

Buckling Behaviors of Cold-Formed Steel Built-Up Columns under Axial Compression Tests: Review Paper

Thu Ya Mon, Janani Selvam

Abstract: In modern-day construction industry, cold-formed steel channels have been more interested as the conventional structural materials in place of hot-rolled steel members in order to reduce the weight of beams and girders without reducing their strength. Cold-formed steel becomes extensively used as structural and non-structural materials in building construction and engineering presentations. Various types of buckling behaviors usually govern the design strength of cold-formed steel channel sections. Because of their complex behaviors, the design guides for cold-formed steel are insufficient to be provided. This leads the questions to investigate the governing modes of failure of cold-formed steel built-up sections in both horizontal and vertical profiles. This article reviews the recent researches on cold-formed steel built up columns of diverse geometric shapes and connections under axial compression load. The objective is to summarize various modes of buckling in each built-up column. At the end of the study, the results are compared in detail through their geometric sections and provide recommendation for further studies.

Keywords: buckling behavior, built-up columns, cold-formed steel, vertical profile

I. INTRODUCTION

Cold-formed steel (CFS) becomes more preferable to substitute in place of wood and hot-rolled steel (HRS) members in modern-day construction due to their lightweight with strong, ductile and easy for installation and save construction cost. According to Steel Framing Industry Association (SFIA) Market Data Report 2018, CFS manufacturers conveyed using 282,355 total tons (raw tons before processing) of steel in the first quarter of 2018, which grew up from 272,305 total tons reported in the previous quarter of 2017. This showed that demand for cold-formed steel channel (CFSC) products grow up in construction industry [1]. To carry heavy loads and be applied for large spans in both profiles, two or more CFSC are connected with self-drillings screws, weld or bolt to form built up sections to be more efficient as the structural members. The design standards, guidelines and specifications are still inadequate methods for designing these types of CFS built-up sections. Experimental investigations on built-up I section columns connecting with two lipped channels are checked analytically with novel Direct Strength Method, DSM, presented by Lu et al, 2017 [2]. Failure modes for multi-limb, built-up cold-formed steel stud columns with three different sections were examined by Liao et al, 2017 [3].

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The buckling modes and failure characteristics of built-up closed sections were investigated under axial and eccentric compression by Nie et al, 2017 [4]. Built-up columns of back-to-back CFS lipped channels are connected with screws through their webs were tested for global buckling mode and collapse behavior by Fratamico et al, 2018 [5]. Compression tests on single detached CFSC and built-up box CFS columns were made and compared by Krishanu et al, 2019 [6]. Short CFS built-up columns with double-lacing configuration and large flat width-to-thickness ratio were tested and studied by Adil Dar et al, 2019 [7]. Built-up CFS lipped channels stud columns submitted to axial compression were tested and compared through experimental and theoretical results by Daemon d' Oliveira and Eduardo de Miranda, 2019 [8]. Compressive strength of axially loaded built-up Sigma CFS columns were presented by experimental as well as numerical method by M. E. Aghoury et al, 2020 [9].

II. DISCUSSION

This article reviews five of the recent researches on buckling behaviors of CFS built-up columns with diverse geometric shapes and connections under axial compression tests. Specimens of two cross sectional area of single detached C and built-up I section columns with three types of length had been tested under unique axial compression loads and the results were compared with the novel analytical method [2]. The interactive buckling modes and collapse behavior of back-to-back I columns through the effectiveness of column end rigidity, web fastener layout and available cross sectional size of built-up members were done by means of built-up I columns with and without EFGs [5]. Load -axial shortening relationship, failure modes and deformed shapes of cold-formed steel box columns under axial compression tests were done with studs and slender of C and box built-up columns [6]. The design strength predictions occurring prominent failure buckling modes were done by means of double-lacing built-up columns [7]. The comparison between the experimental results of tested specimens with the ultimate strength recommended by AISI, the Eurocode-3 and DSM specifications were done through built-up sigma columns [9].

