# Numerical Investigation on Built-Up Cold-Formed Steel Double Decker-I-Beams

G. Beulah Gnana Ananthi and M. S. Deepak

**Abstract** Cold-formed steel (CFS) elements are used as members in buildings; although steel sheets can be formed into complex shapes, it is often difficult to bent to complex forms; hence, built-up (BU) sections are emerging as an alternative where simple sections can be assembled into complex sections. Lipped channel 'C' section is the most common available section that finds wide range of applications. This paper presents the validation conducted on an experimental investigation reported in the literature on back-to-back BU CFS double-channel sections subjected to bending. In this parametric study, the behaviour and capacities of BU double-symmetric section composed of four identical channels and resembles the shape of a double decker-I-beam sections (DDIB) subjected to flexure is presented. The thickness of the DDIB sections is varied from 1 to 3 mm. The lengths of DIBBs are varied from 300 to 2000 mm, and the beams experience various buckling forms under uniform bending. Local, distortional, and lateral buckling are captured from the finite element analysis (FEA) performed using ABAQUS software. It is found that the compression zone above the horizontal centroidal plane in cross-section is subjected to maximum buckling phenomenon on comparison with the bottom zone.

**Keywords** Double decker-I-beam · Built-up · Cold-formed steel · Finite element analysis

G. Beulah Gnana Ananthi (✉)
Department of Civil Engineering, College of Engineering Guindy Campus, Anna University, Chennai, India
e-mail: beulah28@annauniv.edu

M. S. Deepak
Department of Civil Engineering, BMS Institute of Technology and Management, Bengaluru, India

# 1   Introduction

Hot-rolled steel shapes and cold-formed steel shapes are the two most used types of structural steel in building construction. C sections (also known as lipped channels), zee sections, double-channel I beams with stiffened flanges, hat sections with and without intermediate stiffeners, and box sections are examples of open, closed and built-up (BU) sections. These are used in structures for eave struts, purlins and girts and other structural components. The use of CFS has grown in popularity in the building industry. Ananthi et al. [2–10] and Deepak et al. [11, 12] and in this insight, new BU CFS double decker-I-beam sections (DDIB) are proposed in this study.

Glauz [13] established a generalised lateral-torsional buckling (LTB) equation for symmetric and un-symmetric CFS-BU sections. Through a numerical study done by Kucukler et al. [14], a stiffness reduction approach utilising the linear buckling analysis is proposed for LTB-BU members. On the contrary, Wang and Young [15] have reported 35 experiments on CFS-BU beams subjected to four-point bending with various screw patterns. Under four-point bending, Roy et al. [16] conducted studies both experimentally and numerically on CFS-BU beams with various screw patterns. For CFS lipped channel beams subjected to LTB at extreme temperatures, a new design strategy is proposed by Kankanamge and Mahendran [17]. Deepak and Shanthi [18–21] examined the capacity of closed-BU homogeneous and hybrid double-I-box beams experiencing distortional buckling and proposed a simplified EWM equations. Wang and Young [22, 23] conducted four-point bending tests on CFS back-to-back (BB) and face-to-face (FF) channel sections with web openings. Flexural strength of CFS oval hollow section beams is conducted by Zhu et al. [24]. Experimenting with many parameters to estimate moment capacity and structural behaviour of a variety of new CFS cross-sections necessitates a lot of money and time. Numerical analysis using nonlinear finite element analysis (FEA) and commercially accessible software tools is one of the more complete techniques to research that incorporates several parameters. ABAQUS [25] software is utilised in the current work for FEA.

