Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Georgia, Atlanta, April 21-24, 2020

Axial strength and stability behaviour of cold-formed steel battened closed section columns

M. Adil Dar[1], Dipti Ranjan Sahoo[2], Arvind K. Jain[3]

Abstract

Primarily, structural members like columns experience high axial load demands, and the mono-sectional cold-formed steel (CFS) profiles may not be adequate from strength/stiffness considerations, which gives rise to the adoption of CFS built-up sections. Generally, a built-up section is formed by fastening two channel sections in the back-to-back arrangement, and results in an open built-up section. The past research has identified the performance of closed built-up sections being better than the open ones, especially in terms of their stability from the torsional resistance point of view. A closed built-up column which is formed by adequately spaced chords in the transverse direction, with batten plates used to connect the chord members may perform significantly well. Also, the past research output on CFS battened columns has been limited. Therefore, there is a need to study the strength and stability behavior of CFS battened columns with closed sections. This study presents an experimental investigation carried out on CFS built-up columns connected with battened plates. Pin ended support conditions allowing uniaxial bending were adopted. Since the relative slenderness of the unbraced chord with respect to the built-up column is decisive in influencing the structural performance of battened columns, this ratio was varied by changing two parameters, viz., the transverse spacing between the chord members (in Group-A specimens) and intermediate batten spacing (in Group-B specimens). The effect of the variation of both these parameters on the strength/stiffness characteristics was studied. In both these groups, the specimens were designed such that the unbraced chord slenderness was around $1/4^{th}$, $1/2^{nd}$ and $3/4^{th}$ of that of the global column slenderness. Furthermore, the design strengths of the built-up columns were computed using North American Specification and Eurocode for CFS structures. The design strength predictions of both these standards were found to be un-conservative. Also, the design clause on the built-up columns composed of two chords in contact, given in the North American Specification, viz., the unbraced chord slenderness should not exceed half of the global column slenderness did not help in safely predicting the strengths of short and intermediate CFS battened columns with closed sections.

[1] Doctoral Scholar, Indian Institute of Technology Delhi, <madar@civil.iitd.ac.in>
[2] Associate Professor, Indian Institute of Technology Delhi, <drsahoo@civil.iitd.ac.in>
[3] Professor, Indian Institute of Technology Delhi, <akjain@civil.iitd.ac.in>

1. Introduction

Cold-formed steel (CFS) has become popular in the constructional sector, mainly due to its good structural features like light-weighted-ness, easy in fabrication/handling, better strength/weight ratio, durable construction (when compared with other light-weight materials) and better consistency in the material strength. These features make it more adoptable for structural construction, especially when the location of the construction is remote and the ease of transportation and handling of the sections is matters significantly. Also, in the cases where limited time is allotted to complete the construction, CFS sections are highly preferred, as it just takes assembling of the various structural members to complete the project. Although, there are numerous attractive features in CFS sections that encourage their utilization in the construction, the thin-walled nature of CFS section still restricts their adoption due to the local buckling instability of the various cross-sectional thin plate elements (Yu 2010; Zeimian 2010). This has encouraged the structural steel researchers worldwide to work in this area and find a sustainable solution to these instability issues. Many researchers have come out with effective, efficient and economical approaches to improve the buckling resistance of CFS sections experiencing different types of stresses (Landesmann et al. 2016; Camotim et al. 2018; Dar et al. 2020a-b; 2019a-c; 2018a; 2015; Kumar & Sahoo 2016; Bian et al. 2016; Kesawan et al. 2017; Paratesh et al. 2019; Maderia et al. 2015).

2. CFS built-up columns

Generally, a CFS built-up column is formed by connecting two channel sections with the help of self-drilling screws fastened through the webs, at regular longitudinal spacing. These types of sections are commonly used in the CFS construction. Many researchers have contributed towards improving the performance of such built-up columns, by suggesting the limiting values of the sectional compactness of the different cross-sectional plate elements, and by proposing the screw pattern as well as their arrangement (Fratamico et al. 2018a-b). The performance of such columns can further be improved by increasing the transverse spacing between the chords (Subramanian 2016). Different connecting systems have been suggested to ensure the composite action of the chords. The transverse spacing also improves the structural stability of these columns, in addition to improving the torsional resistance (Anbarsu & Dar 2020a; Dabaon et al. 2015a-b; Zhang & Young 2015; Vijayanand & Anbarasu 2019;2020; Anbarasu et al. 2015). However, by adopting the same chord members in the toe-to-toe configuration, the stability, as well as the torsional resistance, can be enhanced substantially (Kherbouche & Megnounif 2019). Closed CFS built-up columns have displayed better axial resistances with improved stability features (Zhang & Young 2018; Liao et al. 2017; Dar et al. 2018b; 2019d-e; 2020d-e; Roy et al. 2019). There has been limited research carried out on CFS built-up columns with closed sectional configuration, connected with battened plates (EI Aghoury et al. 2010; 2013; Dar et al. 2020c; Anbarasu & Dar 2020b; Anbarasu 2020). Moreover, no experimental results on CFS battened columns with closed sections comprising of plain channel sections, have been reported so far.

Therefore, there is a need to study the strength and stability behavior of CFS battened columns with closed sections. This study presents an experimental investigation on CFS built-up columns connected with battened plates. Pin ended support conditions allowing uniaxial bending were adopted. Since the relative slenderness of the unbraced chord with respect to the built-up column is decisive in influencing the structural performance of battened columns, this ratio was varied by changing two parameters, viz., intermediate batten spacing and the transverse spacing between the chord members. The effect of the variation of both these parameters on the strength/stiffness characteristics was studied. Furthermore, the design strengths of the built-up columns were computed using North American Specification and Eurocode for CFS structures.

