 16.89                       | LT           |
| 4     | L1800       | 75 40 20 1.6 1800 100    | 13.27                       | LT + F       |
| 5     | L2100       | 75 40 20 1.6 2100 100    | 11.73                       | LT + F       |
| 6     | H50         | 50 40 20 1.6 1200 100    | 18.24                       | LT           |
| 7     | H55         | 55 40 20 1.6 1200 100    | 18.99                       | LT           |
| 8     | H60         | 60 40 20 1.6 1200 100    | 19.81                       | LT           |
| 9     | H65         | 65 40 20 1.6 1200 100    | 20.28                       | LT           |
| 10    | H70         | 70 40 20 1.6 1200 100    | 21.50                       | LT           |
| 11    | H75         | 75 40 20 1.6 1200 100    | 24.93                       | LT           |
| 12    | H80         | 80 40 20 1.6 1200 100    | 21.32                       | LT           |
| 13    | H85         | 85 40 20 1.6 1200 100    | 20.75                       | LT           |
| 14    | H90         | 90 40 20 1.6 1200 100    | 20.52                       | LT + F       |
| 15    | H95         | 95 40 20 1.6 1200 100    | 20.24                       | LT           |
| 16    | H100        | 100 40 20 1.6 1200 100   | 20.19                       | LT + F       |
| 17    | H125        | 125 40 20 1.6 1200 100   | 18.80                       | LT + F       |
| 18    | H150        | 150 40 20 1.6 1200 100   | 18.25                       | LT + F       |
| 19    | b20         | 75 20 20 1.6 1200 100    | 17.50                       | LT + F       |
| 20    | b30         | 75 30 20 1.6 1200 100    | 20.35                       | LT + F       |
| 21    | b40         | 75 40 20 1.6 1200 100    | 24.93                       | LT + F       |
| 22    | b50         | 75 50 20 1.6 1200 100    | 21.40                       | LT + F       |
| 23    | b60         | 75 60 20 1.6 1200 100    | 21.00                       | LT           |
| 24    | d10         | 75 40 0 1.6 1200 100     | 18.97                       | LT + F       |
| 25    | d5          | 75 40 5 1.6 1200 100     | 20.95                       | LT + F       |
| 26    | d10         | 75 40 10 1.6 1200 100    | 21.20                       | L + F        |
| 27    | d15         | 75 40 15 1.6 1200 100    | 22.50                       | L + F        |
| 28    | d20         | 75 40 20 1.6 1200 100    | 24.95                       | LT           |
| 29    | d25         | 75 40 25 1.6 1200 100    | 21.07                       | LT           |
| 30    | S20         | 75 40 20 1.6 1200 20     | 13.30                       | LT + F       |
| 31    | S30         | 75 40 20 1.6 1200 30     | 16.50                       | LT + F       |
| 32    | S50         | 75 40 20 1.6 1200 50     | 24.40                       | LT + F       |
| 33    | S100        | 75 40 20 1.6 1200 100    | 20.71                       | LT + F       |
| 34    | S150        | 75 40 20 1.6 1200 150    | 18.96                       | LT + F       |
| 35    | S200        | 75 40 20 1.6 1200 200    | 17.45                       | LT + F       |

$L$: local buckling, $LT$: lateral–torsional buckling, $F$: flexural buckling

| S.No | Specimen ID | Flexural strength (kN.m) | $M_{EXP}$ | $M_{FEA}$ | Failure mode |
|------|-------------|--------------------------|-----------|-----------|--------------|
| 1    | SLC         | 5.06 5.23               | 0.97      | L + LT    |
| 2    | SLC-I       | 7.88 8.00               | 0.99      | L + LT    |
| 3    | CLC         | 7.38 7.58               | 0.97      | L + LT    |
| 4    | CLC-I       | 10.21 10.40             | 0.98      | L + LT    |

Mean: 0.98

Standard deviation: 0.01

$L$: local buckling, $LT$: lateral–torsional buckling
Result and discussion

Totally, four types of cross-section are tested and the results are displayed in Table 4, while the load–deflection curve for specimens SLC-I and CLC is illustrated in Fig. 6. In this study, the interaction of LB and LTB is investigated and given in Fig. 7. The flexural strength of the specimens SLC, SLC-I, CLC and CLC-I is 5.06 kN.m, 7.88 kN.m, 7.38 kN.m and 10.21 kN.m, respectively. From Table 4 and Fig. 7, it is observed that the strength of the section increased by improving the section geometries from simple lip to complex lip. Figure 8 shows the load–deflection behaviour of simple and complex lipped channel section with and without intermediate web stiffeners. From Fig. 8, it is observed that CLC-I and CLC perform well in all aspects compared to SLC-I and SLC, because a complex lip improves the torsional rigidity of the section and intermediate web stiffeners reduce the LB of the web element. Another important observation noted is that compared to CLC-I, CLC offers more post-buckling strength. The mean and standard deviation of $M_{\text{EXP}}$ and $M_{\text{FEM}}$ are 0.98 and 0.01, respectively. From Figs. 8 and 9 and Table 4, it seems that the numerical analysis agrees well with the test results. Consequently, an extensive parametric study is carried out to examine the factors which affect the behaviour and strength of all the tested sections.