# 2   Section Description

The section consists of four lipped channel sections assembled in a way that two I section sits on one another which is shown in the Fig. 1 to form DDIB75. The single-channel member is linked BB with the fasteners. Number of fasteners is varied between 10, 5 and 3 numbers for different lengths and different thicknesses as shown in Fig. 2. Length of the sections is varied between 300 to 2000 mm with 100 mm increment. Thickness variations include 1.0, 1.2, 1.4, 2.0, 2.5 and 3.0 mm. Other properties such as elasticity and plasticity are taken from the literature reported by Roy et al. [16] as 200GPa and 550 MPa, respectively.
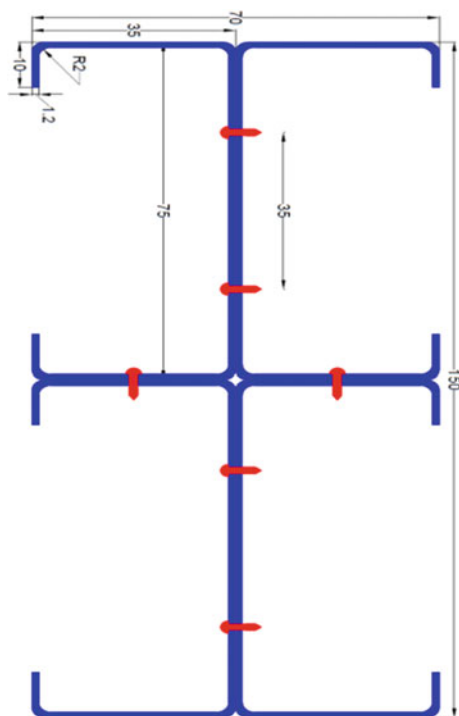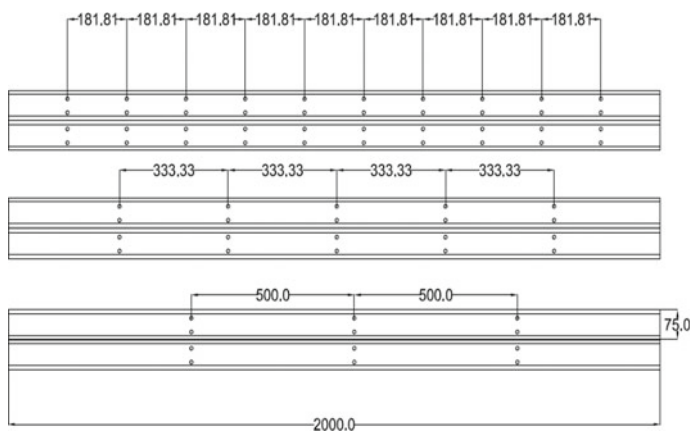
**Fig. 1** Section view DDIB75 sections



**Fig. 2** Longitudinal view of DDIB 75 with different screw spacing

## 3  Parameters Considered for the Study

**Material properties**:

- Yield strength ($f_y$) = 550 MPa; Young's modulus (E) = 200000 MPa; Poison's ratio = 0.3

**Member properties**:

- Length of the section taken is 300–2000 mm with 100 mm increment
- Thickness of the sections includes 1.0, 1.2, 1.4, 2, 2.5 and 3.0 mm
- End condition is simply supported (hinge–roller)

## 4  Numerical Investigation

**General**

The BU-DDIB75 sections are numerically simulated using the finite element (FE) programme using ABAQUS [25]. Finite element analysis (FEA) technique is a substitute method which can be used to predict the ultimate strength and the mode of failure mechanism similar to that of the test conducted in the laboratory. It is a comprehensive way of investigating and particularly advantageous when multiple parameters are required for the study. The modelling techniques described by Deepak and Shanthi [18–21] for the hybrid double-I-box-girders are applied. The FE models are modelled by considering the centre-to-centre line dimensions. The need of a balance between precision and efficiency is emphasised.

## 5  Geometry and Material Properties

The material non-linearity is taken into account in the FE model by considering 'true' values of stresses and strains. A simplified elastic perfectly plastic stress–strain curve is used in the parametric study. The results of the coupon tests defined in the experimental section [16] is used.

## 6  Element Type, Mesh Size and Material Model

In this FE study, S4R5 which is a four-noded element with reduced hourglass integration is used in the modelling. The aspect ratio in the FE modelling is kept as 1.0 for the elements so that a very accurate outcome with minimum time period to compute the analysis is exhibited. A distinctive FE mesh pattern is shown in Fig. 3.