3. Experimental Study

This section comprises of the details pertaining to the test specimens, results of the material properties and the axial tests performed.

3.1 Test Specimens

Five test specimens as shown in Fig.1, were prepared to achieve the objectives of this study. Each column specimen was composed of two plain CFS channel sections of size 100 x 25 x 2, where 100 is the depth of the web element, 25 is the width of the flange element, and 2 is the thickness of the channel section, all in mm. The height of all the specimens was fixed at 2400mm. To connect the two channel sections together, batten plates of thickness 6mm were used. The depths of the end batten and intermediate batten were 150mm and 100 mm respectively. Self-drilling screws of 5mm diameter and 400mm length were used to fasten the channels in the toe-to-toe arrangement. Based on the toe-to-toe spacing and the intermediate batten spacing, two groups of columns were formed. In the first group, i.e., Group-A, the intermediate batten spacing was fixed at 175mm and the toe-to-toe spacing was considered as 0mm in the Model-I, and then increased in the increments of 50mm, for Model-II and Model-III. In the second group, i.e., Group-B, the toe-to-toe spacing was fixed at 50mm and the intermediate batten spacing was adopted as 100mm, 175mm and 265mm in specimens Model-IV, Model-II, and Model-V respectively. In both these groups, the specimens were designed such that the unbraced chord slenderness was around $1/4^{th}$, $1/2^{nd}$ and $3/4^{th}$ of that of the global column slenderness.

3.2 Material Properties

The determination of the actual material properties of the steel used in the chords is important. This was achieved through tensile coupon testing of the coupons, which conformed to Indian Standards (IS 1608, 2005), and were extracted from the CFS channels. An MTS universal testing machine (UTM) was employed for performing these tensile tests. A total of three coupon tests were performed. The average values of the yield strength (f_y in MPa), ultimate strength (f_u in MPa), modulus of elasticity (E in GPa), and elongation (e in %) were noted as 408.5, 540.5, 198 and 23.8. The details of the material tests are given in Fig.2.

3.3 Test Set-up

A robust loading frame with a capacity of 1000kN as shown in Fig. 3, was used in performing the concentric axial compression testing of the CFS battened closed section columns. The axial compression loading was applied by means of a hydraulic jack with a capacity of 250kN. Uniaxial hinges were considered to simulate the pin ended support conditions. The loading is applied to the test specimens was monitored with the help of a load cell. Displacement sensors were adopted for monitoring the axial and lateral displacements during the loading of the specimens. Also, strain gauges were used for strain monitoring during the course of loading. The other details of the test set-up can be found elsewhere (Dar et al. 2018b).

