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Original Article

Experimental Mechanical Properties of Self-Drilling Screw Configuration for Cold-Formed Steel Built-up Back-to-Back Column

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Abstract - *Cold-Formed Steel (CFS) is offered in different sizes, shapes, and dimensions using rolling, bending, and pressing equipment and has been established as a non-structural and structural component for building. Due to its numerous advantages, CFS is studied to propose as a structural component for buildings, which needs to be improved to minimize the structural integrity issue, especially buckling, and maximize stability. An example of the improvement for the CFS section is producing the section to develop a basic CFS built-up section, either in a face-to-face arrangement or back-to-back arrangement, by utilizing a fastener. The fastener, especially the self-drilling screw, is used for forming the CFS built-up back-to-back (CFSBB) column with two considerations, including end spacing and middle spacing. The primary purpose of the study is to ascertain the mechanical properties of self-drilling screw configuration for CFSBB columns by using experimental activity. The self-drilling screw was placed on the CFSBB column in five different configurations. One configuration used only two screws in one row, while the other configuration used four screws in two rows. The CFSBB column was connected to every row with two screws and in different directions. Then, the column was tested using an automatic compression machine under semi-rigid support conditions. The failure shape of the column was observed and recorded. From the experimental result data, the highest ultimate load and compressive strength value of the CFSBB column were at the location of the end spacing of 100 mm and middle spacing of 50 mm.*

Keywords - *Built-up Back-to-back Section, Cold-formed Steel, Self-drilling screw configuration, Mechanical properties column.*

1. Introduction

Material based on steel, such as Cold-Formed Steel (CFS) is introduced for building and construction activity, specifically shaped into desired dimensions and sizes at ambient temperature using rollers, benders, or pressers. Nevertheless, the process of CFS is categorized differently when compared with another steel-based material known as hot-rolled steel, which is formed by high energy and temperature. Normally, CFS possesses numerous advantages, such as flexibility, sustainability, recyclability, durability, suitability for a wide variety of applications, quick handling, quick installation, high strength-to-weight ratio, cost-effectiveness, and resistance to rusting, making it frequently used in construction as structural components. According to Meza and Becque [1], CFS with a high ratio of strength-to-weight contributes to material savings and reduces CO_2 emissions. Utilizing CFS as a structural component is becoming popular for residential houses, small and medium buildings, including industrial and commercial buildings, and infrastructure developments. Structural components include a roof truss system, wall panels, framing system, and floor joist. For design purposes, several codes of practices and standards are used for referring and designing CFS structures in construction, such as the Eurocode 3, Australian/ New Zealand (AS/ NZS), and American Iron and Steel Institute (AISI). The code of practices is applied during the design process to ensure that the CFS complies with requirements and achieves stability, safety, and efficiency.

CFS in marketable sections, such as unlipped channel, lipped channel, sigma, angle, and see, which are classified into open and unsymmetrical sections, are exposed to buckling failure; for instance, local, distortional, flexural-torsional, and lateral-torsional. Local buckling normally happens when the web element or flange element of the section buckles locally and is able to reduce load-carrying capacity and effective cross-sectional area. Local buckling often begins in the middle of the column and moves down its length due to severe compressive loads. On the other hand, distortional buckling occurs when compressive loads cause both local and overall distortions in the cross-section. Subsequently, thin sections are impacted by the distortional buckling, which is ultimately caused by complicated deformation patterns resulting from the interaction between the flange and web elements, distinct from that of the cross-section. When categorized as a section with a smaller thickness, Liu et al. [2] stated that individual or separate CFS sections are prone to failure due to torsional displacement. Contrarily, large values of the width-to-thickness ratio make CFS sections prone to local buckling failure. Flexural-torsional and lateral-torsional buckling occurs when the column is thin or has a high slenderness ratio. A combination of torsional and flexural deformations may cause flexural-torsional buckling, bringing about an abrupt and catastrophic collapse. In contrast, lateral-torsional buckling occurs when the column twists and deforms laterally in response to an axial compressive force. When a CFS column section is short or has a low slenderness ratio, the primary failure mechanism is usually local buckling. Local buckling leads to instability and decreased load-carrying capacity when compressive stresses surpass the local buckling capacity of the flange or web element. Design considerations, such as appropriate and adequate section design characteristics, loading conditions, proper installation technique, adherence to pertinent codes of practices, and efficient bracing and support, should be noted and taken seriously to address the failure of local buckling.

By referring to and observing the failure of the buckling and further issues of structural integrity, the CFS section with open and unsymmetrical conditions should be enhanced by producing the CFS built-up section with closed and symmetrical conditions or by integrating it with other materials like concrete, mortar, soil and timber board. Nevertheless, if the growth of the CFS built-up section is not adequately established, designed, and analyzed, the composite section from merging the built-up section with other materials is irrelevant. In general, a CFS built-up section is suggested by using individual or separate sections with more than two equal units available in the construction market. CFS built-up face-to-face and back-to-back sections are the two types of built-up sections commonly introduced as structural components in buildings like beams or columns. Jiang et al. [3] mentioned that CFS built-up columns, including open and closed sections, are suitable for high-rise construction due to their seismic resistance and fast construction. Besides, when designing the CFS built-up sections, the primary problem is measuring and accounting for the impact of partial composite action. This approach invariably results in a loss of stiffness due to longitudinal shear displacements between the constituent parts [4]. For guaranteeing structural safety and stability as well as to reduce or resolve structural integrity issues, a variety of fasteners are used in the production of CFS built-up sections, such as screws [5, 6], rivets [7], spot welding [8, 9], bolts and nuts, clinching and other innovations fasteners. Chen et al. [10] specified that the CFS built-up section is able to increase the torsion resistance, bearing capacity, buckling resistance, and bending resistance. According to Roy et al. [11], the use of modified slenderness by considering the spacing between fasteners into consideration is part of the guidelines for CFS built-up back-to-back (CFSBB) sections in the code of practice of AISI, and limited information on the research of the section to comprehend the impact of the thickness of the column and axial capacity of slenderness.

The fastener choice for developing the CFS built-up section depends on load conditions, particular applications, and design requirements. As CFS sections are increasingly used in steel structures and buildings, there is a drive to produce CFS built-up sections for use as structural components in modular construction [12]. Dobric et al. [4] reported that the fundamental function of fasteners is to preserve the integrity of the assembled parts, especially the CFS built-up section, when subjected to twisting displacement or global bending. Nevertheless, the full potential of the built-up section is not being utilized due to a lack of understanding of their mechanical properties and a gap in explicit design rules in the major codes of practice [1]. Despite the advancements in construction technology, there is still a large vacuum in codified design procedures and techniques for producing CFS built-up sections [13].