**Fig. 3** Typical FE mesh for
DDIB75-L3000-S10-t3



## 7 Load Application and Applied Boundary Conditions

The length of the beam is measured along the z axis in ABAQUS, and the cross-section is measured along the x–y axis. Translations are represented by1, 2 and 3 in the compass directions, whereas rotations are represented by 4, 5 and 6 in the *x*, *y* and *z* directions, respectively. It is decided to use the simply supported condition. On both ends of the beam model, a reference node of single-point constraints (SPCs) is built as the master node. Four-point bending load is provided in the beam as similar to the literature. Multiple point constraint is used to connect all the nodes in the loading point in the beam to the reference point. Loading and boundary conditions are shown in Fig. 4.
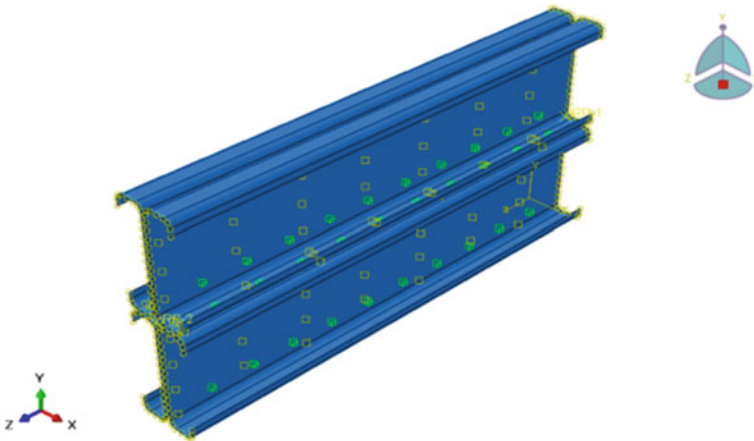


**Fig. 4** DDIB75-L3000-S10-t3 boundary condition with MPC beam connector applied to the finite element model
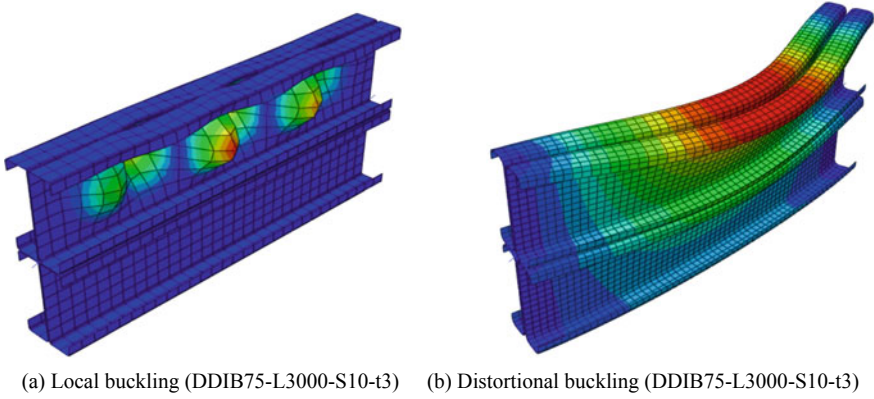
(a) Local buckling (DDIB75-L3000-S10-t3)    (b) Distortional buckling (DDIB75-L3000-S10-t3)

**Fig. 5** Contours of initial imperfection for BU75BU beams

## 8   Modelling of Local and Overall Geometric Imperfections

The Eigen buckling analysis is used to shape a superposition in the critical modes of local buckling and global buckling. The magnitude of the local, distortional and global imperfections is considered as 0.006*w*t, 1.0*t and 1/1000 of the full length of the column, respectively, as per the endorsements of Schafer and Pekoz [26]**.** The local and global buckling modes obtained from the FEA for DDIB75-L3000-S10-t3 are shown in Fig. 5.

## 9   Validation of the FE Model

The FE model is standardised against the test results presented by Roy et al. [16]. Three test samples are modelled by using the FE analysis. Table 1 shows the comparison between the experimental ultimate moment capacity and those estimated using finite element analysis. The cross-section chosen for the validation from the literature is presented Fig. 6. As can be seen in Fig. 7a–b, the test and FE results are in good agreement, both in terms of the moment capacity and the failure modes.