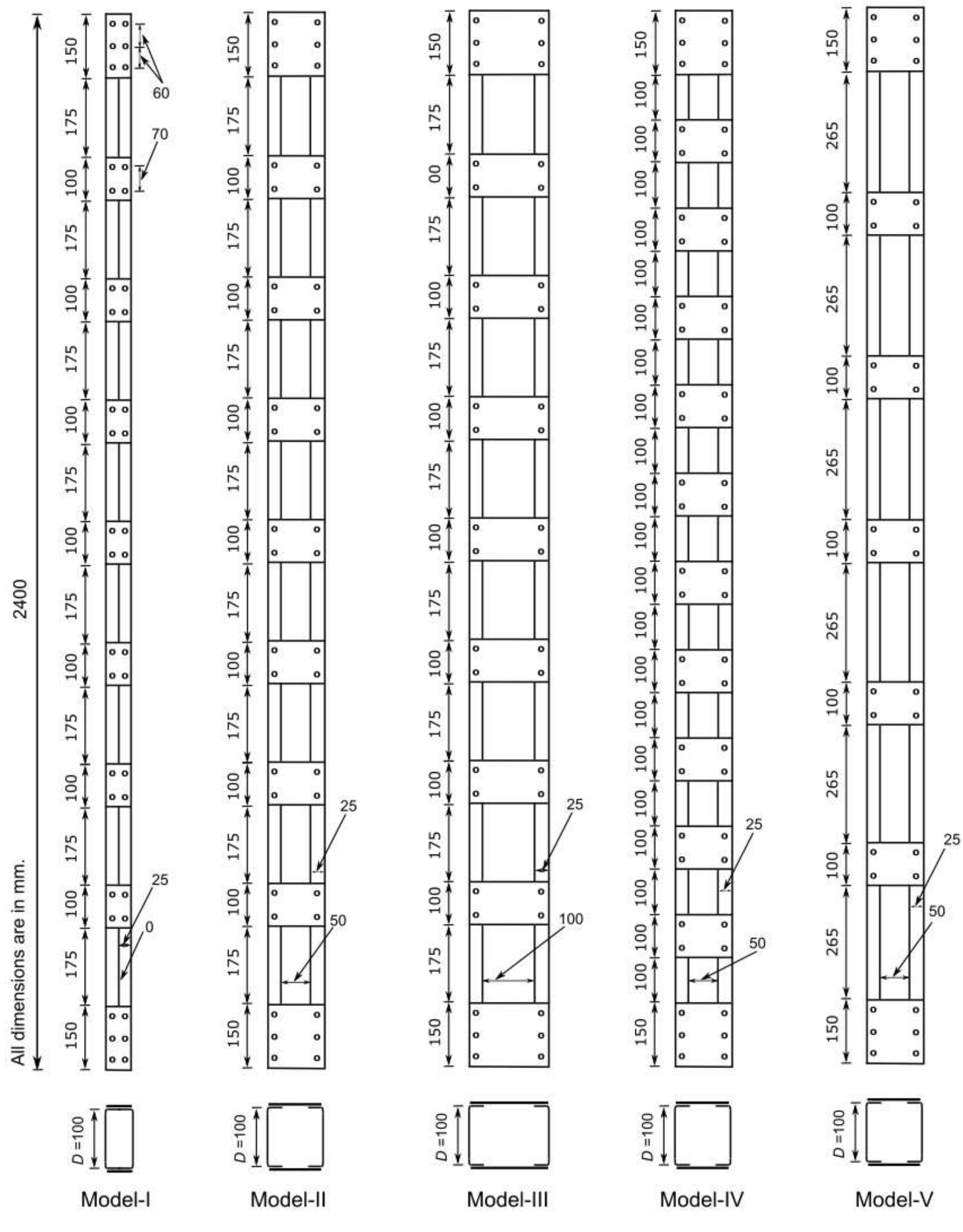


Figure 1: Details of the test specimens

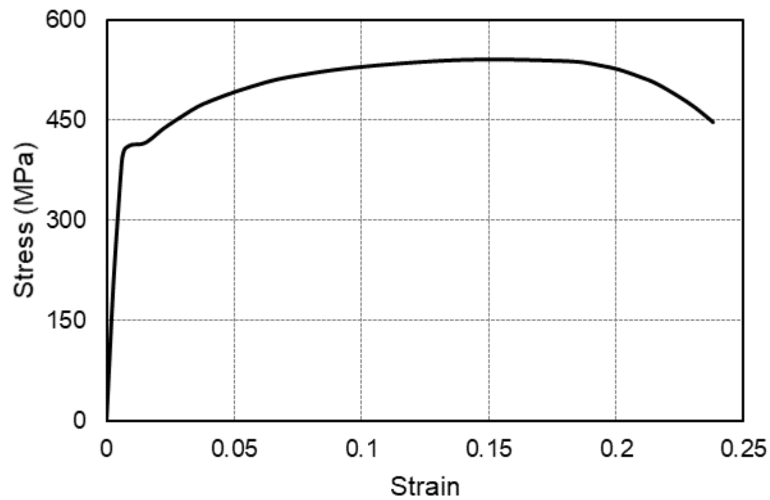


Figure 2: Stress *vs.* strain behavior of the coupons

3.4 Test Results

The load vs. displacement behaviour (axial as well as lateral) of all the specimens is shown in Fig.4. Model-I carried a peak load of 71.5kN with axial displacement of 12.15mm. Since the overall slenderness of the specimen was large, it behaved like a typical intermediate column and exhibited similar behaviour. On increasing the transverse spacing between the chords, the overall slenderness of the specimens dropped, and the specimen fell under the short column category. Model-II carried a peak load of 157.2 kN with axial displacement of 3.56mm, clearly displaying the characteristics of an intermediate column. As the transverse spacing was increased further, the overall slenderness dropped further, and the specimen fell under the short column category. Model-III carried a peak load of 162.2kN with axial displacement of 3.9mm. Despite possessing lower overall slenderness, the axial displacement in Model-III was higher than Model-II. This was mainly due to larger lateral displacement in the non-hinge direction, which was primarily due to lower lateral stiffness in that direction. Model-IV and Model-V carried a peak load of 175.4kN and 143.2kN with axial displacement of 4.2mm and 2.8mm respectively. The normalized lateral displacements of the various specimens with respect to their heights were computed and plotted against their respective overall slenderness, presented in Fig.5. The Model-I being an intermediate column displayed large lateral displacement, which was nearly 2% of its height. On the other hand, Model-III which carried a higher load than Model-I by around 130%, displayed half of the lateral displacement of that of Model-I, i.e., 1% of its height. The strain behaviour in all the specimens was similar to that of a typical thin-walled compression member. Fig.6 shows the state of strain during the compressive loading of Model-I. Strain variation was observed at the initial stages of loading. Also, strain reversals were observed due to the local buckling instability towards the later stages of loading.

Although the sectional compactness of the channel sections used as chords in this study was lower than that of the angle sections used by Dar et al. (2018b), no early local buckling instability was observed here. This clearly reflects that the end conditions of the plate element govern the early local buckling instability under compressive loading. Model-I, which was an intermediate column failed by combined local and flexural buckling. Rest, all the specimens failed by predominant local buckling. Fig.7(a-e) shows that failure modes of Model-I, Model-II, Model-III, Model-IV, and Model-V respectively. Also, no failure at the connection level was observed in any specimen. Therefore, when the connections are adequately designed, the type of the connection used, whether bolts or self-drilling screws don't alter the behaviour of CFS built-up columns.