Parametric study

The effect of length variation of the sections SLC, SLC-I, CLC and CLC-I is investigated and the results are shown in Table 5. The load–deformation curve for SLC and CLC series of specimens is shown in Fig. 10. The failure modes such as LTB and the interaction of LTB and FB are investigated. From this study, the strength of the section is noted to decrease with an increase in the member length.

Theoretical investigation

As per the DSM (22) for CFS structures, the nominal flexural strength ($M_{\text{DSM}}$) is the minimum of lateral–torsional buckling ($M_{\text{LTB}}$), local buckling ($M_{\text{L}}$) and distortional buckling ($M_{\text{d}}$) as given below.
The lateral–torsional buckling strength ($M_{ne}$) is

For $M_{cre} < 0.56M_y$ $M_{ne} = M_{cre}$

(1)

For $2.78M_y > M_{cre}$ $M_{ne} = \frac{10}{9}M_y \left(1 - \frac{10M_y}{36M_{cre}}\right)$

(2)

For $M_{cre} > 2.78M_y$ $M_{ne} = M_y$

The local buckling strength ($M_{nl}$) is

For $\lambda_l \leq 0.776M_{nl} = M_{ne}$

(4)

For $\lambda_l > 0.776$ $M_{nl} = \left(1 - 0.15\left(\frac{M_{crd}}{M_{ne}}\right)^{0.4}\right)\left(\frac{M_{crd}}{M_{ne}}\right)^{0.4}M_{ne}$

(5)

where $\lambda_l = \sqrt{M_{ne}/M_{crd}}$

The distorsional buckling strength ($M_{nd}$)

For $\lambda_d \leq 0.673M_{nd} = M_y$

(6)

For $\lambda_d > 0.776M_{nd} = \left(1 - 0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right)\left(\frac{M_{crd}}{M_y}\right)^{0.5}M_y$

(7)

where $\lambda_d = \sqrt{M_y/M_{crd}}$

The comparison of results of $M_{FEA}$ and $M_{DSM}$ is shown in Table 5 and Fig. 11. Except CLC-I series, DSM specification provides conservative results in the beam length that is less than 1500 mm and this is elaborately discussed in Figs. 11 and 12. The mean and standard deviation between $M_{FEA}$ and $M_{DSM}$ are 0.96 and 0.07, respectively. From this theoretical

Fig. 8 Comparison of failure modes (a) SLC (b) SLC-I (c) CLC (d) CLC-I
investigation, it is concluded that generally DSM specification provides moderate results for built-up flexural members. Hence, in this study, a new design equation is developed as represented in Fig. 13) for the CFS built-up structures.

\[ M_{design} = 0.94M_{DSM} \]  

(8)

**Conclusion**

The FEM using ABAQUS software is perfect in predicting the strength and the behaviour of the beams. Therefore, the FEM developed can be used with a high level of assurance in predicting the capacity of the beams. Design of CFS built-up I beam with and without intermediate web stiffeners requires the consideration of FB and interaction of FB and LTB. Keeping the length and cross-sectional area the same by adding the intermediate web stiffeners has a considerable effect on the strength and the behaviour of the beam, which is due to minimizing the LB and the increase in the moment of inertia about a symmetrical axis and the increase in resistance against torsional buckling. Adding the complex edge stiffener at the flange has a considerable result in terms of the strength and behaviour of the beams. This study has shown that the provision of intermediate web stiffeners and edge stiffeners improves the behaviour and increases the strength of the section.

