

Axial Resistance of Short Built-up Cold-Formed Steel Columns: Effect of Lacing Slenderness



M. Adil Dar, Dipti Ranjan Sahoo, Arvind K. Jain, and Sunil Pulikkal

Abstract Cold-formed steel (CFS) construction has become popular in the recent decades mainly due to their favorable features like higher yield strength, easy fabrication/handling, faster cost-effective construction, etc. Built-up members are often used as columns in structures with demands to resist large axial forces. Past studies have mainly stressed on evaluating the performance of battened CFS columns. Therefore, there is a need to examine the behavior of built-up laced CFS columns under the axial loading conditions. This study stresses on the numerical investigation of the influence of lacing element slenderness on the compression capacity of built-up CFS columns. Cold-formed steel columns consisting of four angle sections were connected by single lacing configuration. Test results from literature were used to calibrate the nonlinear finite element model developed. The design strengths predicted by North American Standards (AISI S-100) are calculated and compared with the test results.

Keywords Built-up columns · Cold-formed section · Lacings · Numerical modeling · Strength

1 Introduction

The adoption of cold-formed steel (CFS) sections in low-rise residential buildings has been extensive due to their favorable features like higher yield strength, easy fabrication/handling, faster cost-effective construction, etc. Premature instability due to thin-walled nature of CFS members is their primary limitation. Past research has identified efficient shaping and judicious stiffening as the measure to overcome these buckling issues. Suitably modified design and detailing of thin-walled CFS members helps in delaying/eliminating their buckling instability, thus significantly enhances their strength and stiffness characteristics [1]. Proper designed CFS sections can develop resistance up to their plastic moment strength [2]. Adequately designed CFS timber composite sections perform better with an advantage of easy fabrication, and

M. A. Dar (✉) · D. R. Sahoo · A. K. Jain · S. Pulikkal
Department of Civil Engineering, IIT Delhi, New Delhi 110016, India
e-mail: dar.adil89@gmail.com

thus have the potential to replace hot rolled steel for better economy and utility [3]. Significant enhancement in load-carrying capacity can be achieved through partial stiffening and strengthening of CFS sections with a higher strength to weight ratio [4, 5]. The use of built-up members as columns is recurrent when demands for resisting axial force in the structures are high. Past studies have mostly stressed on the evaluation of the performance of CFS columns comprising of two channels connected by batten plates. Vijayanand and Anbarasu [6] investigated CFS built-up columns with variation in the number of spacers. Numerous other parameters were varied too. It was observed that an increase in column slenderness ratio led to a drop in the axial resistance. EI-Aghoury et al. [7, 8] studied the behavior of pin ended CFS battened columns under concentric and eccentric loading conditions. Specimens varied in chord width to thickness ratio for both short and medium member slenderness. Outstanding width to thickness ratio, the overall slenderness ratio of column, and global slenderness ratio of angle were the main parameters governing the ultimate strength and behavior of battened columns. The column strength dropped due to the interactive buckling comprising of torsion and flexure. Dabaon et al. [9] evaluated the axial strength of battened CFS pin ended built-up columns fabricated with two channels back to back at different spacing. The batten plates were welded to the channels. The variation in the spacing between the channels was responsible for transforming the failure modes from one mode to the other. Anbarasu et al. [10] examined the behavior of CFS web stiffened built-up battened columns with varying slenderness ratio. When the effect of batten plate depth and the number of batten plates used was neglected, the DSM design strengths obtained were found to be conservative. This trend increased with an increase in the slenderness ratio. When elastic buckling analysis and modified slenderness approach of the NAS [11] Specification was used to calculate the critical buckling load for the columns, un-conservative design strengths were obtained. By increasing the overall slenderness of the columns, the ultimate resistance dropped. Intermediate stiffening of the web helped in eliminating its local buckling completely. Dar et al. [12–14] conducted a detailed numerical study to explore the performance of closed battened CFS columns comprising of two plain channels with pin ended support conditions. On increasing the toe to toe channel spacing, the load-carrying potential of the built-up columns enhanced. Furthermore, very limited research on CFS laced columns has been reported [15–21]. Keeping in view the focus of past research on built-up battened CFS columns, there is a need to evaluate the behavior of CFS built-up laced columns comprising of four angles under the axial loading conditions. Although, there are various parameters that affect the behavior of a laced built-up column, the slenderness ratio of the lacing element does influence substantially. The upper limit on the slenderness ratio of single lacing system specified by ANSI/AISC 360 [22] and IS-800 [23] is 140 and 145, respectively. However, it is applicable to hot rolled steel sections only.