**Table 1** Comparison of F.E results with literature results Roy et al. [16]

| Specimen ID | FE moment capacity $M_{FEA}$ (kNm) | Moment capacity $M_{Test}$ (kNm) [11] | Comparison $(M_{FEA}/M_{Test})$ |
|---|---|---|---|
| BU75-L2000-S1900 | 2.01 | 2.17 | 0.92 |
| BU75-L2000-S950 | 2.28 | 2.34 | 0.97 |
| BU75-L2000-S475 | 2.47 | 2.5 | 0.98 |

**Fig. 6** Chosen section for numerical validation



(a) BU75
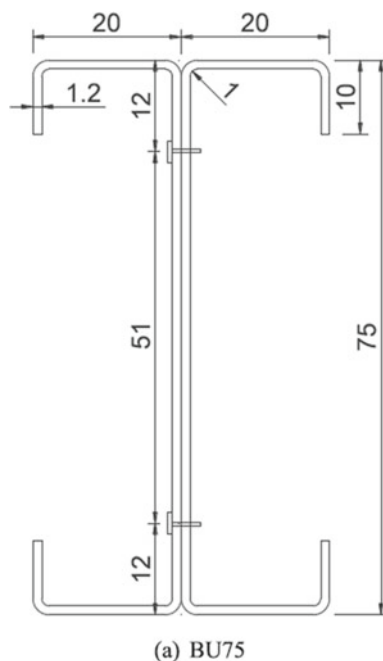
## 10 Parametric Study

A parametric research that includes 324 CFS double decker-I-beam sections (DDIB) is conducted using the verified finite element model. DDIB75 section is considered where 75 denotes the web depth. The effect of screw spacing, variation in thickness and length of the section are investigated in the parametric study. The failure modes of DDIB75-S10-T2 section are shown in Fig. 8.

## 11 Results and Discussion

There are totally 324 models are developed and analysed in this study, and three main parameters of beam such as length, thickness and fastener spacing are varied to find out failure patterns, appropriate capacities, etc. In this study, three different fastener numbers are used in all the sections in order to find out the effects of these fasteners in the beam. The parametric study was designed in such a way that six different thickness (1.00, 1.20, 1.40, 2.00, 2.50 and 3.00 mm) and eighteen different lengths (varying from 300 to 2000 mm) covering stub to slender span beams were considered. The effect of screw spacing on axial capacity was investigated. As can be seen, three different numbers of screws were considered: 10, 5 and 3. These number of screws include screws at the left and right ends of the beam. Figures 9, 10 and
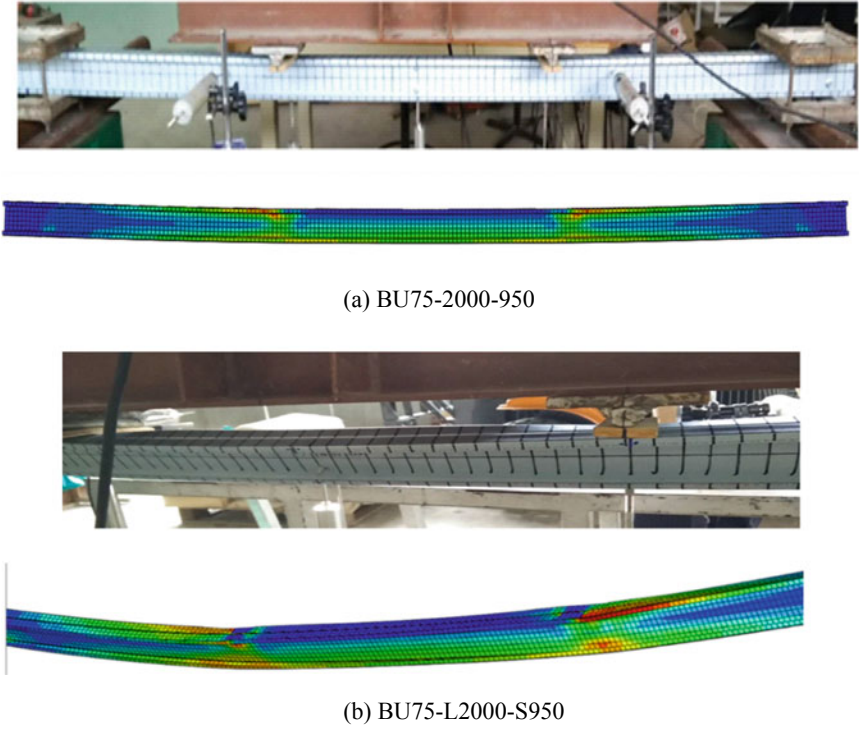
(a) BU75-2000-950



