*Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Denver, Colorado, March 22-25 2022*

Effect of unsupported chord slenderness on the buckling strength and stability response of CFS battened columns

M. Adil Dar[1], Abhishek Verma[2], Pang Sze Dai[3], M. Anbarasu[4], A.R. Dar[5]

Abstract

The global performance of framed structural systems is controlled by the behaviour of column elements, which need to develop sufficient strength and stiffness under different loading conditions. Built-up columns are used in a typical low-rise cold-formed steel (CFS) framing system when the axial load demands are high, and a single channel section does not suffice from strength and or serviceability considerations. Such built-up sections are fabricated by fastening two channels held in the back-to-back configuration. The major drawback of such columns is the inefficient utilization of steel, with low radius of gyration, axial capacity and stability. The previous research has indicated that adequate transverse spacing between the chords significantly improves the axial performance of such gapped built-up columns. Limited tests on CFS battened columns (with channel chords) have revealed that the unsupported chord slenderness significantly impacts the performance of battened columns. Furthermore, it was suggested that the relative slenderness of the unsupported chord should not exceed 0.25, if the current codes for the design of CFS members were to be adopted for strength predictions. However, it needs to be substantiated properly, as few test results were used to bring out this recommendation. This study deals with a numerical investigation on the role of unsupported chord slenderness and chord compactness in governing the axial strength and deformation behaviour of battened columns composed of unstiffened channels. Two plain CFS channels with adequate transverse gap to achieve the cross-sectional aspect ratio as unity, were connected in toe-to-toe arrangement using batten plates to form closed built-up sections. Special emphasis was put on the influence of unsupported chord slenderness on battened columns' buckling strength and stability response. Four zones of relative unbraced chord slenderness (i.e., 0.25, 0.5, 0.75 and 1.0.) for each stub column were investigated. Before conducting the extensive parametric study, the numerical model was adequately validated against the test results on battened columns available in the literature. The results of the numerical analysis were used to check the adequacy of the current North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006) for CFS structures.

[1] Postdoctoral Research Fellow, Department of Civil and Environmental Engineering, National University of Singapore, dar.adil@nus.edu.sg

[2] Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, abhi.verma@iitg.ac.in

[3] Associate Professor, Department of Civil and Environmental Engineering, National University of Singapore, ceepsd@nus.edu.sg

[4] Associate Professor, Department of Civil Engineering, Government College of Engineering Salem, Tamil Nadu, anbarasu@gcesalem.edu.in

[5] Professor, Department of Civil Engineering, National Institute of Technology Srinagar, Jammu & Kashmir, abdulrashid@nitsri.ac.in

1. Introduction

Lightweight construction using cold-formed steel (CFS) sections is very popular, due to various desirable features like flexibility in forming different sectional profiles, the efficient utility of steel material, higher yield strength due to cold work, etc. The lightweight feature of CFS members makes the transportation and the various handling operations very easy, therefore, adding to the cost savings. Furthermore, CFS construction becomes even more advantageous when the construction site is remotely located, and the costs of transportation and handling become minimal. It facilitates timely completion of construction projects as assembling/connecting different structural elements is easy, fabricated in a quality-controlled environment inside a factory. Despite CFS sections offering several advantages over other conventional building materials, such sections are prone to buckling instabilities, resulting in early failure, that too at a lower load. This major drawback limits their application to non-load bearing to moderately loaded elements (Yu 2010; Zeimian 2010). This limited application of CFS sections promoted structural steel researchers to work in this area and to improve their structural stability performance for a higher loading application. The last decade has witnessed a substantial improvement in the structural response of CFS sections across various domains (Zhou et al. 2022; 2021a-b; Nie et al. 2020a-b; Selvaraj & Madhavan 2022; Li and Young 2022; Li et al. 2021; Rasmussen et al. 2020; Landesmann et al. 2016; Camotim et al. 2018; Kumar & Sahoo 2016; Bian et al. 2016; Kesawan et al. 2017; Paratesh et al. 2019; Joorabchian et al. 2021; Derveni, et al. 2020; Maderia et al. 2015; Gatheeshgar et al. 2020).