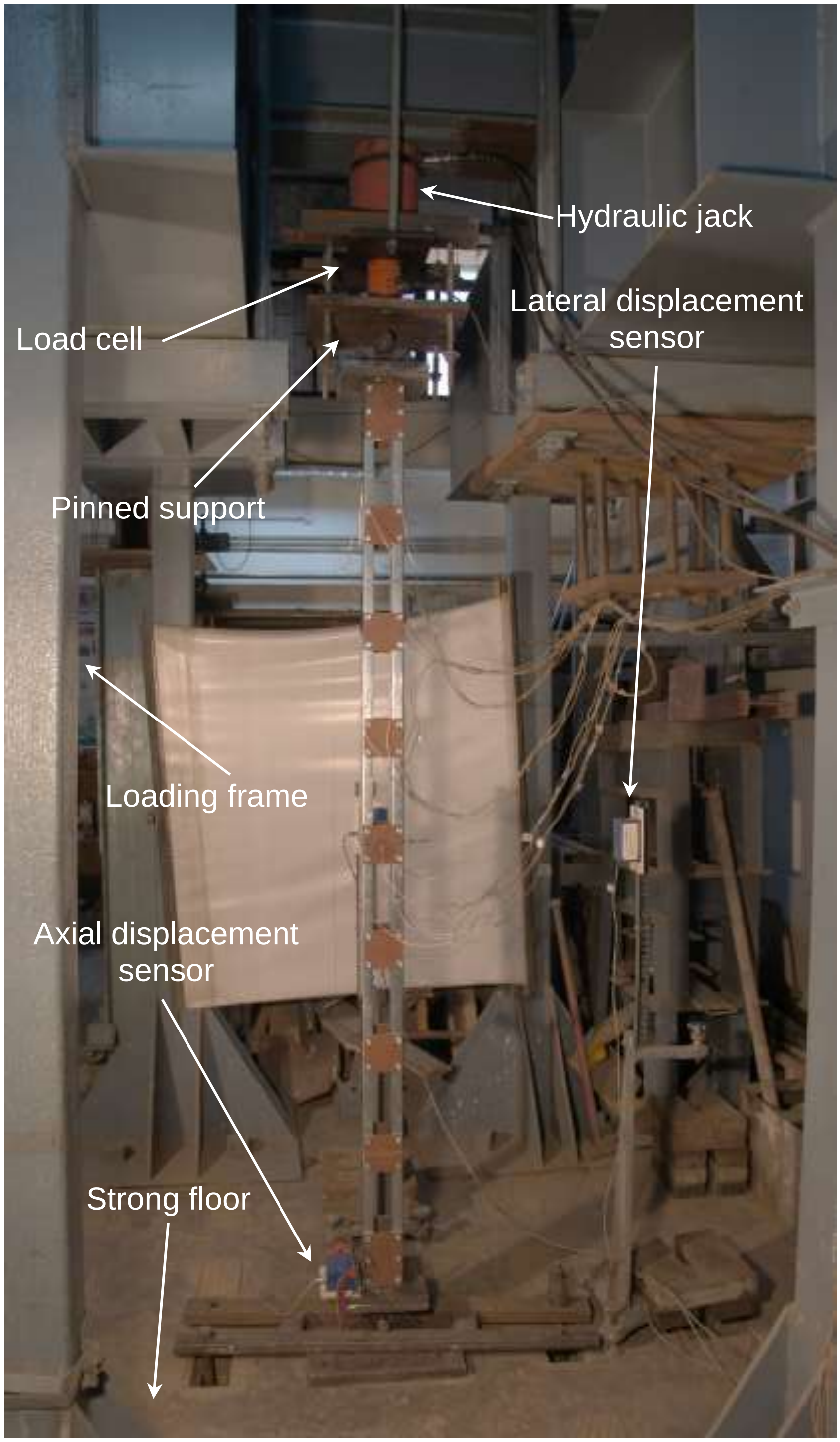
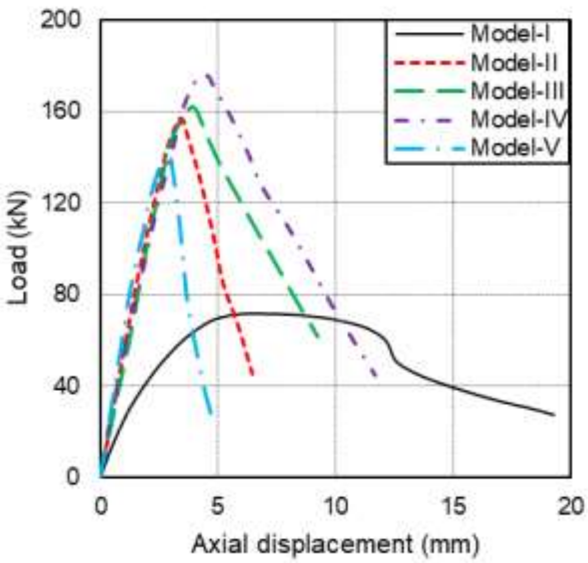