A. Single Detached C and Built-Up I Sections Columns

Lu et al (2017) investigated a novel design method for pure and interactive buckling modes of built-up I-section columns and proposed to predict their ultimate strength [2].

For interactive buckling modes of CFS built-up I-section columns, local-distortional (LD) and local-distortional-global (LDG), the proposed design method, a novel direct strength based method can be applied effectively to predict their ultimate strength. Local and distortional buckling often govern the behaviors of CFS [10], EWM could be inapplicable to estimate their ultimate strength in failing buckling modes and cross sectional distortions. Specimens of two cross sectional area of single detached C columns and built-up I section columns with three types of length were tested under unique axial compression loads. Fig 1 illustrates the arrangement of strain gauges and LVDTs, Linear Variable Differential Transformers, for three types of specimens.

For short column (stud column), two specimens of single C and built-up I columns with nominal width of web equal to 92 mm were failed in local buckling mode under the same compression load. Stud columns specimens with nominal width of web equal to 142 mm occurred distortional buckling in very short time after the local one. These results display the different buckling modes of stud columns with C and built-up I sections vary with the nominal width of web. For medium column, local buckling occurred first unrelated to their section types. Specimens with C section columns failed in interactive buckling mode of LG, local-global, whereas specimens with built-up I section columns failed in LDG, local-distortional-global buckling mode. For long column, all specimens regardless of their sections and nominal width of web failed in pure global buckling mode without occurring local and other forms of cross-section distortions. Through these experiments, strength erosion occurs due to interaction of LD and LDG buckling modes that affect significantly on the built-up I section columns. When the screw spacing of built-up I columns is greater than the half-wavelength of C-section, their local buckling strength is almost twice that of C-section parts.

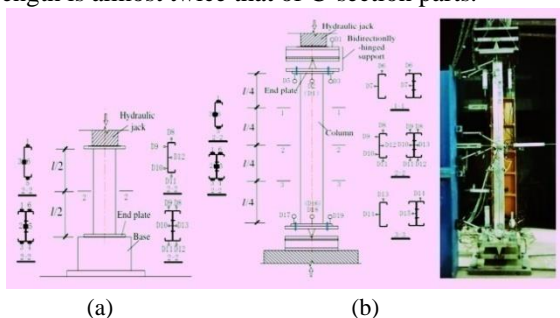


Fig 1: Arrangement of strain gauges and LVDTs: (a) SC type specimens (b) MC and LC type specimens [2]

B. Built-Up CFS I Section Columns with and without EFGs

Fratamico et al (2018) studied the effectiveness of the use of EFGs to the built-up I columns [5]. In their research, 16 different CFS lipped channel sizes were used to form back-to-back built-up columns to address buckling and their collapse behaviors. The focus of this experimental method was to establish the interactive buckling modes and collapse behavior of built-up back-to-back I columns through the effectiveness of column end rigidity, web fastener layout and available cross sectional size of built-up members. 32 numbers of back-to-back cold-formed specimens were prepared. Concentrated compressive loading with

monotonic and displacement-controlled was applied on each specimen with 100 kips (445 kN) MTS universal testing rig, which has a servo-controlled hydraulic actuator. Specimens of 16 different section sizes with the nominal steel thickness ranging from 0.84 mm to 1.72 mm were selected. Specimen columns at a length of 1830 mm with nominal web stretching from 63.5 mm to 152 mm and flanges from 34.9 mm to 41.3 mm were listed in the test matrix. For sections with 0.84 mm to 1.09 mm plate thickness, Posi-Grip #8 self-drilling screws were used to fasten the lipped sections together. Simpson #10 self-drilling screws were used for the plate thickness from 1.37 mm to 1.72 mm.