2. CFS built-up columns

Built-up columns are generally adopted in typical low-rise CFS framing structures when the axial load demands exceed a mono-profile's capacity from strength or serviceability aspects. Such built-up sections very easy to construct, as it just takes two channels held in the back-to-back configuration, and fastened through the webs, to make a built-up column member. Numerous studies were carried out to enhance the buckling stability performance of such traditional built-up built-up columns by specifying the limits to the cross-sectional compactness, and proposing suitable pattern of the screwed connections at various locations, and different other aspects (Selvaraj & Madhavan 2021; Mahar et al. 2021a;b; Mahar and Jayachandran 2021; Roy et al. 2018; Fratamico et al. 2018a-b). However, this traditional sectional arrangement is very inefficient, and it is one of the main drawbacks of such built-up sections. The introduction of a suitable transverse gap between the channels can further enhance the capacity of such built-up columns (Subramanian 2016). Furthermore, adopting CFS sheets as lateral connectors along the entire column height improves the structural performance of such built-up sections (Anbarasu and Venkatesh, 2019; Ghannam, 2017). Furthermore, adequately designed lateral connecting systems at discrete locations along the column height improve the strength-to-weight ratio and structural performance. The transverse gap also controls the stability characteristics and the torsional resistance in such columns (Dabaon et al. 2015; Anbarasu & Dar 2020a-b Zhang & Young 2015; Anbarasu 2020; Vijayanand & Anbarasu 2021;2020; Anbarasu et al. 2015). However, the toe-to-toe configuration between the chord members has indicated an improved performance over the ones with the chords arranged in the back-to-back orientation (Meza et al. 2020a-b; Kherbouche & Megnounif 2019), and owes that improvement to the closed sectional configuration of these built-up cross-sections, which has been confirmed through more studies (Zhang & Young 2018; Liao et al. 2017; Dar et al. 2018; 2019a-b; 2020a-c;2021a-f; 2022 Roy et al. 2019). These advantages of closed section built-up columns promote their adoption over the open-section ones.

3. CFS battened built-up columns

The past studies on CFS closed section battened columns have been limited (EI Aghoury et al. 2010; 2013; Dar et al. 2021c-d; 2020a-d; Anbarasu & Dar 2020a;b; Anbarasu 2020; Rahnavard et al. 2021). The finding from these studies identified that the unsupported chord slenderness (slenderness of the chord between the intermediate battens) controls the structural behaviour of such columns, especially in the short and intermediate slenderness range. However, the practical range of the unsupported chord slenderness from design practice consideration has not been addressed properly. The present study attempts address deficit by investigating numerically the role of unsupported chord slenderness and chord compactness in governing the axial strength and deformation behaviour of battened columns composed of unstiffened channels. Two plain CFS channels with adequate transverse gap to achieve the cross-sectional aspect ratio as unity, were connected in toe-to-toe arrangement using batten plates to form closed built-up sections. Special emphasis was put on the influence of unsupported chord slenderness on the buckling strength and stability response of battened columns. Four zones of relative unbraced chord slenderness (i.e., 0.25, 0.5, 0.75 and 1.0) for each stub column were investigated. Before conducting the extensive parametric study, the numerical model was adequately validated against the test results on battened columns available in the literature. The numerical analysis results were used to check the adequacy of the current North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006) for CFS structures.

4. Development of the numerical model

ABAQUS 6.14 was used to simulate the compression response of CFS battened columns, comprising of plain channels, as shown in Fig.1. The channels were oriented in the toe-to-toe configuration and connected laterally with batten plates at distinct locations along the column height. Both the chords and batten plates were simulated using S4R type of shell elements. A mesh convergence study favored the adoption of square meshes (10 mm) for the flat zones. A finer mesh (3 parts) was adopted at the corner zones (flange-web joints). The CFS material behavior with strain hardening effect was adopted through the material model (proposed by Gardner and Yun, 2018). The engineering stress-strain was converted into the true stress and plastic strain, using the method given in the ABAQUS manual. A rigid body condition (with tie constraints) that considers warping restrained end condition was used to replicate the boundary conditions. These rigid body constraints were attached to the centroid at each end of the battened column section through reference points located there. Pinned support conditions were simulated by restricting the translations and releasing the rotations at each reference point. The fasteners were simulated using 3D beam connecting elements. Surface interactions were considered by adopting hard contact between the contact surfaces, with small sliding, addressing both tangential and normal contact response. A two-step analysis, considering linear eigen buckling formulation to identify the relevant buckling modes, was achieved in the first step. Riks method that considers both the local as well as the global buckling mode, extracted from the previous step, was adopted for performing the nonlinear analysis of CFS battened columns. A similar modelling technique has been elaborated in the previous studies on CFS built-up columns (Dar et al. 2021c; 2020c; Anbarasu and Dar 2020a). The FE model of the CFS battened column