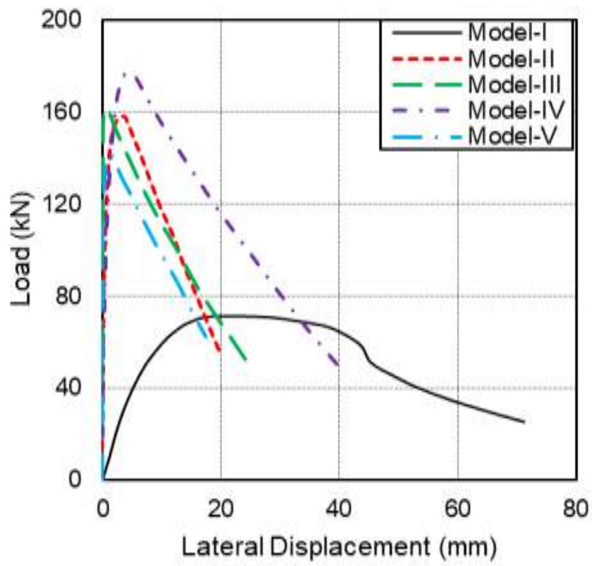
Figure 3: Details of the test set-up

Table 1: Comparison of test results, numerical results are design strengths

Specimen	λ	Test results	Design strengths					
			NAS			EC3		
		P_{Test} (kN)	λ_c	P_{NAS} (kN)	P_{NAS}/P_{Test}	$\bar{\lambda}$	P_{EC3} (kN)	P_{EC3}/P_{Test}
Model-I	108.65	71.50	1.62	79.77	1.11	108.65	75.54	1.05
Model-II	51.62	157.41	0.83	172.53	1.09	51.62	160.14	1.01
Model-III	33.65	163.01	0.61	191.87	1.17	33.65	182.30	1.11
Model-IV	51.62	176.20	0.78	177.75	1.00	51.62	160.14	0.90
Model-V	51.62	143.10	0.93	162.55	1.13	51.62	160.14	1.11



(a)Axial displacement



(b) Lateral displacement

Figure 4: Load *vs.* displacement response

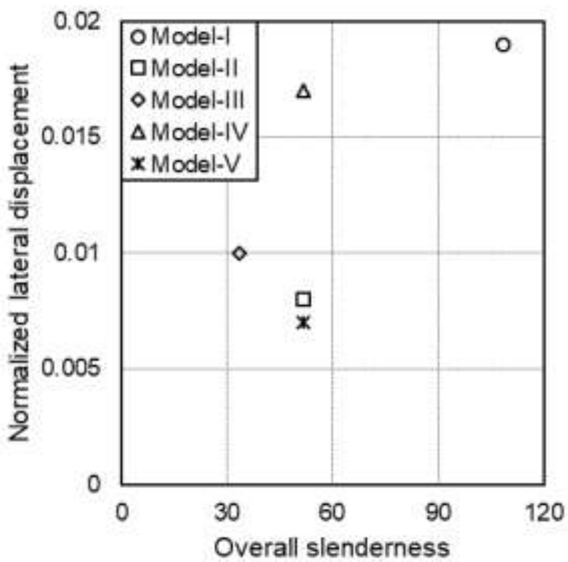


Figure 5: Absolute displacement response

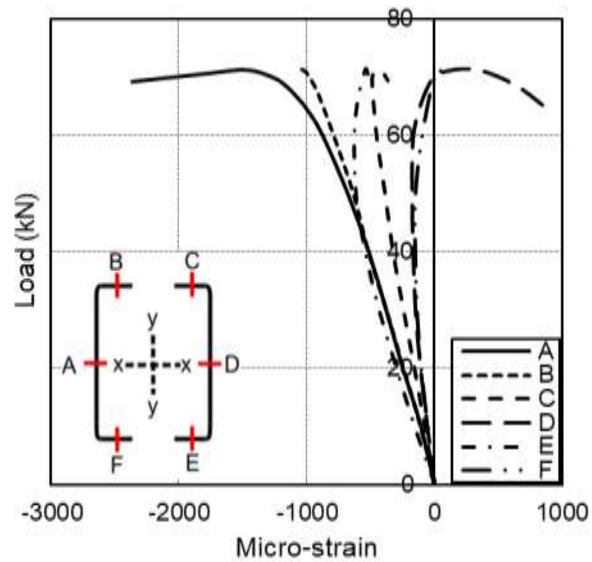
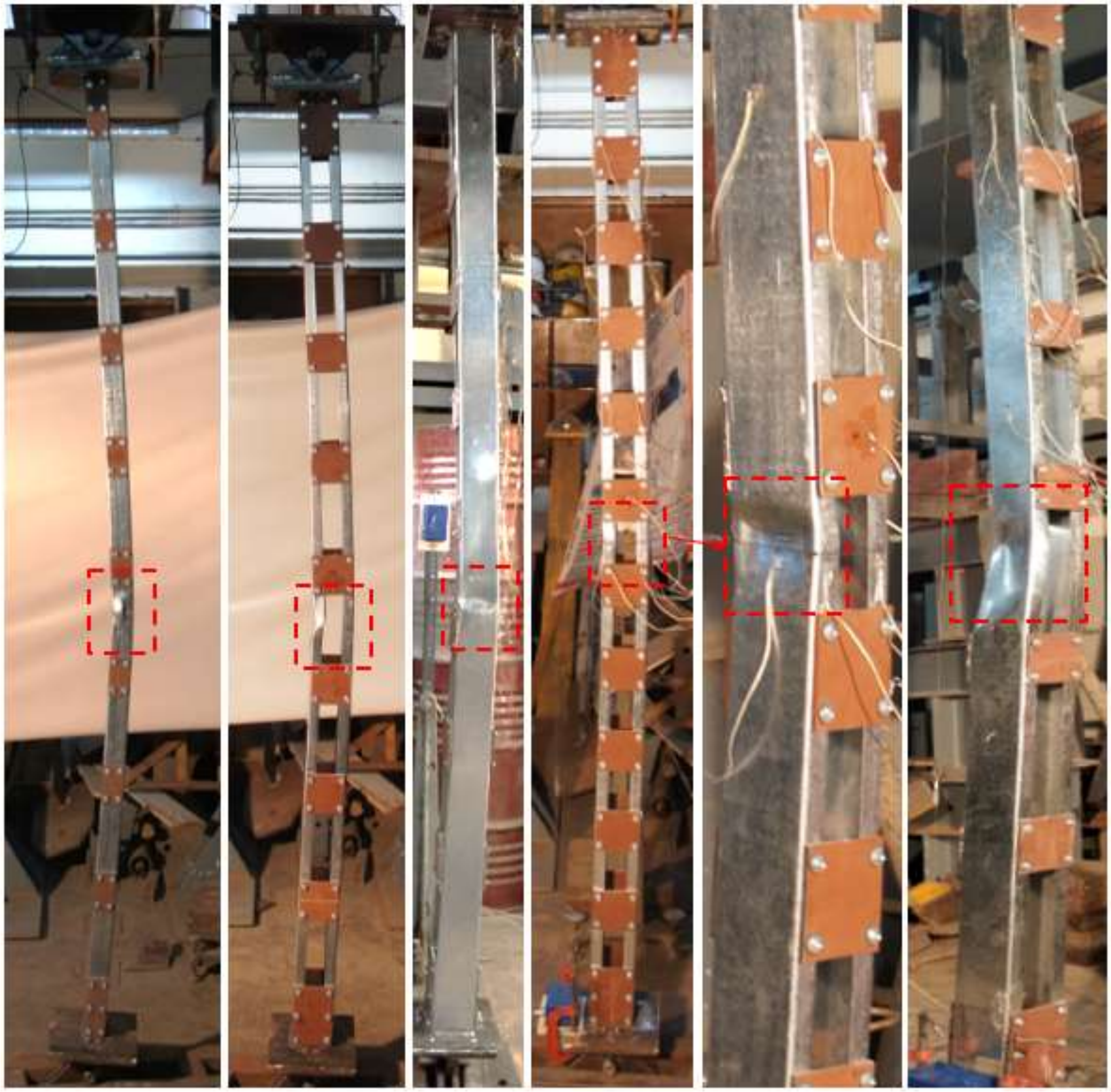