A fastener is a mechanical tool used to secure or unite two or more individual or separate sections to propose the built-up section. It is made to join the sections temporarily or permanently. Besides, a fastener is used to make the built-up section simple to assemble, disassemble or reorganize systems of structures. The most widely used fasteners for CFS built-up sections are usually self-drilling screws and self-tapping screws. Nevertheless, particular designs and applications may be known for using alternative fasteners. Many variables, including load requirements, corrosion resistance, installation time, and the particular connection design, influence the choice of fasteners. In general, fasteners for CFS built-up sections need to be robust to withstand tensile and shear stresses while continuously preventing corrosion. Vy et al. [14] mentioned that no established rules and guidelines exist in codes of practice about the quantity, configuration, and position of screws needed in each row of the CFSBB section, which results in different presumptions.

Several previous studies have investigated the type of fastener and fastener spacing. For example, M8 bolts with end spacing of 25 mm and middle spacing of 50 mm [4], screws with 50 mm, 100 mm, and 150 mm end spacing, and 100 mm, 200 mm, and 300 mm middle spacing [15], M16-10.9 grade hexagonal bolt with end spacing and middle spacing of 100 mm [16] and screw with end spacing of 50 mm and middle spacing of 237.5 mm [17]. Other examples of fastener spacing and the type of fastener from previous studies are tabulated in Table 1. Table 1 exemplifies that the lowest end spacing value is 15 mm, whereas the highest is 140 mm. Meanwhile, the lowest middle spacing value is 45 mm, and the highest is 150 mm. The findings of previous studies are not reported in Table 1 due to the varying studies that do not focus on fastener configuration. Self-drilling screws are typically chosen to produce the built-up sections connecting a separate CFS section due to their practical operation and economic rationale [18]. For the purpose of drilling in its hole, the self-drilling screw has a drill bit tip and is often used for joining between steel surfaces and thinner steel sections. The advantages of the self-drilling screw are rapid assembly because of the absence of a pre-drilling process, ease of installation, adaptability in design, versatility, efficiency in installation, cost-effectiveness, durability, corrosion resistance, and strong holding power and connection.

Table 1. Examples of previous studies for explaining the type of fastener and fastener spacing

Author & Year	Types of Fasteners	Types of CFS Section	Types of Built-up Section	Column Height	End Spacing	Middle Spacing
Sang et al. [19]	Self-drilling screw with 25 mm of length and 4.8 mm of diameter	Lipped channel section without stiffener – 122 mm × 52 mm × 17 mm × 1.2 mm	Back-to-back section (I-section)	360 mm	45 mm	45 mm
					90 mm	90 mm
					105 mm	150 mm
		Lipped channel section without stiffener – 142 mm × 52 mm × 22 mm × 1.2 mm	Back-to-back section (I-section)	420 mm	60 mm	50 mm
					60 mm	150 mm
					110 mm	100 mm
Ananthi et al. [12]	Self-drilling screw	Unequal-lipped angles without stiffener – 120 mm × 60 mm × 15 mm × 2.0 mm, 150 mm × 75 mm × 15 mm × 2.0 mm and 180 mm × 90 mm × 15 mm × 2.0 mm	Face-to-face section (box-up section)	300 mm	50 mm	50 mm
Nie et al. [20]	Self-drilling screw with 16 mm of length and 4.8 mm of diameter	Lipped channel section without stiffener – 143 mm × 43 mm × 15 mm × 1.5 mm and unlipped channel section – 147 mm × 118 mm × 1.5 mm	Face-to-face section (box-up section)	420 mm	140 mm	140 mm
Mahar et al. [21]	Self-drilling screw and self-tapping screw	Unlipped channel section without stiffener – 80 mm × 35 mm and 50 mm × 1.2 mm	Face-to-face section (box-up section) and back-to-back (I-section)	500 mm	75 mm	75 mm
Teoh et al. [22]	Breakstem rivet with 4.76 mm of diameter	Lipped channel section with double web stiffener – 102 mm × 51 mm × 12 mm × 1.0 mm	Back-to-back section (box-up section)	300 mm	15 mm	90 mm
		Lipped channel section with double web stiffener – 75 mm × 40 mm × 8.0 mm × 1.0 mm, 75 mm × 40 mm × 8.0 mm × 0.75 mm and 75 mm × 40 mm × 8.0 mm × 0.6 mm	Back-to-back section (box-up section)	230 mm	15 mm	67 mm

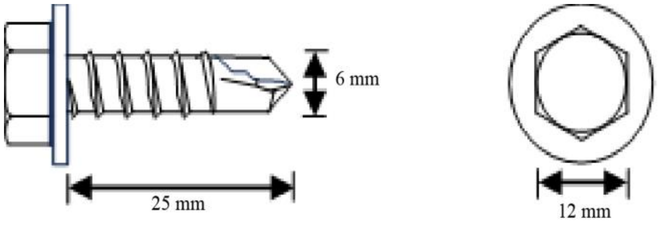
The limited information and knowledge of specific design criteria and rule in the development of CFSBB sections in codes of practice is an important way to study the mechanical properties of the self-drilling screw configuration and self-drilling screw direction. Besides, previous studies have focused on fastener type, column height, CFS cross-section type, CFS built-up section type, self-drilling screw spacing, and self-drilling screw direction. There is no information on semi-rigid support conditions. All these parameters are still being studied to add to the current codes of practices and standards of the CFS section to solve or minimize structural integrity. Based on Table 1, the novelty of the study is the self-drilling screw spacing, including end spacing and middle spacing with different lengths, different self-drilling screw directions in every row, and the dimension of the stub column by using lipped CFS channel section of 100 mm × 50 mm × 12 mm × 1.55 mm, and the height of the column specimen of 250 mm. Before the CFSBB section is used for further experimental activities, such as proposing the composite structure, its mechanical properties are investigated. The primary goal of the study is to use two CFS channel sections for experimenting on CFSBB columns to ascertain the mechanical properties of the self-drilling screw configuration.

2. Experimental Column Specimen and Apparatus Setup

A lipped CFS channel cross-section without web stiffeners was preferred due to its availability in the Malaysian construction industry. The lipped CFS channel section of 100 mm × 50 mm × 12 mm × 1.55 mm is selected. Other parameters comprise G450 steel grade, 450 MPa of yield stress, and 329 mm^2 of a CFS area. The lipped CFS channel section was cut to a fixed depth of 250 mm and cleaned up, classified as a low value of stiffness factor and a short column.

Two individual CFS channel sections were developed and joined back-to-back arrangement by using a self-drilling screw to form a CFS built-up section. Self-drilling screws of 25.4 mm in length and 6 mm in diameter were bought from the construction industry market, as depicted in Figures 1 and 2 with schematic diagrams and actual images, respectively. The important value of self-drilling screw spacing was divided into two categories, including end spacing, *es,* and middle spacing, *ms*, as illustrated in Table 2, which followed and were modified according to Ma et al. [15].