Figure 1: Cross-sectional details of the built-up column specimens

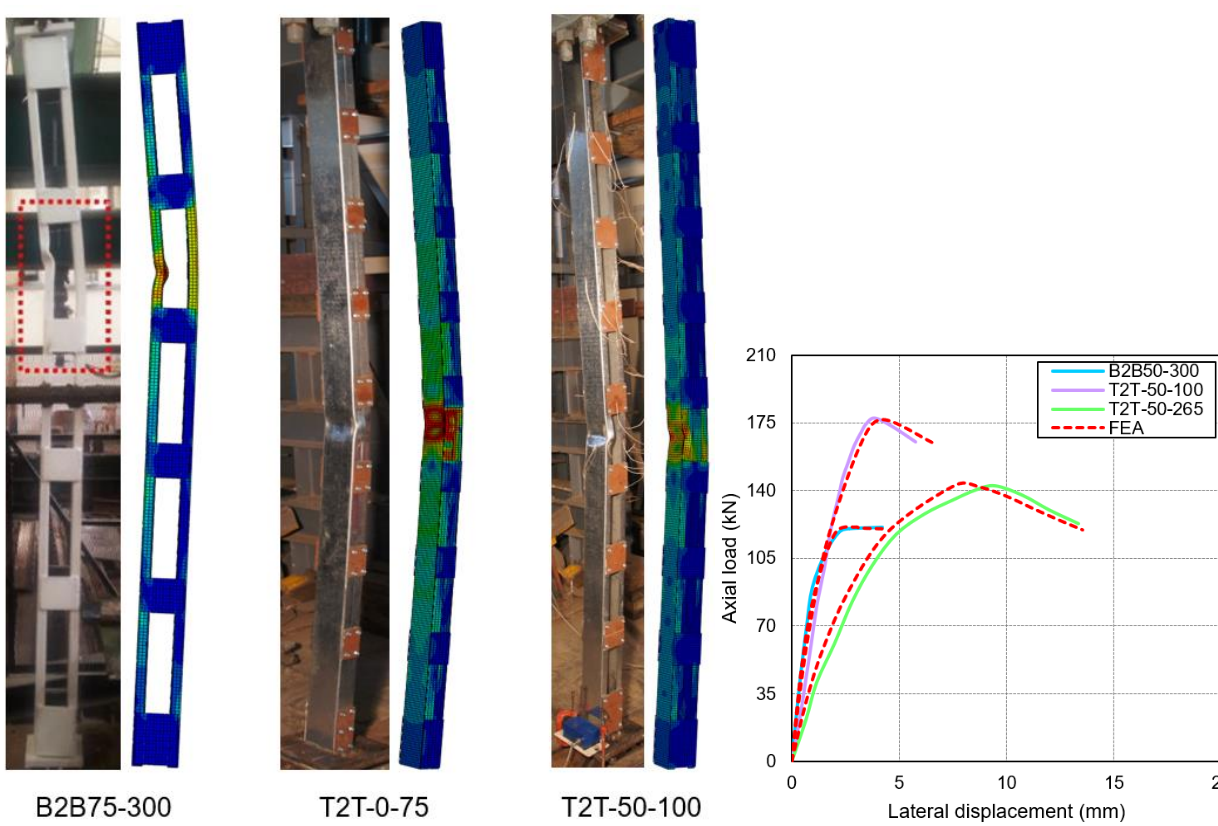


Figure 2: Validation of the numerical models (Dabaon et al. 2015; Dar et al. 2021c)