(b) BU75-L2000-S950

**Fig. 7** Validation of the back-to-back BU cold-formed steel channel sections Roy et al. [16]



(a) 300mm                              (b) 1000mm

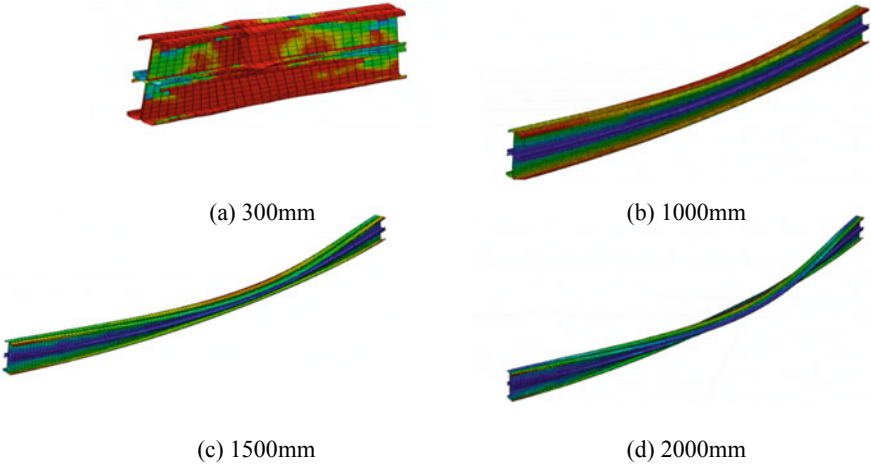(c) 1500mm                             (d) 2000mm

**Fig. 8** Effect of length on the failure pattern on DDIB75-S10-T2

**Fig. 9** Variation of moment capacity against length for DDIB75-3 screws
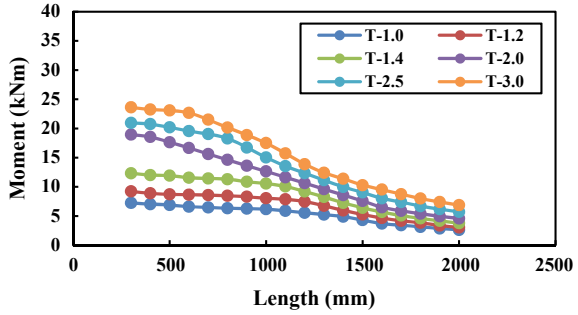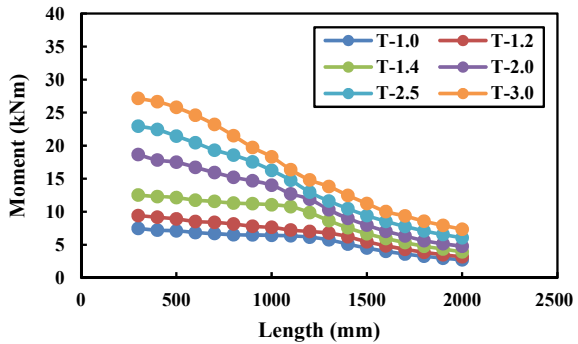


**Fig. 10** Variation of moment capacity against length for DDIB75-5 screws



11 show the ultimate moment capacity versus length for DDIB75 for 3 screws, 5 screws and 10 screws, respectively. From Figs. 9, 10 and 11, it is clear that number of screws doesn't really matter for section 1.0 mm thickness since all of them yields more or less same results. It is found that flexural capacity of DDIB75 sections on 2000 mm length increases capacity up to 6% from 10 to 3 screws for 1.0-mm-thickness models, whereas for 3 mm thickness, percentage increases up to 16%. This shows that as the steel weight increases dependence of fastener spacing increases too. Flexural capacities of the sections increase tremendously if the section weight or thickness of the beam increases. 60% increase in capacity from 1.0 to 2 mm for