Furthermore, the end spacing and middle spacing were selected based on an analysis of previous studies with a multiple calculation of 25 for end spacing and a multiple calculation of 50 for middle spacing. There are clear descriptions of the specimen with specimen labels and screw spacing, as tabulated in Table 2. The SDS1 specimen had a mass between 1.330–1.335 kg, while the SDS2, SDS3, SDS4, and SDS5 specimens had masses between 1.350–1.355 kg. SDS0 was used in the experiment and classified as a control specimen without any combination with other individual or separate sections. According to Figure 3, the CFS built-up section had a square cross-section of 100 mm in breadth and 100 mm in width. As a reference, Wang et al. [23] reported that the end spacing of the self-drilling screw at the web element is 25 mm. The total area of the CFS built-up section was 658 mm^2, with a depth-to-width ratio of 2.5.



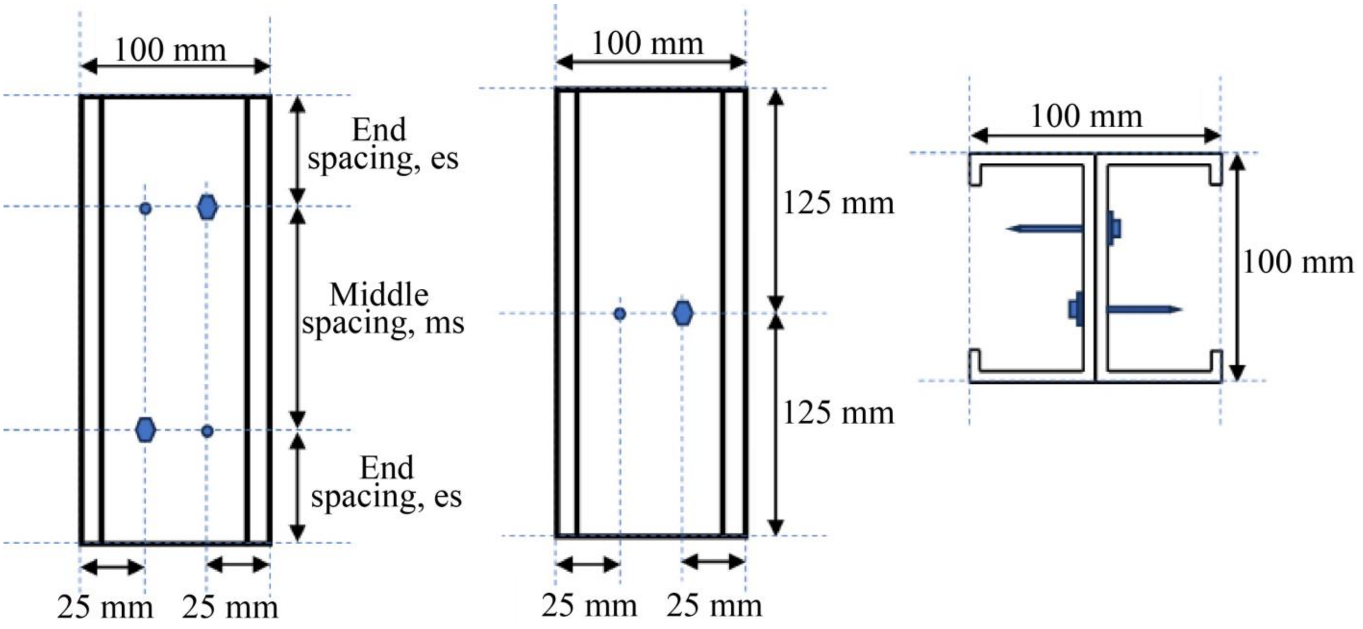
(a) (b)

Fig. 1 The perspective view of the self-drilling screw from (a) side and (b) top

Fig. 2 The actual image of the self-drilling screw

Table 2. Description of the CFS column specimen with specimen label and self-drilling screw spacing

Specimen Labels	Description of CFS Column Specimen	End Spacing, *es* (mm)	Middle spacing, *ms* (mm)
SDS0	CFS channel section	0	0
SDS1	Self-drilling screw located at the mid-span of the column with a total of two numbers.	125	0
SDS2	Self-drilling screw, which is positioned at two locations of the column with a total of four numbers.	100	50
SDS3	Self-drilling screw, which is positioned at two locations of the column with a total of four numbers.	75	100
SDS4	Self-drilling screw, which is positioned at two locations of the column with a total of four numbers.	50	150
SDS5	Self-drilling screw, which is positioned at two locations of the column with a total of four numbers.	25	200



(a) **(b)** **(c)**

Fig. 3 The schematic diagram of the (a) general front view, (b) example front view of the SDS1 specimen, and (c) top view

A 2000 kN Automated compression machine was used to investigate the mechanical properties of the self-drilling screw configuration for CFSBB columns. The column was tested under axial compression load with a loading rate of 1.80 kN/s and under semi-rigid supported boundary end conditions. The specimens were positioned in the middle part of the steel plate of the automatic compression machine. The axial compression load test was employed based on Muftah et al. [5].

The ultimate load and compressive strength result data were obtained and compared with the separate CFS channel section, SDS0, and the larger size of the CFSBB column by utilizing 120 mm × 40 mm × 15 mm × 2 mm with a height consistency of 250 mm. The SDS0 specimen was recognized as a control specimen, tested without forming into a built-up section.

Meanwhile, the larger size of the CFSBB column was formed by using three numbers of self-drilling screws, which were positioned at the mid-span of the column with a length of 125 mm and in the same direction as the screw. The mass of the column is 1.43 kg. Finally, the failure shape of all column specimens was examined and categorized.

3. Results and Discussion

From the experimental activity, complete results of the column's mechanical properties with a difference in self-drilling screw configuration were classified. The failure shape of the column was recorded and categorized. Finally, the best configuration and optimal self-drilling screw configuration with the highest ultimate load and compressive strength value was identified.

3.1. Mechanical Properties of Cold-formed Steel Built-up Back-to-back (CFSBB) Column

Table 2 summarises and tabulates the ultimate load and compressive strength results for the CFSBB column. Figure 4 and Figure 5 highlight the obvious disparities between these specimens regarding ultimate load and compressive strength. The highest ultimate load and compressive strength value for the CFSBB column was SDS2, whereas the lowest was SDS5. There was a 10.37% percentage difference between these two specimens. The ultimate load and compressive strength value of the CFSBB column decreased when the end spacing was decreased by 100 mm and increased by more than 100 mm. When comparing the CFSBB column to separate CFS channel sections, the ultimate load difference ranged from 57% to 61%. Meanwhile, the percentage difference in compressive strength was 22.73% and 23.58% when compared between the separate sections, SDS0 with SDS1 and SDS2, respectively. 17.64% and 21.98% were reported to be obtained when the compressive strength of SDS0 was compared with SDS3 and SDS4, respectively. 1.10%, 2.05%, 7.21%, and 10.37% were recorded when the highest value of compressive strength, SDS2, was distinguished from SDS1, SDS4, SDS3, and SDS5, respectively. All specimens were determined to have a compressive strength value of more than 350 MPa. Finally, the percentage difference in compressive strength between SDS0 and SDS5 was 14.74%. All specimens of the CFSBB column represented more than 14% of the compressive strength due to the column having a double web element thicker than individual or separate CFS channel sections. Therefore, the SDS2 specimen was selected and classified as suitable for use as the column.