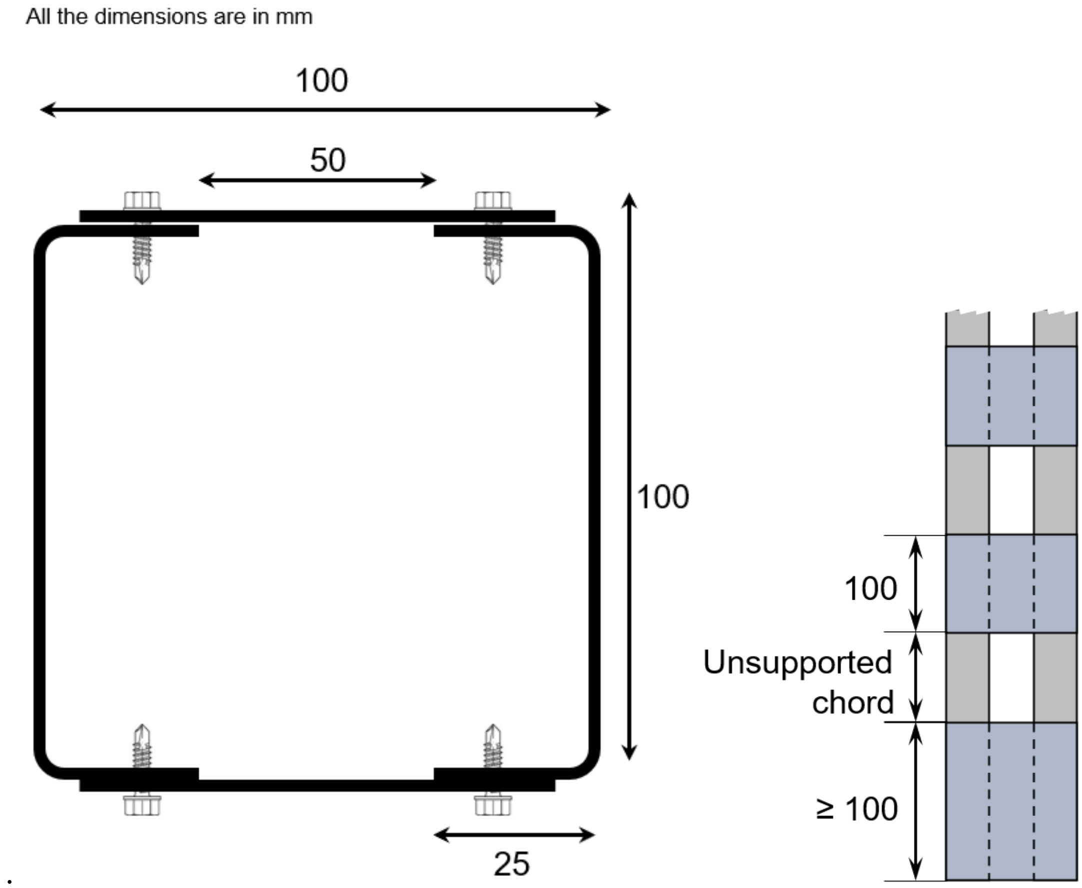
developed was calibrated against the test results on CFS battened columns composed on plain channels **(**Dabaon et al. 2015; Dar et al. 2021c**)** available in the literature. Both the failure modes as well as the load vs. lateral displacement curves were validated, as shown in Fig. 2. Table 1 presents the comparison of the FEA strengths and test strengths on CFS battened columns composed of plain channels [16,19]. A mean value of 1.01 with a standard deviation of 0.013 was achieved for the ratio of test strength to FEA strength. The comparison of the FEA results and test results in all three aspects (peak strength, failure mode and load vs. displacement relationship) indicate a good match. Therefore, the FE model is fit to be adopted for the intended parametric studies.

Table 1 Comparison of FEA strengths with test strengths of battened column specimens (Dabaon et al. 2015; Dar et al. 2021c)

Specimen	P_{Test} (kN)	P_{FEA} (kN)	P_{Test}/ P_{FEA}
T2T-0-175	71.5	70.20	1.02
T2T-50-175	157.41	159.07	0.99
T2T-100-175	163.01	160.71	1.01
T2T-50-100	176.2	175.48	1.00
T2T-50-265	143.1	143.96	0.99
B2B25-300	109.9	108.1	1.02
B2B50-300	119.1	121.1	0.98
B2B75-300	125.3	123.3	1.02
B2B50-150	133.1	132.9	1.00
B2B50-400	112.3	110.1	1.02
		Mean	1.01
		Std. Dev.	0.013

5. Parametric study

The cross-sectional of the specimens used by Dar *et al*., 2021c were extended to the current parametric. The cross-sectional and longitudinal details pertaining to the built-up section are shown in Fig.3. The transverse spacing between the chords was so adopted that the cross-sectional aspect ratio of unity was achieved, and was kept constant throughout the parametric study. The current North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006) for CFS structures limit the sectional compactness of plain channel to 60. Accordingly, the current study varied the sectional compactness as 40, 50, 60, 70 and 80. The overall slenderness of the built-up columns was fixed as 10, to qualify as stub columns. For each value of sectional compactness, the unsupported chord slenderness was varied as 0.25, 0.5, 0.75 and 1.0. The length and thickness of all the battens were constant, and were 100 mm and 6 mm, respectively. The width of all the intermediate battens was kept constant (100 mm). At both ends, all degrees of freedom were restrained, except the rotation about the Y-axis at both ends and translation along the Z-axis at the loaded end. The nomenclature of the specimens is suitably selected to reflect the corresponding critical design parameters. For example, in "BC-S40-0.25-10", BC represents battened column; S40 designates sectional compactness of 40; 0.25 specifies that the unsupported chord slenderness is 0.25; and last figure 10 indicates the overall slenderness of the built-up column specimen. Screwed connections along with the pattern adopted by Dar et al. 2021c were adequate in maintaining the necessary structural integrity between the batten plates and the chords, which was accordingly extended to the current parametric study.



.