**Fig. 11** Variation of moment capacity against length for DDIB75-10 screws
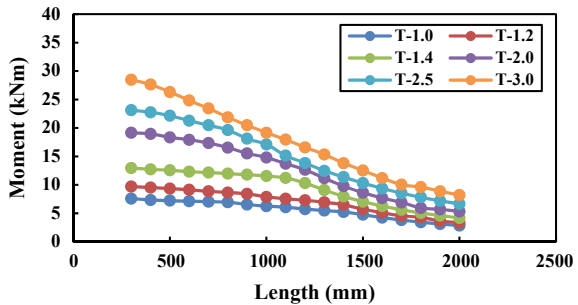
300 mm length, and there is 45% increase in capacity for 2000 mm length. From 2.0 to 3.0 mm for 300 mm length, percentage increase reduced into almost half by 32%, and for 2000 mm, it is 35%. Deflection of sections increases by 6.7% when thickness increases from 1 to 2 mm, and from 2 to 3 mm, it is around 12%. This shows that as the thickness increases even though strength increases deflection of the section too increases due to increase weight. Future researchers and CFS practicing engineers can use the FE model results reported in this paper to forecast the flexural capacities of DDIB-CFS channel section beams. Irrespective of the span and the spacing of longitudinal fasteners, the failure of all the BB75 beams was initiated by local buckling for thickness up to 1.4 mm, and beyond which, the combination of local plus flexural buckling was observed even in the case of stub section beams. All the slender beams failed due to flexural buckling.

## 12  Conclusion

This paper presents numerical investigation double decker-I-beam sections (DDIB75) placed on top of one another screw fastened built-up channel sections under uniform bending. Total of 324 FE models are created and analysed. Length, thickness, and screw spacing of sections are varied to find out effects of each parameter. Failure of section is by local buckling for smaller lengths and by lateral torsional buckling for lengths more than 1500 mm. The following are the outcomes from this study:

- It is found that flexural capacity of DDIB75 sections on 2000 mm length increases capacity up to 6% from 10 to 3 screws for 1.0-mm-thickness models, whereas for 3 mm thickness, percentage increases up to 16%.
- This shows that as the steel weight increases dependence of fastener spacing increases too.
- Flexural capacities of the sections increase tremendously if the section weight or thickness of the beam increases 60% in capacity from 1.0 to 2 mm for 300 mm length, and there is 45% increase in capacity for 2000 mm length. From 2.0 to 3.0 mm for 300 mm length, percentage increase reduced into almost half by 32% and for 2000 mm its 35%.
- Deflection of sections increases by 6.7% when thickness increases from 1 to 2 mm and from 2 to 3 mm its around 12%.
- Irrespective of the span and the spacing of longitudinal fasteners, the failure of all the BB75 beams was initiated by local buckling for thickness up to 1.4 mm, and beyond which, the combination of local plus flexural buckling was observed even in the case of stub section beams. All the slender beams failed due to flexural buckling.
- This shows that as the thickness increases even though strength increases deflection of the section too increases due to increases weight.

- FE model results presented in this paper can be used by future researchers and CFS practicing engineers to predict the flexural capacities of DDIB75 sections.
- For further studies, this work can be extended to study the composite action by comparing with double BB75 sections so that it can be proved that 4-channels beam section can carry more than twice the flexural capacity of 2-channel beam section. This can be also studied by comparing with the available Codal provisions.