Accordingly, in this study, the influence of lacing slenderness on the compression capacity of CFS built-up laced columns with single lacing arrangement is investigated. These members comprise of four angle sections connected by lacing bars. In the current study, a nonlinear numerical model was developed to investigate the effect of lacing slenderness on the behavior of built-up columns. The models were

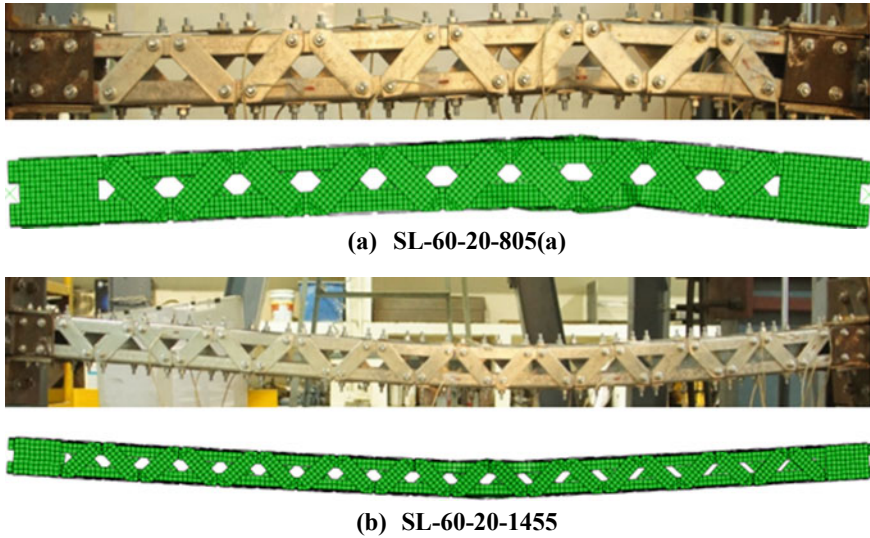


Fig. 1 Failure mode comparison-experimental versus FEM

calibrated against the relevant experimental results available in the literature. In the parametric study, the lacing slenderness ratio variation was adopted from 79 to 395. In addition to this, the numerical results were compared with strength predictions made by North American Specification [11], American National Standard [22], and Indian Standards [23] (Fig. 1).

2 Finite Element Modeling

Finite element method is used to numerically investigate the behavior of built-up laced columns. ABAQUS [24] a commercial general-purpose program was adopted for carrying out the finite element analysis. The details of the finite element model are given in Table 1. The test results of Dar et al. [16] and EI-Aghoury et al. [7] were used for calibrating the finite element model developed for conducting the parametric study in order to investigate the role of lacing slenderness in influencing the axial resistance of built-up CFS columns. The comparison between the ultimate loads obtained from the test results of Dar et al., 2018 [16] and the results obtained from finite element analysis is shown in Table 2. Figure 1 shows the failure mode comparison of specimens SL-60-20-805(a) and SL-60-20-1455. The comparison between the ultimate load obtained from the test result of the battened column (1000B80L30B6) conducted by EI-Aghoury et al. [7] and the result acquired from the finite element analysis is presented in Table 3. Figure 2 shows the comparison of the load vs. displacement between the test result of EI-Aghoury et al. [7] and FEM.