(b)

Figure 3: Details of the specimens, (a) cross-sectional; (b) longitudinal

6. Results

As per the current European Standards EN1993-1-3 (2006) for CFS structures, the zone of the column buckling curves falling within the non-dimensional slenderness of up to 0.2 represents the yield plateau (plastic) region. Therefore, all the buckling curves in this region share the same normalized strength value of unity. Accordingly, such columns are categorized as stub columns. In the current study, all the specimens had an overall slenderness value of 10, resulting in the corresponding non-dimensional slenderness value equal to 0.18, which is less than 0.2, therefore fulfilling this criterion, and thus are categorized as stub columns. All the column specimens experienced strong local buckling. Fig. 4 shows the load-axial shortening curves of the column specimens. In the load-displacement response of the specimen BC-S40-0.25-10, the nonlinearity in the curve began slightly before the attainment of the peak load, reflecting the beginning of the column's cross-sectional yielding. Specimen BC-S40-0.25-10 underwent sectional yielding of the entire built-up section in the unsupported chord region, as shown in Fig. 5a. The further increase in the axial resulted in the local buckling in one of the unsupported chords, leading to a sudden drop in the column resistance, as shown in Fig. 4. Although, the axial load reduction noted was small. Furthermore, the subsequent increase in the axial displacement (beyond local buckling) resulted in a gradual spread of the yielded region due to the large post-buckling strength present in the chord and the strain hardening effect. On increasing the unsupported chord slenderness from 0.25 to 0.5 (viz. BC-S40-0.50-10), the sectional yielding of the built-up section (similar to the previous specimens) still occurs, as shown in Fig. 5b. The further increment in the axial displacement led to propagating local buckling deformations. Still, the yielded regions remain confined to only one of the panels and do not spread like the previous specimens. This resulted in relatively a steeper strength degradation in this model than in BC-S40-0.25-10 (see Fig. 4). All stub columns with unsupported chords equal to 0.25 showed significantly superior post-peak response than the other specimens with higher unsupported chord slenderness.

7. Design strengths

Currently, no design guidelines predict the axial strengths of CFS battened columns composed of channels sections as chords. Therefore, North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006), meant for designing CFS structures were used to quantify the design strengths of the various specimens. Both these standards give basic design steps for conventional CFS built-up column made by fastening two channel sections in a back-to-back configuration, through the webs at standard longitudinal spacing. Table 2 presents the comparison of the design strength prediction of these standards against the test strengths. It was noted that both the North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006) mostly predicted the strengths of CFS battened columns composed of plain channels unconservatively, particularly when the unsupported chord slenderness is high and the sectional compactness of the chords are low, except when the unsupported chord slenderness is limited to 0,25. For this value of unsupported slenderness, both North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006) predicted well. However, for stub columns with higher sectional compactness, and lower unsupported chord slenderness, the predictions by both these codes were higher than the numerical strengths. The primary reason behind this behaviour is the high shear stiffness produced by the small unsupported chords, and the strain hardening effect, which is not accounted for by either code.

Table 1: Comparison of numerical strength with the design strengths

Specimen	P_{NAS} (kN)	P_{FEA} (kN)	P_{FEA}/P_{NAS}	P_{EC3} (kN)	P_{FEA}/P_{EC3}
BC-S40-0.25-10	264.35	299.83	1.13	271.21	1.11
BC-S50-0.25-10	188.24	215.95	1.15	194.83	1.11
BC-S60-0.25-10	139.83	167.40	1.20	145.14	1.15
BC-S70-0.25-10	106.92	139.07	1.30	111.31	1.25
BC-S80-0.25-10	83.34	119.32	1.43	87.06	1.37
BC-S40-0.50-10	264.38	276.35	1.05	271.21	1.02
BC-S50-0.50-10	188.26	199.90	1.06	194.83	1.03
BC-S60-0.50-10	139.85	137.20	0.98	145.14	0.95
BC-S70-0.50-10	106.93	119.37	1.12	111.31	1.07
BC-S80-0.50-10	83.35	92.73	1.11	87.06	1.07
BC-S40-0.75-10	264.40	260.31	0.98	271.21	0.96
BC-S50-0.75-10	188.28	179.44	0.95	194.83	0.92
BC-S60-0.75-10	139.87	124.66	0.89	145.14	0.86
BC-S70-0.75-10	106.95	103.36	0.97	111.31	0.93
BC-S80-0.75-10	83.37	82.15	0.99	87.06	0.94
BC-S40-1.00-10	264.43	247.76	0.94	271.21	0.91
BC-S50-1.00-10	188.31	173.72	0.92	194.83	0.89
BC-S60-1.00-10	139.89	121.60	0.87	145.14	0.84
BC-S70-1.00-10	106.97	97.77	0.91	111.31	0.88
BC-S80-1.00-10	83.38	76.54	0.92	87.06	0.88