Figure 6: Typical strain plot



(a) (b) (c) (d) (e)

Figure 7: Failure in the test models

As of now, there are no standards that explicitly bring out guidelines for designing CFS battened columns. Therefore, using the effective width approach, the design strengths of the various CFS battened closed section columns were determined using both North American Standard (AISI S-100, 2016) as well as European Code (EN1993-1-3 2006). The comparison of the test results with the different design strengths is given in Table 1 and Fig.8. It was noted that except for Model-IV (where the intermediate batten spacing was small and the unbraced chord slenderness was less than 1/4th of that of the global column slenderness.), both these standards un-conservatively predicted the strengths of these built-up columns. The North American Standard (AISI S-100, 2016) was more un-conservative than the European Code (EN1993-1-3 2006). Also, the design clause (I1.2) on the built-up columns composed of two chords in contact, given in the North American Specification (AISI S-100, 2016), viz., the unbraced chord slenderness should not exceed half of the global column slenderness did not help in safely predicting the strengths of short and intermediate CFS battened columns with closed sections.

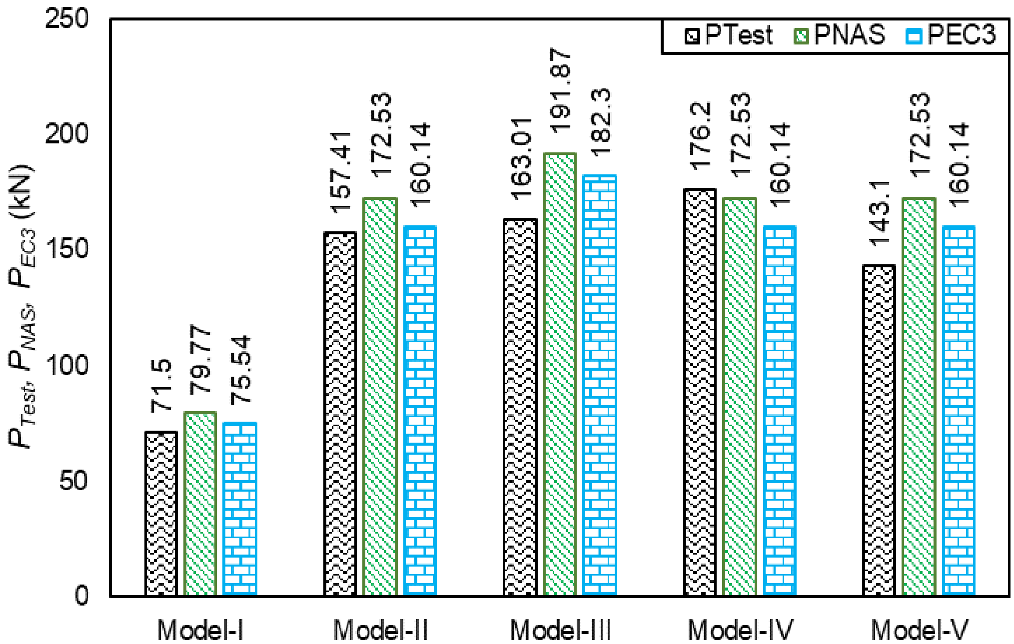


Figure 8: Comparison of test results with the design strength predictions

4. Summary and Conclusions

This study presented an experimental investigation on CFS built-up columns connected with battened plates. Pin ended support conditions allowing uniaxial bending were adopted. The effect of the variation of both the transverse spacing between the chords and the intermediate batten spacing on the strength/stiffness characteristics was studied. Furthermore, the design strengths of the built-up columns were computed using North American Specification and Eurocode for CFS structures. This study indicated that except for intermediate columns, where the overall slenderness influences the column behavior, the intermediate batten spacing affected the performance of columns falling under the short column category. Also, the boundary conditions of the plate element of the cross-section control the early local buckling response. Furthermore, the failure mode was not greatly affected by the variation in the transverse chord spacing and the intermediate batten spacing, except for intermediate columns. Both the North American Standard (AISI S-100, 2016) and the European Code (EN1993-1-3 2006) are inadequate for predicting the strengths of CFS battened closed section columns, particularly when the unbraced chord slenderness is large. Also, the design clause on the built-up columns composed of two chords in contact, given in the North American Specification, viz., the unbraced chord slenderness should not exceed half of the global column slenderness did not help in safely predicting the strengths of short and intermediate CFS battened columns with closed sections.