A series of 42 coupon tests were accomplished in accordance with ASTM A370-12a [11]. These coupon sections were manufactured with a yield stress of 345 MPa (50 ksi) and Young’s modulus of 203 GPa (29,500 ksi). In this matrix, the 16 section types (4 cross sections and 4 thicknesses) were categorized due to the capacity of testing rig and wider range of studs used in cold-formed steel columns. Each section was tested in two categories: with EFGs, end fastener groups, and without them. In the first case, EFGs were superimposed on even spacing length of L/4 owing to AISI S100 [12] and the second with the even fastener spacing without EFGs. EFGs lengths were calculated as 1.5 times the maximum width of built-up section.

By comparing the results of A1-54 and A2-54, 20% boost in capacity was observed when EFGs are added to the columns. Furthermore, these thinner sections were observed to be more localized imperfections in their flanges and lips. Except A1-33 and A2-33, the remaining couples in A series prevailed single mode global (flexural) (G) deformation. Trials such as B1-33 and B2-33, however, no increase in strength were occurred with the addition of EFGs. In-group B, except B1-68 and B2-68, the trial results of the rest indicated there were local-global (LG) interactions buckling mode between them. This interactive buckling mode was observed due to the increment of plate thickness (1.73 mm). For B1-68 and B2-68, the strength capacity increased 42% by adding EFGs to the columns and only flexural (global) buckling mode prevailed. The results disclosed the effectiveness of EFGs to columns is only with flexural buckling mode (G), not the local (L) one. For groups C and D, result data indicated generally that enhanced the strength capacity of built-up columns with EFGs except C1-43 & C2-43 and D1-43 & D2-43. In these groups, C and D, only local-global interaction mode was observed.

C. Single Detached C and Built-Up Box Section Columns

Krishanu et al (2019) investigated load-axial shortening relationship, failure modes and deformed shapes of built-up box sections cold-formed steel columns under axial compression tests [6]. The experiments employed 16 specimens, 8 for single detached C-sections columns and the rest for built-up box sections columns. The tests were conducted under two categories; stud (short) columns 500 mm and slender columns 1,500 mm in height respectively.



In preparing for test specimens, C75-L500 and B75-L500 were for studs and C75-L1500 and B75-L1500 for slender columns. The symbol C represented as single detached channel and B, built-up box sections. 75 is the nominal depth (web) in mm of the specimens. Fig 2 shows the formation of built-up box sections with two identical lipped channel sections connected front-to-front by self-drilling screws. The longitudinal spacing of screws was considered 100 mm in this experiment.

Table 1 indicates the failure loads results from experimental tests for stud and slender columns of single and built-up box sections. In this table, the results are associated based on the specimens' geometric models. By comparing the mean values of the experimental results depending on their channel sections, C or box, it is obviously seen that built-up box sections have greater value of failure loads, 2.27 times for studs and 2.17 for slender columns. If these results are compared based on column types, stud or slender, for both geometric models, stud columns have greater values of failure loads than those of slender. Table 2 describes the results linkage between column types.

Through 16 experimental trials, different buckling modes were observed. Either distortional buckling (D) or local-distortional modes (LD) were investigated in short single detached C columns where as built-up short columns failed through local buckling (L). All slender columns, either C or box section were failed by global buckling (G) mode. Failure buckling modes obtained through the experiments are exposed in fig 3.

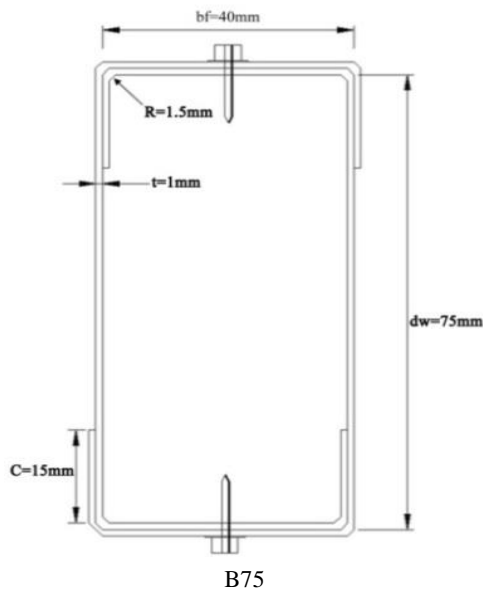


Fig 2: Nominal cross-section of CFS built-up box section [6]