Table 3. The experimental result and failure shape of the CFSBB column specimen

Specimen	Ultimate load (kN)	Compressive Strength (MPa)	Failure Shape
SDS0	100.6	305.78	Local and Distortional Buckling
SDS1	260.4	395.74	Local and Distortional Buckling
SDS2	263.3	400.15	Local and Distortional Buckling
SDS3	244.3	371.28	Local and Distortional Buckling
SDS4	257.9	391.95	Local and Distortional Buckling
SDS5	236.0	358.66	Local and Distortional Buckling

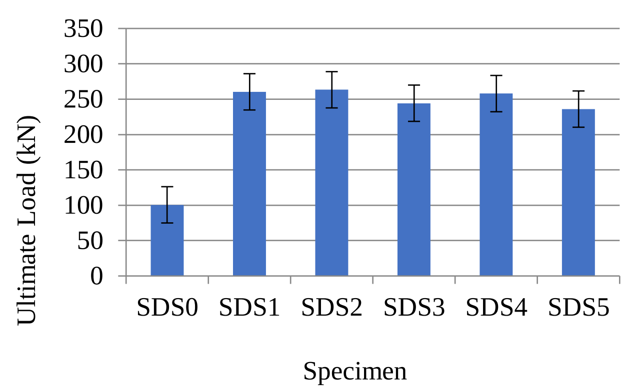


Fig. 4 The ultimate load result for all specimens of the CFSBB column

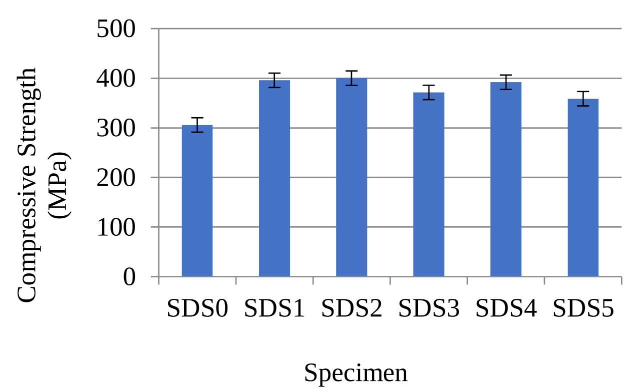


Fig. 5 The compressive strength result of the CFSBB column specimen

With a larger CFS channel section, the ultimate load of the CFSBB column was found to be 152.8 kN. It was compared with SDS1, which had the same configuration but with a different screw direction, and the number of screws was approximately 41.32%. Therefore, the size of the CFS channel section, number of screws, and screw direction are important for CFSBB columns to give the appropriate data of ultimate load and compressive strength. Figures 6 and 7 illustrate the link between compressive strength and end spacing and compressive strength and middle spacing, respectively. The compressive strength was reduced by decreasing the end spacing and increasing the middle spacing. The link between the compressive strength and the end spacing and middle spacing of the CFSBB column was not linear and had an uneven connection. The highest and lowest values of the compressive strength of the CFSBB column specimen were 100 mm and 25 mm of end spacing, respectively. Nevertheless, the highest compressive strength value of the CFS built-up column specimen was 50 mm of middle spacing.

In comparison, the lowest compressive strength value of the CFS built-up column specimen was 200 mm of middle spacing. The end spacing of the column with sufficient spacing is very important to study to avoid the initial failure of the column at the loading and support. Furthermore, adequate middle spacing of the column specimen is suitable to evade buckling failure on the middle height of the column, which improved in a basic theory whereby a large deformation will happen at the mid-span.

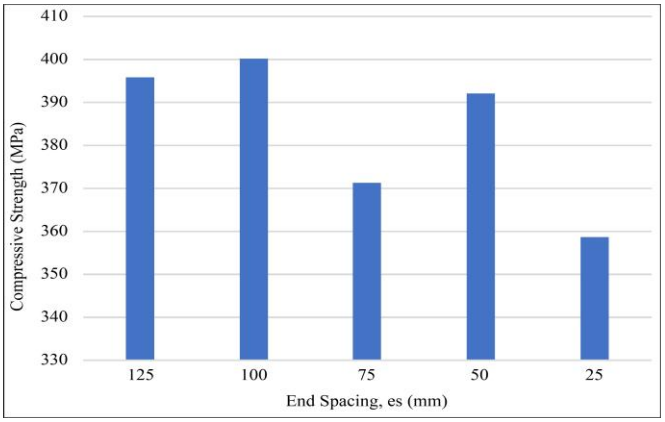


Fig. 6 The link between the compressive strength and end spacing

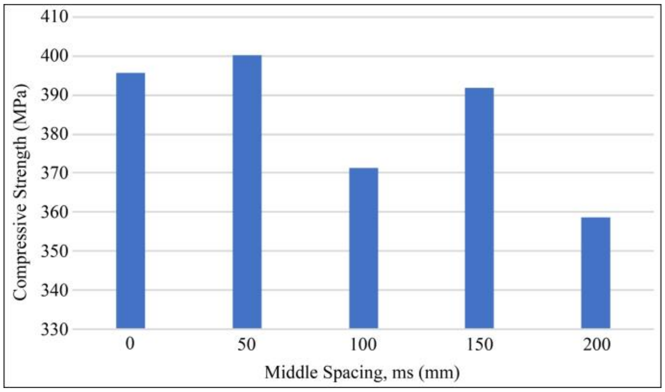


Fig. 7 The link between the compressive strength and middle spacing

3.2. Failure Shape of Cold-formed Steel Built-up Back-to-back (CFSBB) Column

The failure shape of all specimens was determined and categorized as having local buckling and distortional buckling, which happened on the web element and flange element. From the observation, the local buckling appeared in the first part before experiencing distortional buckling. No failures occurred on the self-drilling screw, either shear failure or pull-out failure. The failure shape of all specimens is depicted in Figures 8 to 12, which bears similarities to the study of Sang et al. [19].

The red circle in the figures presented the column specimen's failure. Figure 8 shows the buckling failure on the web and flange on one side, which is far from the position of the self-drilling screw. The web element was slightly bent from the origin and classified as not critical as the flange element. The flange element was observed to have buckling, which moved out or in from the origin. Jiang et al. [3] reported that the CFS built-up section exhibits and experiences distortional buckling under axial compression load after the local buckling failure appears.