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**Fig. 9** Comparison of stiffness evaluation (a) SLC and CLC (b) SLC-I and CLC-I (c) SLC and SLC-I (d) CLC and CLC-I
Table 5 Results of the parametric study

| Specimen ID | Section dimensions (mm) | M_{FEA} (kN.m) | M_{DSM} (kN.m) | Failure modes |
|-------------|-------------------------|----------------|----------------|--------------|
| SLC-L900H140 | H 140, b 50, d 20, t 1.6, s 0, L 900 | 7.10 | 8.30 | 0.86 | LT |
| SLC-L1200H140 | H 140, b 50, d 20, t 1.6, s 0, L 1200 | 6.10 | 7.02 | 0.87 | L + LT |
| SLC-L1500H140 | H 140, b 50, d 20, t 1.6, s 0, L 1500 | 5.57 | 6.50 | 0.86 | L + LT |
| SLC-L1800H140 | H 140, b 50, d 20, t 1.6, s 0, L 1800 | 5.29 | 5.46 | 0.97 | L + LT |
| SLC-L2100H140 | H 140, b 50, d 20, t 1.6, s 0, L 2100 | 5.04 | 5.21 | 0.97 | L + LT |
| SLC-L2400H140 | H 140, b 50, d 20, t 1.6, s 0, L 2400 | 4.65 | 4.93 | 0.94 | F + LT |
| SLC-L2700H140 | H 140, b 50, d 20, t 1.6, s 0, L 2700 | 3.95 | 4.03 | 0.98 | F + LT |
| SLC-I-L900H140 | H 140, b 45, d 20, t 1.6, s 20, L 900 | 9.51 | 10.71 | 0.89 | L + LT |
| SLC-I-L1200H140 | H 140, b 45, d 20, t 1.6, s 20, L 1200 | 8.68 | 9.88 | 0.88 | L + LT |
| SLC-I-L1500H140 | H 140, b 45, d 20, t 1.6, s 20, L 1500 | 8.24 | 7.94 | 1.04 | L + LT |
| SLC-I-L1800H140 | H 140, b 45, d 20, t 1.6, s 20, L 1800 | 7.86 | 7.56 | 1.04 | F + LT |
| SLC-I-L2100H140 | H 140, b 45, d 20, t 1.6, s 20, L 2100 | 7.26 | 6.96 | 1.04 | F + LT |
| SLC-I-L2400H140 | H 140, b 45, d 20, t 1.6, s 20, L 2400 | 6.16 | 5.86 | 1.05 | F + LT |
| CLC-L900H140 | H 140, b 50, d 20, t 1.6, s 0, L 900 | 12.20 | 13.40 | 0.91 | LT |
| CLC-L1200H140 | H 140, b 50, d 20, t 1.6, s 0, L 1200 | 11.93 | 12.98 | 0.92 | L + LT |
| CLC-L1500H140 | H 140, b 50, d 20, t 1.6, s 0, L 1500 | 11.41 | 11.45 | 1.00 | L + LT |
| CLC-L1800H140 | H 140, b 50, d 20, t 1.6, s 0, L 1800 | 10.31 | 9.89 | 1.04 | F + LT |
| CLC-L2100H140 | H 140, b 50, d 20, t 1.6, s 0, L 2100 | 9.02 | 8.56 | 1.05 | F + LT |
| CLC-L2400H140 | H 140, b 50, d 20, t 1.6, s 0, L 2400 | 7.42 | 7.12 | 1.04 | F + LT |
| CLC-L2700H140 | H 140, b 50, d 20, t 1.6, s 0, L 2700 | 5.57 | 5.05 | 1.10 | F + LT |
| CLC-I-L900H140 | H 140, b 45, d 20, t 1.6, s 20, L 900 | 16.88 | 18.33 | 0.92 | LT |
| CLC-I-L1200H140 | H 140, b 45, d 20, t 1.6, s 20, L 1200 | 15.78 | 16.22 | 0.97 | L + LT |
| CLC-I-L1500H140 | H 140, b 45, d 20, t 1.6, s 20, L 1500 | 14.25 | 16.01 | 0.89 | F + LT |
| CLC-I-L1800H140 | H 140, b 45, d 20, t 1.6, s 20, L 1800 | 12.48 | 13.23 | 0.94 | F + LT |
| CLC-I-L2100H140 | H 140, b 45, d 20, t 1.6, s 20, L 2100 | 10.26 | 11.45 | 0.90 | F + LT |
| CLC-I-L2400H140 | H 140, b 45, d 20, t 1.6, s 20, L 2400 | 7.71 | 8.56 | 0.90 | F + LT |
| Mean | | 0.96 | | |
| Standard deviation | | 0.07 | | |

L: local buckling, LT: lateral–torsional buckling, F: flexural buckling.

Fig. 10 Load–deformation curve for specimen (a) SLC-series (b) CLC-series
Fig. 11 Comparison of results between FEA and DSM (a) SLC series (b) SLC-I series (c) CLC series (d) CLC-I series

Fig. 12 Variability of results between FEA and DSM

Fig. 13 Correlation between FEA and DSM
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