Table-I: Experimental results for failure loads (kN)

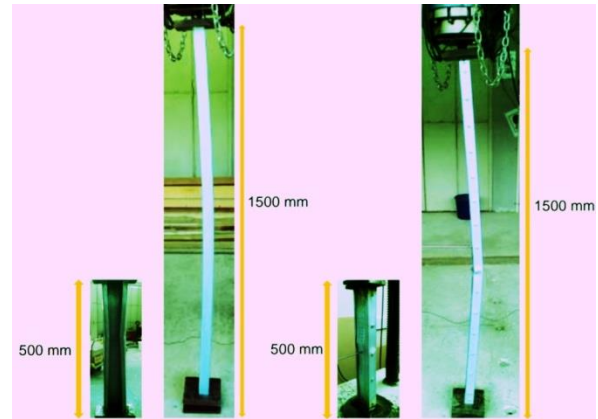
Specimens	Studs		Slender	
	C75	B75	C75	B75
1	57.5	124.8	39.0	88.4
2	55.5	127.5	40.5	89.7
3	54.2	130.5	42.0	91.4
4	57.7	129.7	45.5	92.7
Mean value	56.225	128.125	41.75	90.55

Data in Table 1 are reference from [6]

Table-II: Experimental results for failure loads (kN)

Specimens	C75		B75	
	Stud	Slender	Stud	Slender
1	57.5	39.0	124.8	88.4
2	55.5	40.5	127.5	89.7
3	54.2	42.0	130.5	91.4
4	57.7	45.5	129.7	92.7
Mean value	56.225	41.75	128.125	90.55

Data in Table 2 are reference from [6]



(i) C75-L500-1 (ii) C75-L1500-1 (i) B75-L500-1 (ii) B75-L1500-1

(a) Single channel sections (b) CFS built-up box sections
Fig 3: CFS single and built-up columns at failure buckling modes [6]

D. Double-Lacing Built-Up CFS Columns

Adil Dar et al (2019) reported an experimental study on the built-up CFS columns with double-lacing configuration and large flat width-to-thickness ratio [7]. End supports of specimens with pins in this research allowed uniaxial bending. The primary focus of this research was comparison of experimental results with the design strength predictions, though; there occurred prominent failure buckling modes for the specimen built-up columns.

Four specimens of built-up CFS columns were constructed with two different sizes of angle sections as 60x60x1.6 mm and 100x100x1.6 mm. These specimens were cross braced with 25mm width lacing bars, 2.5 mm thickness for specimens A and B and 4 mm for C and D. Lacing bars were connected with CFS angle sections by using 6mm diameter bolts. Concentric loading with loading frame of 1,000 kN was used to carry out axial testing of CFS built-up columns. Hydraulic loading jack of 250 kN capacity was applied as the compressive loading on the test specimens. 25 mm thickness end bearing plates were connected at the ends of these specimens as the hinge mechanism to minimize the friction. LVDT, Linear Variable Displacement Transducer, was used for measuring the axial shortening and two displacements sensors were for the lateral displacement.

No visible initial local buckling waves were observed at the early stages of loading for all specimens. Local buckling of the chord members observed as the major failure modes of buckling in all cases. No connection failure in any mode was observed. Mode of failure in all specimens can be seen in fig 4.