Additionally, Figure 9 illustrates the failure shape of the SDS2 specimen in which the web and flange element at the end part were buckled. The failure of the SDS2 was more critically bent when compared with the SDS1 specimen because the mid-span of the column at mid-span was fully restrained. This outcome was because the self-drilling screw configuration, which was located in the middle part, was influenced to be stronger and more stable but affected the end part of the column. Figure 10 and Figure 11 illustrate the failure shape of the SDS3 and SDS4 specimens, respectively, and were observed to have similar buckling failure on the flange element and web element at the end part of the column specimen. Next, Figure 12 demonstrates the failure shape of the SDS5 specimen, and buckling failure was seen towards the end part of the column, especially on the flange element and web element.

The failure shape of SDS5 occurred near the self-drilling screw when subjected to compression load and was classified as more critical when compared with SDS3 and SDS4. Therefore, the self-drilling screw was not suitable to be placed near the end part of the column because it produced an additional localized strength, which was affected when under compression load. Chen et al. [12] claimed that a slenderness ratio less than or equal to 72.9 is influenced by failure when local-distortional buckling interacts, and it also clarified that the column's slenderness ratio is significantly inclined to bearing capacity and failure shape.

Additionally, the failure shape of the CFSBB column was contrasted with the larger size of the CFS channel section in the CFSBB column, as shown in Figure 13. From Figure 13, the column failed at both ends of the column. It was categorized as having critical and severe buckling on the web element and flange element when compared to other specimens. All specimens had failure shapes that were somewhat comparable to those found in studies by Muftah et al. [5] and Roy et al. [11].