# References

1. Ananthi, G. B. G., Vishnuvardhan, S., & Knight, G. M. S. (2015). Experimental, theoretical and numerical study on thin walled steel single and compound channel sections in axial compression. *Indian Journal of Engineering and Materials Sciences, 22*(5), 570–580.
2. Ananthi, G. B. G., Vishnuvardhan, S., & Knight, G. M. S. (2015). Experimental and numerical investigation on thin walled single and starred angle sections under compression. *Arabian Journal for Science and Engineering, 40*(12), 3417–3427.
3. Ananthi, G. B. G., Palani, G. S., & Iyer, N. R. (2016). A study on cold-formed steel web stiffened lipped battened channel columns. *Journal of Structural Engineering (JoSE), 4*(43), 133–141.
4. Ananthi, G. B. G. (2018). A study on cold-formed steel compound angle section subjected to axial compression. *KSCE Journal Civil Engineering, 22*(5), 1803–1815.
5. Ananthi, G. B. G., & Ashvini, B. (2019). Experimental theoretical and numerical studies on cold-formed steel stub channel columns with stiffeners. *Asian Journal of Civil Engineering, 20*, 171–185.
6. Ananthi, G. B. G., Roy, K., & Lim, J. B. P. (2019). Experimental and numerical investigations on axial strength of back-to-back built-up cold-formed steel angle columns. *Steel Composite Structures International Journal, 31*(6), 601–615.
7. Ananthi, G. B. G., Roy, K., Chen, B., & Lim, J. B. P. (2019c). Testing, simulation and design of back-to-back built-up cold-formed steel unequal angle sections under axial compression. *Steel Composite Structures, International Journal, 33*(4), 595–614.
8. Ananthi, G. B. G., Roy, K., Ahmed, A. M. M., & Lim, J. B. P. (2021). Non-linear behaviour and design of web stiffened battened built-up stainless steel channel sections under axial compression. *Structures, 30*, 477–494.
9. Ananthi, G. B. G., Deepak, M. S., Roy, K., & Lim, J. B. P. (2021). Influence of intermediate stiffeners on the axial capacity of cold-formed steel back-to-back built-up unequal angle sections. *Structures., 32*, 827–848.
10. Ananthi, G. B. G., Roy, K., & Lim, J. B. P. (2021). Tests and finite element modelling of cold-formed steel zed and hat section columns under axial compression. *International Journal of Steel Structures., 21*(4), 1305–1331.
11. Deepak, M. S., & Ananthi, G. B. G. (2021). Local buckling behaviour and capacities of cold-formed steel double-I-box stub and short column sections. *Structures, 34*, 1761–1784.
12. Deepak, M. S., & Ananthi, G. B. G. (2021). Buckling capacities of double-T-box girders—A numerical approach. *Structures, 34*, 4574–4595.
13. Glauz, R. S. (2017). Elastic lateral-torsional buckling of general cold-formed steel beams under uniform moment. *Thin-Walled Structures, 119*, 586–592.
14. Kucukler, M., Gardner, L., & Macorini, L. (2015). Lateral-torsional buckling assessment of steel beams through a stiffness reduction method. *Journal of Constructional Steel Research, 109*, 87–100.
15. Wang, L. P., & Young, B. (2015). Beam tests of cold-formed steel built-up sections with web perforations. *Journal of Constructional Steel Research, 115*, 18–33.

16. Roy, K., Ting, T. C. H., Lau, H. H., Chen, B., & Lim, J. B. P. (2021). Flexural behaviour of back-to-back built-up cold-formed steel channel beams: Experiments and finite element modelling. *Structures, 29*, 235–253.
17. Kankanamge, N. D., & Mahendran M. (2012). Thin-walled structures behaviour and design of cold-formed steel beams subject to lateral-torsional buckling at elevated temperatures. *Thin Walled Structures, 61*, 213–228.
18. Deepak, M. S., & Shanthi, V. M. (2018). Distortional buckling–moment resistance capacity of hybrid double-I-box beams. *Journal of Structural Engineering, ASCE, 144*(9), 04018132.
19. Deepak, M. S., & Shanthi, V. M. (2018). Lateral-torsional buckling capacity of hybrid double-I-box beams: A numerical approach. *Advances in Structural Engineering, 22*(3), 641–655.
20. Deepak, M. S., & Shanthi, V. M. (2018). Member distortional buckling behaviour of hybrid-double-I-box beams. *Canadian Journal of Civil Engineering, 45*(8), 605–622.
21. Deepak, M. S., & Shanthi, V. M. (2018). Section bending resistance of new hybrid double-I-box beams. *Advances in Structural Engineering, 21*(11), 1676–1695.
22. Wang, L. P., & Young, B. (2017). Design of cold-formed steel built-up sections with web perforations subjected to bending. *Thin-Walled Structures, 120*, 458–469.
23. Wang, L. P., & Young, B. (2018). Behaviour and design of cold-formed steel built-up section beams with different screw arrangements. *Thin-Walled Structures, 131*, 16–32.
24. Zhu, J. H, Su, M.-N., Zhu, X., Daniels, J., & Young, B. (2021). Flexural behaviour of cold-formed steel oval hollow section beams. *J Constr Steel Res, 180*, 106605.
25. ABAQUS. (2018). Version 6.14–2, USA: SIMULIA, Providence.
26. Schafer, B. W., & Pekoz, T. (1998). Computational modelling of cold-formed steel: Characterizing geometric imperfections and residual stresses. *Journal of Constructional Steel Research, 47*, 193–210.