References

AISI S-100 (2016), "*North American specification for the design of cold-formed steel structural members*", AISI Standard, Washington, DC.

Anbarasu, M. (2020) "Behaviour of cold-formed steel built-up battened columns composed of four lipped angles: Tests and numerical validation", *Advances in Structural Engineering*, 23(1) 51–64.

Anbarasu, M., Dar, M.A. (2020a) "Axial capacity of CFS built-up columns comprising of lipped channels with spacers: Nonlinear response and design", *Engineering Structures*, 213, 110559.

Anbarasu, M., Dar, M.A. (2020b) "Improved design procedure for battened cold-formed steel built-up columns composed of lipped angles", *Journal on Constructional Steel Research*, 164,105781.

Anbarasu, M., Kanagarasu, K., Sukumar, S. (2015) "Investigation on the behaviour and strength of cold-formed steel web stiffened built-up battened columns", *Materials & Structures*, 48(12) 4029-4038.

Bian, G., Peterman, K.D., Torabian, S., Schafer, B.W. (2016) "Torsion of cold-formed steel lipped channels dominated by warping response", *Thin Walled Structures*, 98(B) 565-577.

BS EN1993-1-3 (2006), *Design of steel structures. Part1-3: General rules – Supplementary rules for cold-formed members and sheeting*, Brussels: European Committee for Standardization.

Camotim, D., Dinid, P.B., Martins, A.D., Young, B. (2018) "Review: Interactive behaviour, failure and DSM design of cold-formed steel members prone to distortional buckling", Thin-Walled Structures, 128 12-42.

Dabaon, M., Ellobody, E., Ramzy, K. (2015a) "Experimental investigation of built-up cold-formed steel section battened columns", *Thin-Walled Structures*, 92 137-145.

Dabaon, M., Ellobody, E., Ramzy, K. (2015b) "Nonlinear behaviour of built-up cold-formed steel section battened columns", *Journal on Constructional Steel Research*, 110 16-28.

Dar, M.A., Subramanian, N., Dar, D.A., Dar, A.R., Anbarasu, M., Lim, J.B.P., Mahjoubi, S. (2020a) "Flexural Strength of cold-formed steel built-up composite beams with rectangular compression flanges", *Steel & Composite Structures*, 34(2) 171-188.

Dar, M.A., Subramanian, N., Mir, A., Dar, A.R., Anbarasu, M., Lim, J.B.P. (2020b) "Efficient cross-sectional profiling of built up CFS beams for improved flexural performance", *Steel & Composite Structures*, 34(3) 333-345.

Dar, M.A., Sahoo, D.R., Jain, A.K. (2020c) "Numerical Study on the Structural Integrity of Built-up Cold-Formed Steel Battened Columns", In: Prakash, R., Suresh Kumar, R., Nagesha, A., Sasikala, G., Bhaduri, A. (Eds) Structural Integrity Assessment. *Lectures Notes in Mechanical Engineering*, Springer Singapore.

Dar, M.A., Pulikkal, S., Sahoo, D.R., Jain, A.K. (2020d) "Axial Resistance of Short Built-up Cold-formed Steel Columns: Effect of Lacing Slenderness", In: Prakash, R., Dutta, S., Inann, E., Dwivedy, S.K. (Eds), Advances in Structural Vibration, *Lecture Notes in Mechanical Engineering*, Springer Singapore.

Dar, M.A., Sahoo, D.R., Jain, A.K. (2020e) "Axial Compression Capacity of CFS Built-Up Columns with N-Type Lacing: Influence of Lacing Slenderness", *Indian Structural Steel Conference* (ISSC-2020), IIT Hyderabad,

Dar, M.A., Subramanian, N., Dar, A.R., Muheeb, M., Haseeb, M., Mugees, T. (2019a) "Structural efficiency of various strengthening schemes for cold-formed steel beams: Effect of global imperfections", *Steel & Composite Structures*, 30(4) 393-403.

Dar, M.A., Subramanian, N., Rather, A.I., Dar, A.R., Lim, J.B.P., Anbarasu, M., Roy, K. (2019b) "Effect of angle stiffeners on the flexural strength and stiffness of cold-formed steel beams", *Steel & Composite Structures*, 32(2) 225-243.

Dar, M.A., Subramanian, N., Dar, A.R., Anbarasu, M., Lim, J.B.P., Mir, A. (2019c) "Behaviour of partly stiffened cold-formed steel built-up beams: Experimental investigation and numerical validation", *Advances in Structural Engineering*, 22(1) 172-186.