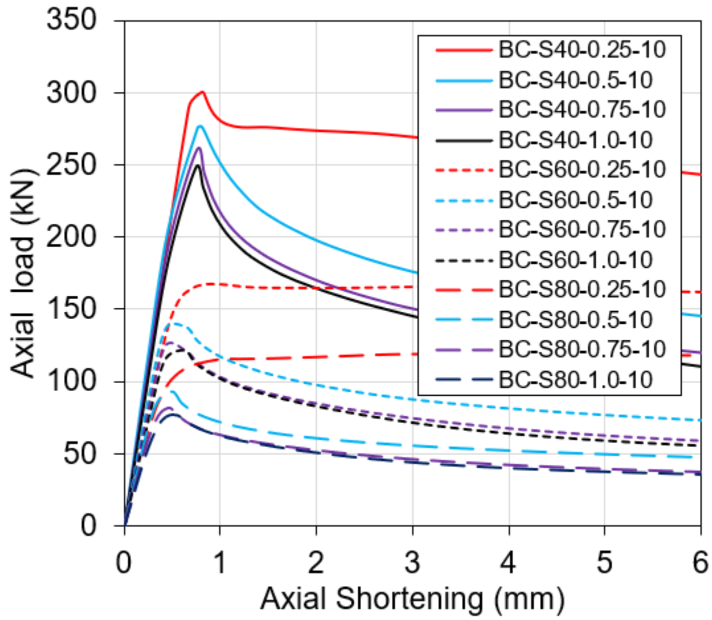


Figure 4: Details of the test set-up

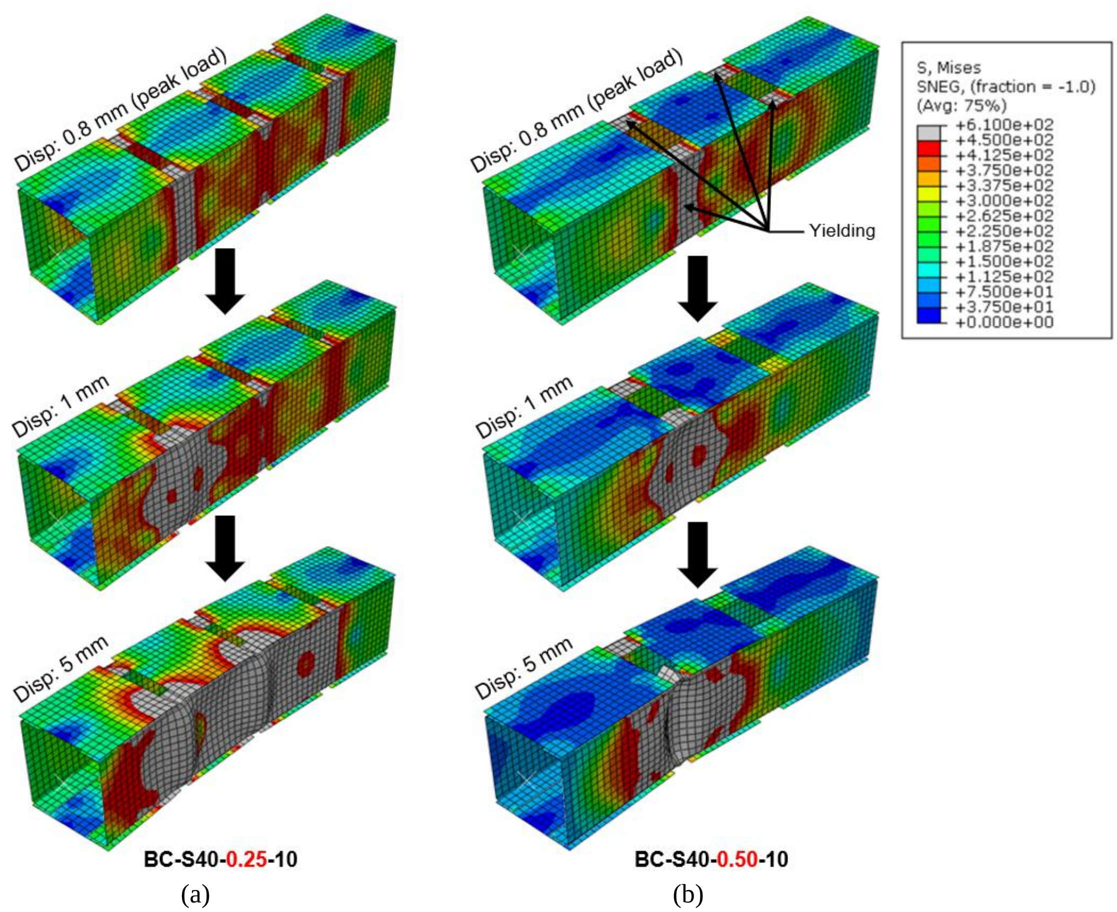


Figure 5 Failure modes and their progression in stub columns (a) unsupported chord slenderness ratio = 0.25, (b) unsupported chord slenderness ratio = 0.5.