Table 1 Details of the finite element model

Detail type	Feature adopted	Detail type	Feature adopted
Type of element	Shell element (S4R5)	Support condition at the other end	Pined end
Mesh size & Aspect ratio	$5 \times 5 \text{ mm}^2$ & 1.0	Application of axial load	By applying an axial displacement at loaded end
Material model	Elastic perfectly plastic	Connection between the lacing and sections	Mesh independent fastener option available in ABAQUS
Modulus of Elasticity (E)	$2 \times 10^5 \text{ MPa}$	Local imperfection	$0.006 \times w \times t$ [17]
Yield stress (f_y)	450 MPa	Global imperfection	1/500 of column height [25]
Support condition at loaded end	Pined end with displacement in the longitudinal direction permitted	Types of analysis	Linear buckling analysis, followed by a nonlinear analysis

Table 2 Comparison of test results with numerical results for laced column

Specimen	P_{uExp} (kN)	P_{uFEM} (kN)	P_{uExp}/P_{uFEM}
SL-60-20-805(a)	68.9	65.83	0.98
SL-60-20-1455	44.6	48.78	0.94

P_{uExp} : Ultimate load obtained from experiment

P_{uFEM} : Ultimate load obtained from FEM

Table 3 Comparison of test result with numerical result for battened column

Researcher	P_{uExp} (kN)	P_{uFEM} (kN)	P_{uExp}/P_{uFEM}
EI-Aghoury	52	53	0.98
Dar	52	51.5	1.00

P_{uExp} : Ultimate load obtained from experiment

P_{uFEM} : Ultimate load obtained from FEM

Fig. 2 Comparison of experimental and FEM result for battened column 1000B80L30B6

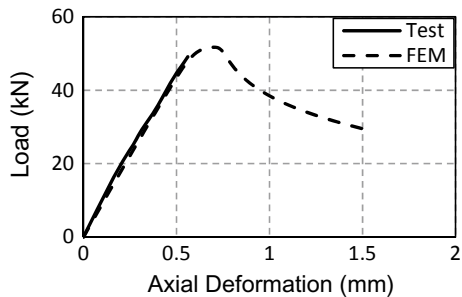
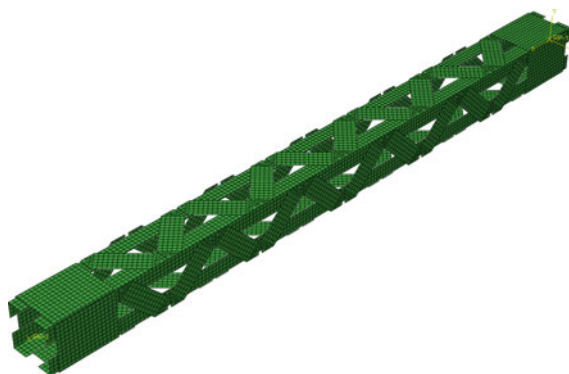


Fig. 3 Numerical model of the laced built-up column



The results shown in Tables 2, 3 and Fig. 2 indicate that the agreement between the results of FEM and the experiments is good. Hence, this model can be used for parametric study.

3 Parametric Study

In the parametric study, numerical models were developed to carry out analyses on the cross-section of the specimen SL-60-20-805(a) used by Dar et al. [16] (See Fig. 3). The slenderness ratio of the lacing elements was varied from 395 to 79. The results of this variation in lacing slenderness on the behavior of laced built-up columns including the comparison of the FEA predicted strengths with the design strengths predicted by AISI S-100, ANSI/AISC 360, and IS-800 are given in Table 4. The load versus axial deformation curves for Model-I with single lacing arrangement are shown in Fig. 4. The models were labeled as Model type, type of lacing arrangement, and slenderness of the lacing element. For example, the label “Model-I-S-395” defines the following: Model-I indicates the type of model to choose from the tested specimens (all the dimensions of Model-I to be used), S indicates the type of lacing arrangement (S stands for single lacing) used, and 395 indicates the slenderness ratio of the lacing element.