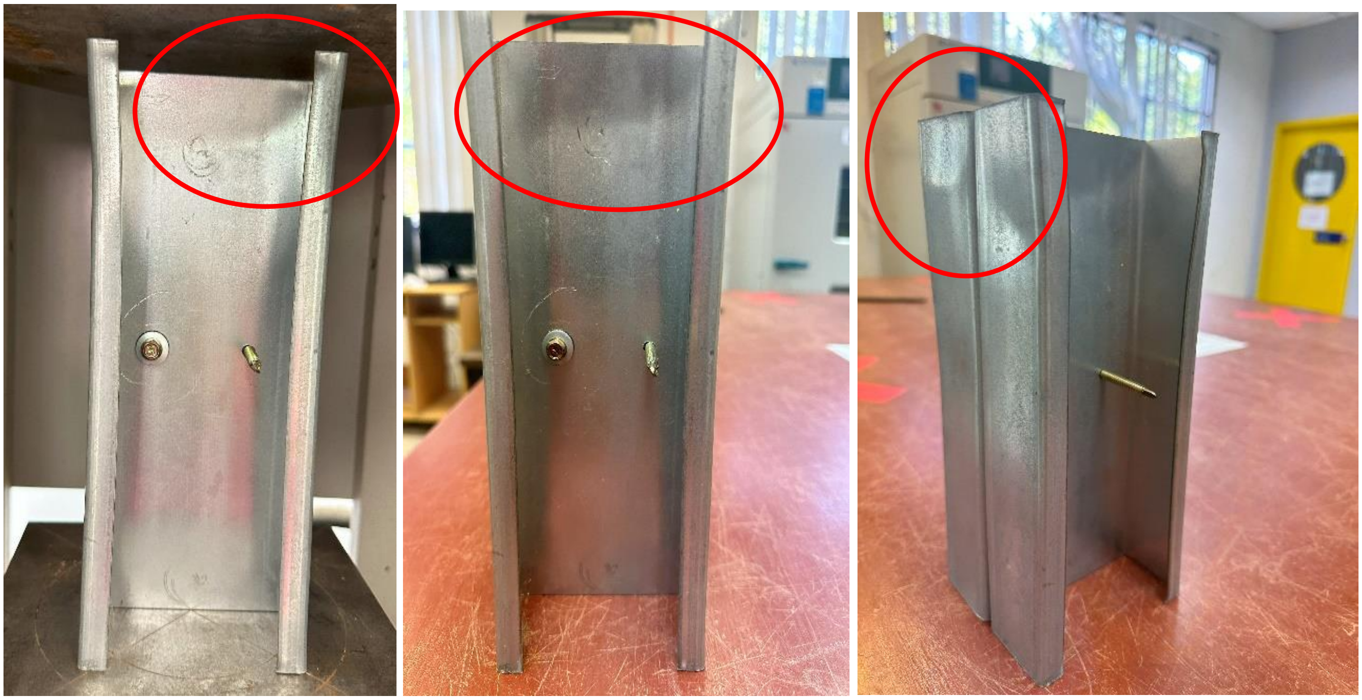


Fig. 8 The failure shape of the SDS1 specimen

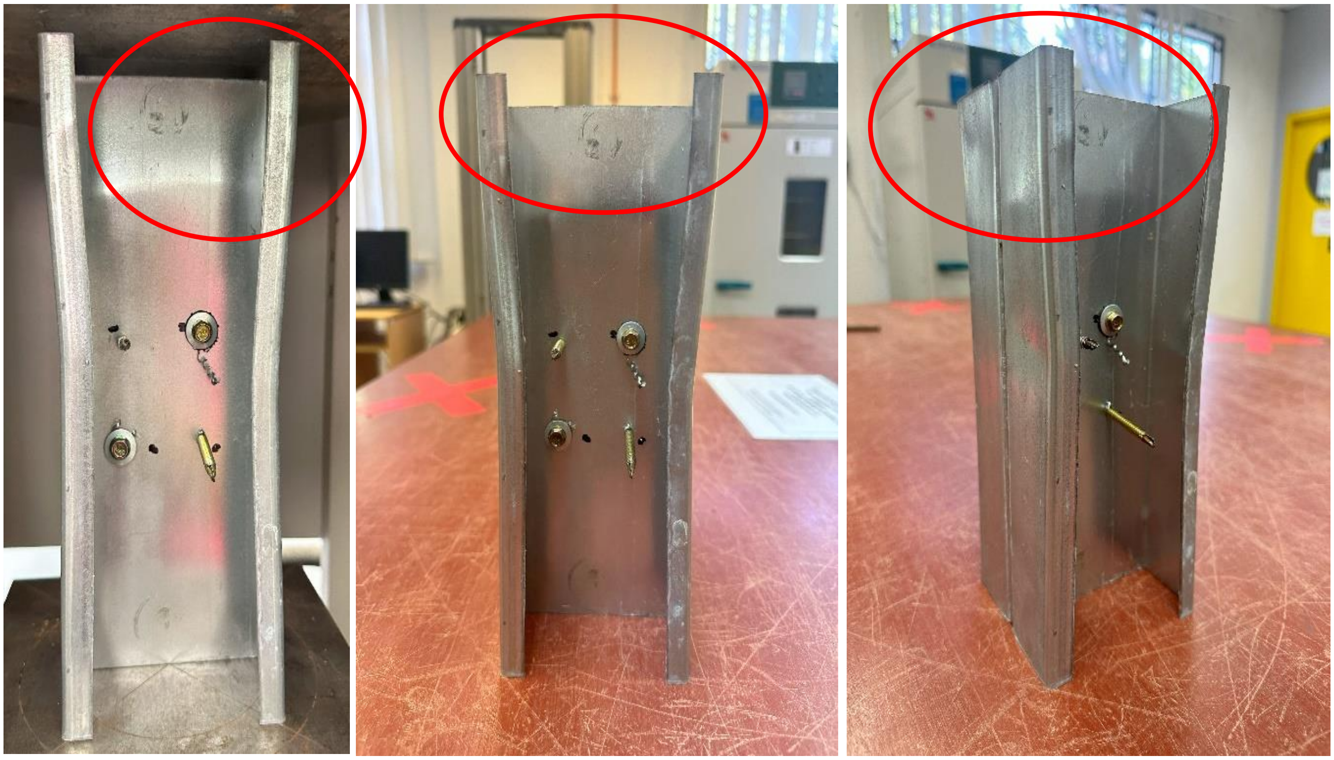


Fig. 9 The failure shape of the SDS2 specimen

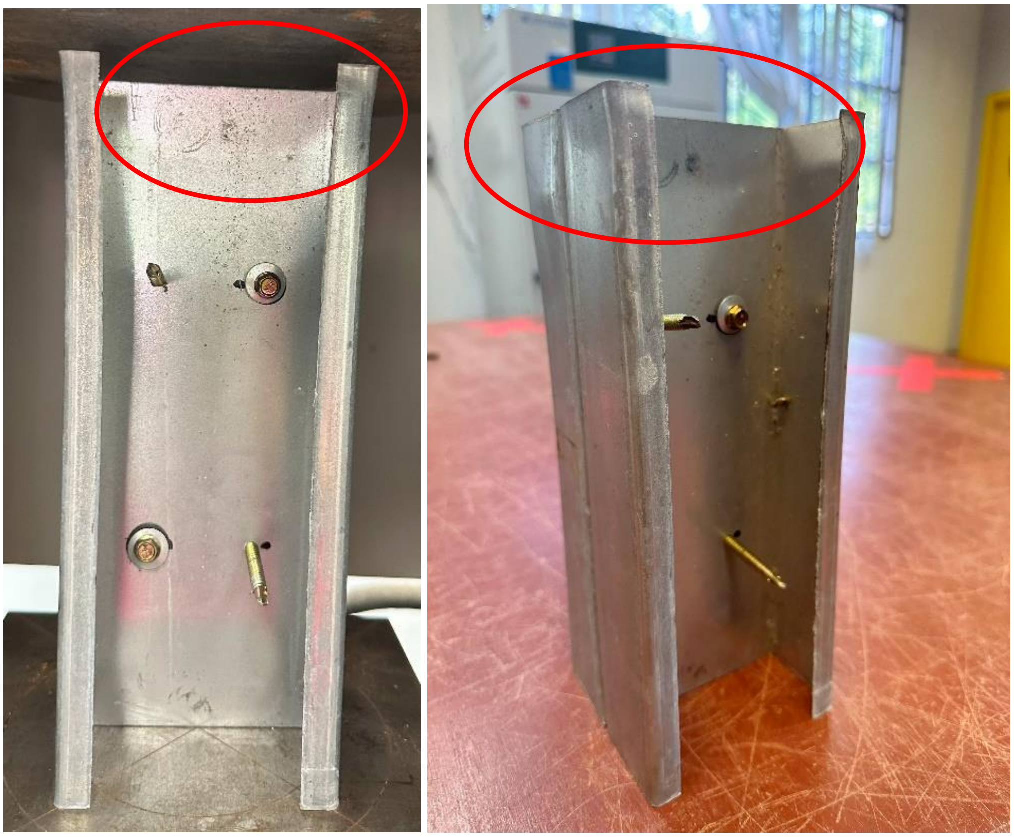


Fig. 10 The failure shape of the SDS3 specimen

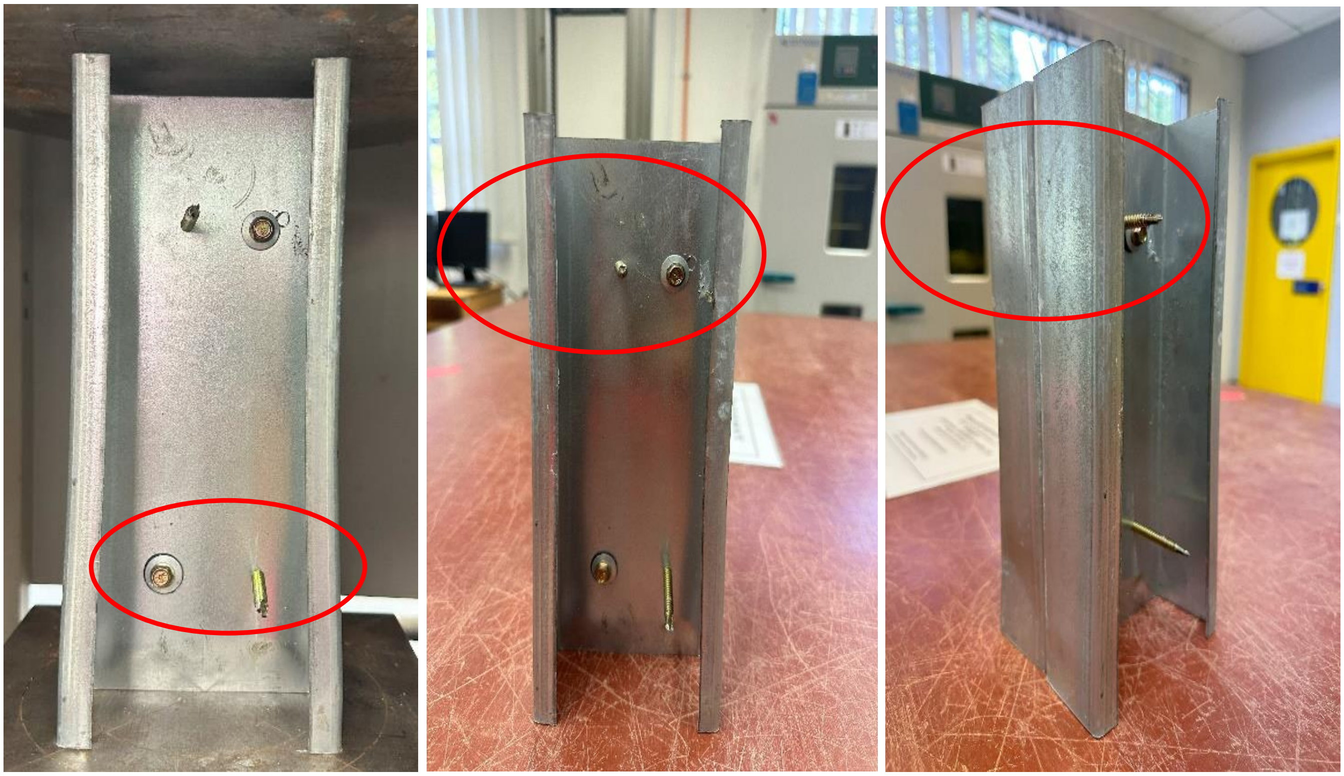


Fig. 11 The failure shape of the SDS4 specimen

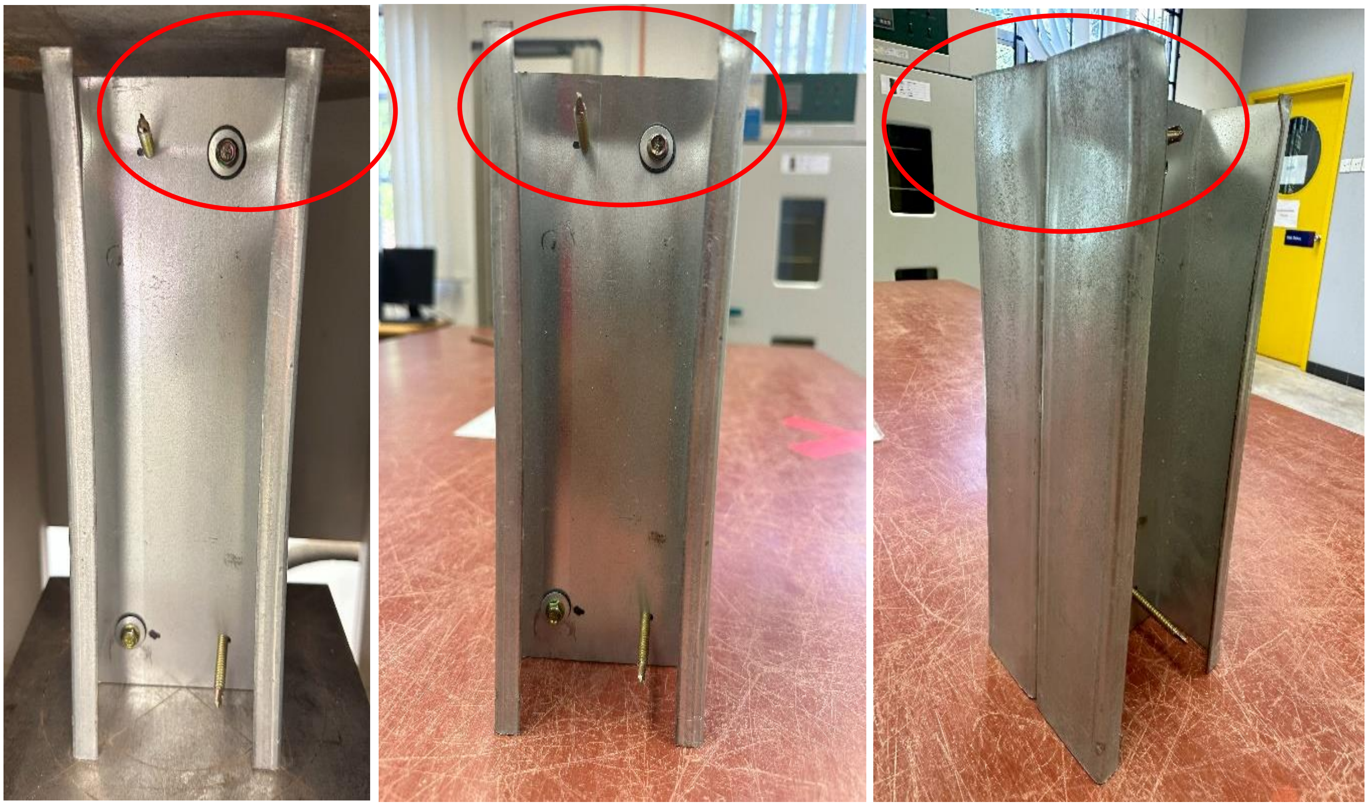


Fig. 12 The failure shape of the SDS5 specimen