5. Summary and Conclusions

The current research study performed a numerical investigation on pin ended CFS battened stub columns composed of closely spaced plain channel sections. The critical role of unsupported chord slenderness of the axial strength and buckling stability behaviour of closed section CFS battened stub columns was examined. The variation in the structural behavior of the built-up stub columns was monitored in terms of their resisted peak loads, load-displacement characteristics and modes of failure. Lastly, the accuracy of the design strengths was assessed using the current North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006) for CFS structures. The strength comparison reflected the inconsistencies in both these design codes, as none of them cater to the design of CFS battened columns. Both the North American Specification (AISI S100:2020) and European Standards EN1993-1-3 (2006) resulted in unconservative predictions, particularly when the unsupported slenderness was large, and th e sectional compactness was low. All the stub column specimens experienced local buckling failure of the chord element, with no signs of any specific type of failure at the connections. Furthermore, the web of the channel was mainly influenced by the local buckling failure, as its sectional compactness was lower than that of the flanges. The adequacy of the connection design adopted was clearly reflected through the proper structural integrity between the battens and the chords achieved throughout the entire loading history.

References

ABAQUS User's Manual, Version 6.14 Hibbit, Karlsson, and Sorenson, Inc., Providence, RI, 2004.

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., Venkatesan M (2019), “Behaviour of cold-formed steel built-up I-section columns composed of our U-profiles”, *Advances in Structural Engineering*, 22(3):613-625.

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.

AISI S100-16 North American specification for the design of cold-formed steel structural members. Washington, DC: American Iron and Steel Institute; 2016.

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. (2015) “Experimental investigation of built-up cold-formed steel section battened columns”, *Thin-Walled Structures*, 92 137-145.

Dar, M.A., Sahoo, D.R., Jain, A.K., Verma, A. (2022) “Tests on CFS laced columns composed of plain channels: Behavior and design”, *Journal of Structural Engineering ASCE*, (Accepted)

Dar, M.A., Pulikkal, S., Sahoo, D.R., Jain, A.K. (2021a) “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. (2021b) “Interaction between chord compactness and lacing slenderness in CFS built-up columns”, *Structures*, 30, 985-995.

Dar, M.A., Sahoo, D.R., Jain, A.K., Sharma, S. (2021c) “Monotonic tests and numerical validation of cold-formed steel battened built-up columns”, *Thin-Walled Structures*, 159 c107275.

Dar, M.A., Subramanian, N., Anbarasu, M., Ghowsi, A.F., Arif, P.A., Dar, A.R. (2021d), "Testing and FE simulation of lightweight CFS composite built-up columns: Axial strength and deformation behaviour", *Thin-Walled Structures*, 169, 108222.

Dar, M.A., Subramanian, N. Arif, P.A., Anbarasu, M., Ghowsi, A.F., Dar, A.R. (2021e) "Compression and stability response of short CFS battened columns with lightweight composite chords", *Proceedings of SSRC Annual Stability Conference*, Louisville, Kentucky, USA, April 13-16.

Dar, A.R., Vijayanand S., Anbarasu, M., Dar, M.A. (2021f), "CFS battened built-up columns- Experimental behaviour and verification of different design rules developed", *Advances in Structural Engineering*, 25(2), 321–335

Dar, M.A., Sahoo, D.R., Jain, A.K. (2020a) "Axial strength and stability behaviour of cold-formed steel battened closed section columns", *Proceedings of SSRC Annual Stability Conference*, Atlanta, Georgia, USA.

Dar, M.A., Sahoo, D.R., Jain, A.K. (2020b) "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., Sahoo, D.R., Jain, A.K. (2020c) "Influence of chord compactness and slenderness on axial compression behavior of built-up battened CFS columns", *Journal on Building Engineering*, 32, 101743.

Dar, M.A., Sahoo, D.R., Jain, A.K. (2019a) "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. (2019b) "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., Sahoo, D.R., Pulikkal,S., Jain, A.K. (2018) "Behaviour of laced built-up cold-formed steel columns: Experimental investigation and numerical validation", *Thin Walled Structures* 132 398-409.

Derveni, F., Gerasimidis, S., Peterman, K.D. (2020) "Behavior of cold-formed steel shear walls sheathed with high-capacity sheathing", *Engineering Structures*, 225,111280.

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.

Gardner, L., Yun, X. (2018) "Description of stress-strain curves for cold-formed steels", *Construction and Building Materials*, 189 527-538.

Gatheeshgar, P., Poologanathan, K., Gunalan, S., Konstantinos, D.T., Nagaratnam, G., Iacovidou, E. (2020) "Optimised Cold-Formed Steel Beams in Modular Building Applications", *Journal of Building Engineering*, 32 101607.

Ghannam, M. (2017). "Axial Load Capacity of Cold-formed Steel Built-up Stub Columns" *International Journal of Steel Structures*, 17(3), 1–11.

Joorabchian, A., Li, Z., Peterman, K.D. (2021) "Experimental and numerical investigation of fixed-height cold-formed steel wall assemblies bearing on concrete slabs", *Thin-Walled Structures*, 166, 107940.