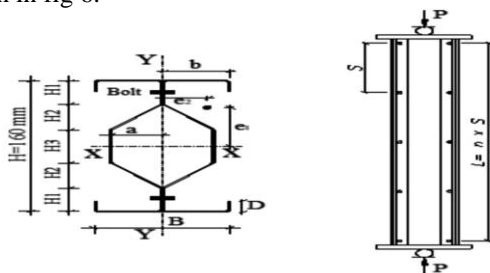
(a) Model-A (b) Model-C (c) Model-B (d) Model-D
Fig 4: Failure buckling mode in the test models [7]

E. Built-Up Sigma Section Columns

M. E. Aghoury et al (2020) studied experimental together with numerical analysis of the strength of pinned-pinned axially compression loads through the back-to-back CFS sigma sections columns [9]. The focus of this paper was the comparison between the experimental results of tested specimens with the ultimate strength recommended by AISI, the Eurocode-3 and DSM specifications. The failure buckling modes of stud (short columns), furthermore, were reflected through these results.

Two flanges width of 40 mm and 50 mm were selected with the section thickness 1mm constant for 8 specimens of built-up sigma section columns. Connecting back-to-back CFS sigma sections with fasteners, M6 H.S.B. grade 8.8 bolts made the specimens with different column heights. Column geometry and cross-sectional dimensions are illustrated in fig 5 and dimensions of the tested specimens in Table 3. Two 20 mm thickness head plates were bolted at the end of the specimens in order to certify equal stresses distribution across the sections. End condition of plates allowed rotation about strong and weak axes. The compressive loads were gradually applied on the upper end of the tested columns by a 250 kN jack where as the lower one resisted the developed reactions. To measure horizontal displacements of the web mid points and the flange lip juncture points, three LVDT were attached at the mid-height point of the tested columns while one employed vertically for axial shortening.

Through the tests, it was observed that pure distortional buckling (D) mode occurred for studs while interactive overall sectional buckling (local distortional-LD) mode for intermediate height columns and overall buckling (Global G) for long columns. If the spacing of connecting fasteners was decreased, the sectional buckling of higher values of web recess depth to thickness ratio changed from distortional (D) to local (L) buckling mode. Sample failure modes of the specimens S40-75-50 and S50-25-100 are shown in fig 6.



(a) Cross-sectional dimensions (b) Pinned-pinned column
Fig 5: Column geometry and cross-sectional dimensions [9]

Table-III: Test specimens' dimensions

Specimen	Section Dimensions (mm)							L (mm)
	H	H1	H2	H3	B	D	a	
S40-25-50	160	50	10	40	40	13.3	10	895
S40-25-100	160	50	10	40	40	13.3	10	1788
S40-75-50	160	30	30	40	40	13.3	30	1125
S40-75-100	160	30	30	40	40	13.3	30	2250
S50-25-50	160	47.5	12.5	40	50	13.3	12.5	1140
S50-25-100	160	47.5	12.5	40	50	13.3	12.5	2282
S50-75-50	160	30	30	40	50	13.3	30	1142
S50-75-100	160	30	30	40	50	13.3	30	2500

Note: L is the height of the specimens
 Data in Table 3 are reference from [9]



(a) S40-75-50 (b) S50-25-100

Fig 6: Failure modes of specimens S40-75-50 &S50-25-100 [9]

III. CONCLUSION

Outstanding to these researches, the buckling behaviors of CFS built-up columns can be summarized as; (i) the different buckling modes, local and distortional, for stud columns with built-up I sections vary with the nominal width of web while the medium columns fail in interactive mode, local-distortional-global buckling and long columns in pure global buckling mode, (ii) for back-to-back built-up I columns, the effectiveness of EFGs to columns is only with flexural buckling mode, not the local one, (iii) for built-up box section, short columns failed through local buckling while the slender columns failed by global buckling mode, (iv) for built-up columns with double-lacing configuration and large flat width-to-thickness ratio, local buckling of the chord members observed as the major failure mode of buckling in all cases and no connection failure occurred in any mode of observation, (v) for built-up sigma section columns, pure distortional buckling mode occurred for studs while interactive buckling (local-distortional) for intermediate height columns and pure global for long columns.

It is recommended that more detail investigations are desirable to compare among the specimens of built-up box, sigma and I sections columns under uniaxial compression loads for global buckling and judge against the results with analytical and numerical methods.



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