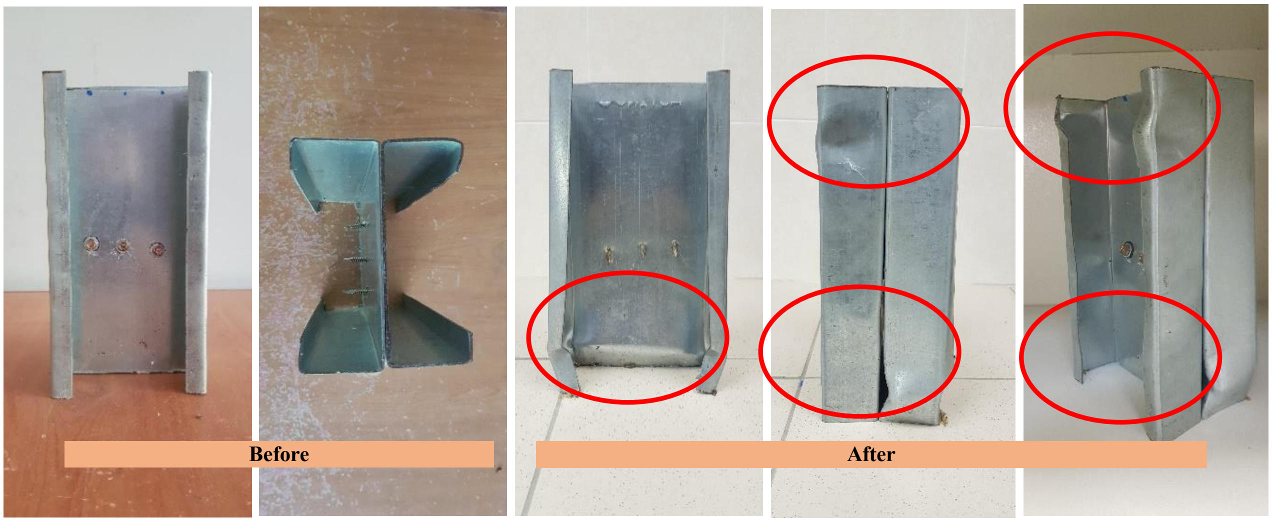


Fig. 13 The failure shape of the CFSBB column with a larger size of the CFS channel section before and after experiments

4. Conclusion and Recommendation

Several conclusions and recommendations were drawn from the experimental activity results and the shape observation's failure to serve as a guide when producing the CFS built-up back-to-back (CFSBB) column examined here.