Kechidi, S., Fratamico, D.C., Schafer, B.W., Castro, J.M., Bourahla, N. (2020) "Simulation of screw connected built-up cold-formed steel back-to-back lipped channels under axial compression" *Engineering Structures*, 206,110109.

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.

Li, Q.Y., Young, B. (2022) "Experimental and numerical investigation on cold-formed steel built-up section pin-ended columns", *Thin-Walled Structures*, 170, 108444.

Li, Y., Zhou, T., Lei, Zhang, Ding, J., Zhang, X. (2021) "Distortional buckling behavior of cold-formed steel built-up closed section columns", *Thin-Walled Structures*, 166, 108069.

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.

Mahar, A.M., Jayachandran, S.A., Mahendran, M. (2021a) "Global buckling strength of discretely fastened back-to-back built-up cold-formed steel columns", *Journal on Constructional Steel Research*,187, 106998.

Mahar, A.M., Jayachandran, S.A., Mahendran, M. (2021b) "Direct Strength Method for Cold-Formed Steel Unlipped Channel Columns Subject to Local Buckling", *International Journal of Steel Structures*,21, 1977–1987.

Mahar, A.M., Jayachandran, S.A., (2021) "A Computational Study on Buckling Behavior of Cold-Formed Steel Built-Up Columns Using Compound Spline Finite Strip Method", *International Journal of Structural Stability and Dynamics*,21, 2150064. Meza, F.J., Becque, J., Hajirasouliha, I. (2020a) "Experimental study of cold-formed steel built-up columns" *Thin-Walled Structures* 149 106291.

Meza, F.J., Becque, J., Hajirasouliha, I. (2020b) "Experimental study of the cross-sectional capacity of cold-formed steel built-up columns" *Thin-Walled Structures*, 159 106958.

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

Nie, S.F., Zhou, T.H.., Zhang, Y., Liu, B. (2020a) "Compressive behavior of built-up closed box section columns consisting of two cold-formed steel channels", *Thin-Walled Structures*, 151, 106762.

Nie, S.F., Zhou, T., Eatherton, M.R., Li, J., Zhang, Y., (2020b) "Compressive behavior of built-up double-box columns consisting of four cold-formed steel channels", *Engineering Structures*, 222, 111133.

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.

Rahnavard, R., Craveiro, H.D., Laím, L., Simões, R.A., Napolitano, R. 2021 "Numerical investigation on the composite action of cold-formed steel built-up battened columns." *Thin-Walled Structures*, 162: 107553.

Rasmussen, K.J.R., Khezri, M., Schafer, B.W., Zhang, H. (2020) "The mechanics of built-up cold-formed steel members" *Thin-Walled Structures* 154 106756.

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.

Roy, K., Ting, T.C.H., Lau, H.H., Lim, J.B.P. (2018) "Effect of thickness on the behaviour of axially loaded back-to-back cold-formed steel built-up channel sections - Experimental and numerical investigation" *Structures*, 16 327-346.

Selvaraj, S., Madhavan, M. (2022) "Design of Cold-formed Steel Built-Up Closed Section Columns using Direct Strength Method" *Thin-Walled Structures* 171, 108746.

Selvaraj, S., Madhavan, M. (2021) "Design of cold-formed steel built-up columns subjected to local-global interactive buckling using direct strength method" *Thin-Walled Structures* 159, 107305.

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

Vijayanand, S., Anbarasu, M. (2021) "Parametric study and Improved design guidelines of CFS battened built-up columns", *Steel & Composite Structures*, 40(5) 733-746.

Vijayanand, S., Anbarasu, M. (2020) "Behavior of CFS Built-up Battened Columns: Parametric study and Design recommendations", *Structural Engineering & Mechanics*, 74(3) 381-394.

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.

Zhou, X., Xiang, Y., Shi, Y., Xu, L., Zou, Y. (2021a) "Simplified design method of cold-formed steel columns with built-up box sections", *Engineering Structures*, 228, 111532.

Zhou, T., Li, Y, Ren, L., Sang, L., Zhang, L. (2021b) "Research on the elastic buckling of composite webs in cold-formed steel back-to-back built-up columns – Part I: Experimental and numerical investigation", *Structures*, 30, 115-133.

Zhou, T., Li, Y., Wu, H., Lu, Y., Ren, L. (2022) "Analysis to determine flexural buckling of cold-formed steel built-up back-to-back section columns", *Journal of Constructional Steel Research*, 166, 105898.

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

Notations

CFS	: Cold-formed steel
P_{NAS}	: Design strength predicted by North American Specification (AISI S100:2020)
P_{EC3}	: Design strength predicted by and European Standards EN1993-1-3 (2006)
P_{FEA}	: Peak test strength