Dar, M.A., Sahoo, D.R., Jain, A.K. (2019d) "Axial compression behavior of laced cold-formed steel built-up columns with unstiffened angle sections", *Journal on Constructional Steel Research*, 162, 105727

Dar, M.A., Sahoo, D.R., Jain, A.K. (2019e) "Compression capacity of short cold-formed steel built-up columns with double lacing configuration and low sectional compactness", *Proceedings of SSRC Annual Stability Conference*, St. Lousi, Missouri, USA, 1 472-482.

Dar, M.A., Subramanian, N., Anbarasu, Dar, A.R., M., Lim, J.B.P. (2018a) "Structural Performance of Cold-formed Steel Composite Beams", *Steel & Composite Structures*, 27(5) 545-554.

Dar, M.A., Sahoo, D.R., Pulikkal,S., Jain, A.K. (2018b) "Behaviour of laced built-up cold-formed steel columns: Experimental investigation and numerical validation", *Thin Walled Structures* 132 398-409.

Dar, M.A., Yusuf, M., Dar, A.R., Raju, J. (2015) "Experimental Study on Innovative Sections for Cold Formed Steel Beams", *Steel & Composite Structures*, 19(6) 1599-1610.

El Aghoury, M.A., Salem, A.H., Hanna, M.T., Amoush, E.A. (2010) "Experimental investigation for the behaviour of battened beam-columns composed of four equal slender angles", *Thin Walled Structures,* 48(9) 669-683.

El Aghoury, M.A., Salem, A.H., Hanna, M.T., Amoush, E.A. (2013) "Strength of cold formed battened columns subjected to eccentric axial compressive force", *Journal on Constructional Steel Research*, 113 58-70.

Fratamico, D.C., Torabian, S., Zhao, X., Rasmussen, K.J.R., Schafer, B.W. (2018a) "Experiments on the global buckling and collapse of built-up cold-formed steel columns", *Journal on Constructional Steel Research*, 144 65–80.

Fratamico, D.C., Torabian, S., Zhao, X., Rasmussen, K.J.R., Schafer, B.W. (2018b) "Experimental study on the composite action in sheathed and bare built-up cold-formed steel columns", *Thin-Walled Structures*, 127 290-305.

IS 1608: 2005, *Indian Standard- Metallic Materials - Tensile Testing at Ambient Temperature*, Bureau of Indian Standards, New Delhi, India.

Kesawan, S., Mahendran, M., Dias, Y., Zhao, W. (2017) "Compression tests of built-up cold-formed steel hollow flange sections", *Thin Walled Structures,* 116 180-193.

Kherbouche, S., Megnounif, A. (2019) "Numerical study and design of thin walled cold formed steel built-up open and closed section columns", *Engineering Structures,* 179 670-682.

Kumar, N., Sahoo, D.R. (2016) "Optimization of lip length and aspect ratio of thin channel sections under minor axes bending", *Thin-Walled Structures*, 100 158-169.

Landesmann, A., Camotim, D., Garcia, R. (2016) "On the strength and DSM design of cold-formed steel web/flange-stiffened lipped channel columns buckling and failing in distortional modes", *Thin Walled Structures* 105 248-265.

Liao, F., Wu, H., Wang, R., Zhou, T. (2017) "Compression test and analysis of multi-limbs built-up cold-formed steel stub columns", *Journal on Constructional Steel Research*, 128 405-415.

Madeira, J.F.A., Dias, J., Silvertre, N. (2015) "Multiobjective optimization of cold-formed steel columns", *Thin Walled Structures,* 96 29-38.

Parastesh, H., Hajirasouliha, I., Taji, H., Sabbagh,B.A. (2019) "Shape optimization of cold-formed steel beam-columns with practical and manufacturing constraints", *Journal on Constructional Steel Research*, 155 249-259.

Roy, K., Ting, T.C.H., Lau, H.H., Lim, J.B.P. (2019) "Experimental and numerical investigations on the axial capacity of cold-formed steel built-up box sections" *Journal on Constructional Steel Research*, 160 411-427.

Subramanian, N. (2016) "*Design of Steel Structures-Limit States Method*" Second Edition, Oxford University Press, New Delhi,

Vijayanand, S., Anbarasu, M. (2019) "Strength and behavior of cold-formed steel built-up battened columns: tests and numerical validation", *Journal of Structural Engineering-Madras*, 46(2) 154-165.

Vijayanand, S., Anbarasu, M. (2020) "Behavior of CFS Built-up Battened Columns: Parametric study and Design recommendations", *Structural Engineering & Mechanics*, [Accepted]

Yu, W.-W. (2010) "*Cold-Formed Steel Structures"* Forth Edition, McGraw-Hill, New York.

Zhang, J., Young, B. (2015) "Numerical investigation and design of cold-formed steel built-up open section columns with longitudinal stiffeners", *Thin-Walled Structures*, 89 178-191.

Zhang, Z., Young, B. (2018) "Experimental investigation of cold-formed steel built-up closed section columns with web stiffeners", *Journal on Constructional Steel Research*,147 380-392.

Ziemian, R.D. (2010) "*Guide to Stability Design Criteria for Metal Structures"*, 6^{th} Ed, Wiley, New York.

Notations

CFS : Cold-formed steel
E : Modulus of elasticity
f_u : Ultimate strength
f_y : Yield strength
LVDT : Linear variable displacement transducer
P_{EC3} : Design strength predicted by EC-1993-3
P_{NAS} : Design strength predicted by AISI-S100
P_{Test} : Ultimate test strength
ε : Strain at fracture
λ : Overall column slenderness ratio
λc : Critical slenderness
λ : Overall non-dimensional slenderness