According to the CFSBB column, the SDS2 and SDS5 specimens exhibited the highest and lowest compressive strength, respectively. There was a 10.37% percentage difference between these two specimens. When the SDS2 and SDS5 specimens were compared with SDS0, classified as a separate CFS channel section, values of 23.58% and 14.74%, respectively, were recorded. A percentage difference of 1.10% was reported when the SDS1 specimen was compared with the SDS2 specimen. This finding showed that the SDS1 and SDS2 specimens were suitable for structural components, especially columns and compression members.

The end spacing and middle spacing are important to consider when producing CFSBB columns because the section could minimize the buckling effect and promote stable conditions. According to reports, the highest and lowest compressive strength values were found at end spacings of 100 mm and 25 mm, respectively. Meanwhile, the middle spacing of 50 mm exhibited the highest compressive strength value, whilst the middle spacing of 200 mm demonstrated the lowest compressive strength value. The specific value was suitable to add to the codes of practices for determining the ultimate load and compressive strength for the CFSBB section for design recommendations and flowcharts.

All specimens were illustrated to have the local buckling at the first part and continued with the distortional buckling, in which the web and flange elements were moved out or in from the origin line. The failure shape of the SDS0 specimen, which was in the separate CFS channel section, was improved by proposing the CFSBB column due to the increasing thickness of the web elements.

For recommendation, the CFSBB column should be compared and analyzed with the mechanical properties of the self-drilling screw configuration and the CFS built-up face-to-face column or with other innovative CFS built-up columns or with a combination of other materials. Next, determining the mechanical properties of CFSBB columns should be extended to a slender section by discussing the slenderness ratio, and lastly, verified with a numerical analysis using finite element modelling and analytical analysis.

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References

[1] Francisco J. Meza, and Jurgen Becque, “Numerical Modelling of Cold-Formed Steel Built-Up Columns,” *Thin-walled Structures*, vol. 188, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[2] Ruoqi Liu et al., “Buckling Behavior and Failure Mechanism of Cold-Formed Steel Built-Up Special Shape Cross-Section Columns,” *Engineering Failure Analysis*, vol. 165, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Liqiang Jiang et al., “Compressive Behavior of Novel Cold-Formed Steel Built-Up Closed L-Shaped Section Columns,” *Journal of Building Engineering*, vol. 86, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[4] Jelena Dobrić et al., "Buckling Strengths of Cold-Formed Built-Up Cruciform Section Columns under Axial Compression," *Thin-Walled Structures*, vol. 200, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Fadhluhartini Muftah, Mohd Syahrul Hisyam Mohd Sani, and N. Nindyawati, "Preliminary Study on Built-Up Back-To-Back Cold-Formed Steel Stub Column Filled with Washed Bottom Ash Concrete," *Advanced Structured Materials*, vol. 208, pp. 153-165, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Hélder D. Craveiro, João Paulo C. Rodrigues, and Luís Laím, "Experimental Analysis of Built-Up Closed Cold-Formed Steel Columns with Restrained Thermal Elongation under Fire Conditions," *Thin-walled Structures*, vol. 107, pp. 564-579, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[7] Hai-Ting Li et al., "Experimental Investigation of Cold-Formed Stainless Steel Built-Up Closed Section Stub Columns," *Engineering Structures*, vol. 306, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[8] Viorel Ungureanu et al., "Experimental and Numerical Investigations on Built-Up Cold-Formed Steel Beams using Resistance Spot Welding," *Thin-walled Structures*, vol. 161, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[9] Judyta Niemiro-Maźniak, and Piotr Lacki, "Experimental and Numerical Analysis of Joints and Thin-Walled Steel Beams Fabricated through Resistance Spot Welding and Hot-Dip Galvanizing," *Thin-walled Structures*, vol. 202, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] Ming Chen et al., "Research on Axial Compression behaviour of Cold-Formed Steel Built-Up T-Shaped Columns," *Structures*, vol. 70, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[11] Krishanu Roy et al., "Effect of Thickness on the Behaviour of Axially Loaded Back-to-Back Cold-Formed Steel Built-Up Channel Sections - Experimental and Numerical Investigation," *Structures*, vol. 16, pp. 327-346, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[12] G. Beulah Gnana Ananthi et al., "An Investigation on Stiffened Cold-Formed Steel Unequal Angle Box Section Columns," *Journal of Building Engineering*, vol. 76, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Jingjie Yang et al., "Axial Compressive behavior of Cold-Formed Steel Built-Up Box-Shape Columns with Longitudinal Stiffeners," *Journal of Constructional Steel Research*, vol. 212, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[14] Son Tung Vy, Mahen Mahendran, and Thananjayan Sivaprakasam, "Built-up Back-to-Back Cold-Formed Steel Compression Members Failing by Local and Distortional Buckling," *Thin-walled Structures*, vol. 159, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Chicheng Ma et al., "Experimental and Numerical Investigations of High-Strength Cold-Formed Steel Multi-Limb Built-Up Section Columns," *Engineering Structures*, vol. 309, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[16] M.S. Deepak, and G. Beulah Gnana Ananthi, "Local Buckling Behaviour and Capacities of Cold-Formed Steel Double-I-Box Stub and Short Column Sections," *Structures*, vol. 34, pp. 1761-1784, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[17] Hélder D. Craveiro et al., "Buckling behavior of Closed Built-Up Cold-Formed Steel Columns under Compression," *Thin-walled Structures,* vol. 179, pp. 1-27, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Hanheng Wu et al., "Shear-Slip Constitutive Model of Screw-Fastened Connections and Application in Numerical Analysis of Built-Up Back-To-Back Cold-Formed Steel Columns," *Thin-walled Structures*, vol. 186, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[19] Liurui Sang et al., "Local Buckling in Cold-Formed Steel Built-Up I-Section Columns: Experiments, Numerical Validations and Design Considerations," *Structures*, vol. 47, pp. 134-152, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[20] Shaofeng Nie et al., "Investigation of Built-Up Box Columns Composed of Four Cold-Formed Steel Channels," *Thin-walled Structures*, vol. 175, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[21] Akshay Mangal Mahar, S. Arul Jayachandran, and Mahen Mahendran, "Design of Locally Buckling Cold-Formed Steel Built-Up Columns Formed by Unlipped Channel Sections," *Thin-walled Structures*, vol. 174, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[22] Keat Bin Teoh et al., "Experimental Investigation of Lightweight Aggregate Concrete-Filled Cold-Formed Built-Up Box Section (CFBBS) Stub Columns under Axial Compression," *Engineering Structures*, vol. 279, pp. 1-17, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[23] Liping Wang, Mahmud B. Dawud, and Yancheng Cai, "Flexural behavior and Design of Cold-Formed Steel Gapped Back-to-Back Built-Up Beams with Discontinuous Connecting Plates," *Thin-walled Structures*, vol. 205, 2024. [CrossRef] [Google Scholar] [Publisher Link]