4 Discussion

There was a slight drop in the initial stiffness of the columns between 45 to 55 kN until their ultimate capacities. As the lacing slenderness increased from 79 to 395, the ultimate capacities of the columns dropped from 65.8 kN to 57.7 kN (around 12.3%). However, it was observed that post the peak load, with an increase in the lacing slenderness, the stiffness of the curve dropped. The variation of strength with

Table 4 Results of parametric study

Model-I	Lacing slenderness	P_{uFEM} (kN).	P_{uFEM}/P_{uNAS}	P_{uFEM}/P_{uAISC}	$P_{uFEM}/P_{uIS-800}$	Mode of failure
S-395	395	57.74	0.86	0.91	0.84	L
S-263	263	58.91	0.87	0.93	0.86	L
S-197	197	58.99	0.88	0.93	0.86	L
S-158	158	60.72	0.90	0.96	0.88	L
S-132	132	62.52	0.93	0.99	0.91	L
S-113	113	62.55	0.93	0.99	0.91	L
S-99	99	64.46	0.96	1.02	0.94	L
S-88	88	64.61	0.96	1.02	0.94	L
S-79	79	65.83	0.98	1.03	0.96	L

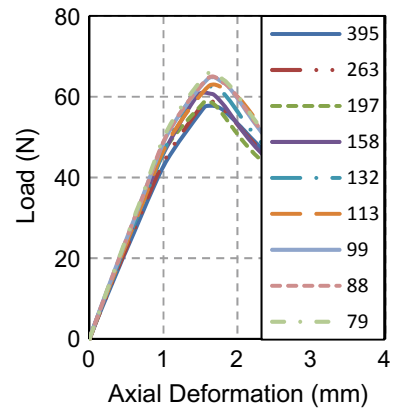
P_{uNAS} Design strength predicted by NAS S-100

P_{uAISC} Design strength predicted by ANSI/AISC 360

$P_{uIS-800}$ Design strength predicted by IS-800

P_{uFEM} Ultimate load obtained by finite element analysis

L Local buckling

Fig. 4 Effect of lacing slenderness

respect to lacing slenderness in a single lacing arrangement is shown in Fig. 5. The failure mode in all the models was governed by local buckling as shown in Fig. 6a for Model-I-S-395. For Model-I-S-395, the buckling of lacing during failure was prominent as shown in Fig. 6b.

5 Conclusions

This research has stressed on the influence of lacing slenderness on the compression resistance of cold-formed steel built-up columns using FEA. The cold-formed steel columns consisted of four angle sections connected by a single lacing configuration. The following were the main conclusions drawn out of the present study.

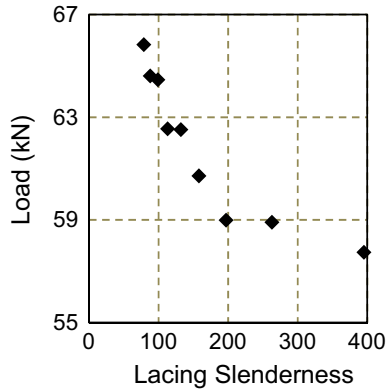
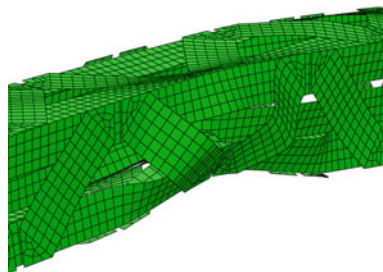


Fig. 5 Variation of strength with respect to lacing slenderness



(a) Failure mode in Model-I-S-395



(b) Lacing buckling in Model-I-S-395

Fig. 6 Failure in model-I-S-395

- The parametric study confirmed that slenderness of the lacing element affects the behavior of built-up columns, particularly their strength.
- With the increase in lacing slenderness from 79 to 395, the ultimate capacities of the columns dropped from 65.8 kN to 57.7 kN (around 12.3%)
- Post the peak load, with an increase in the lacing slenderness, the stiffness of the curve dropped.
- With reference to the upper limit of 140 and 145 specified on the slenderness ratio of a single lacing system by ANSI/AISC 360 and IS-800, respectively, a slenderness ratio <110 appears to do well with short cold-formed steel built-up columns with $b/t < 15$. Beyond this value, the drop in column strength is significant.
- Although there are no well-defined guidelines for the design of laced cold-formed steel columns comprising of four members, the design strengths predicted by AISI

S-100 and IS-800 were conservative. However, the design strengths predicted by AISC-360 were slightly on the un-conservative side.

- The agreement between experimental and FEM results was good. The difference on an average was less than 3%. Mostly, the FEM results were higher.

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