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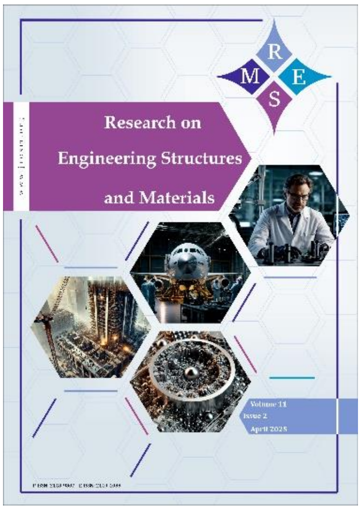

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Research Article

An experimental study on the structural behavior and strength of built-up battened columns using square hollow sections (SHS) under axial loading

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Abstract

Cold-formed steel (CFS) built-up battened columns using Square Hollow Sections (SHS) offer promising potential for lightweight, high-strength structural applications. However, current design standards mainly address open-section configurations, leaving limited guidance for closed-section members. This study investigates the axial compression behavior of built-up battened columns fabricated from SHS, focusing on section thickness and batten spacing (300 mm and 400 mm). Six full-scale specimens were tested under axial loading to evaluate load-carrying capacity, failure modes, and lateral stability. Results show that built-up battened columns significantly outperform single SHS columns, with enhanced strength and improved resistance to global and local buckling. Closer batten spacing consistently yielded higher axial capacity and more ductile failure behavior, while wider spacing led to reduced performance and premature batten plate detachment. Failure mechanisms ranged from global buckling in single columns to combined local and flexural buckling in built-up specimens. The built-up column S3-H2-B300 achieved a peak axial load of 263.95 kN, outperforming single SHS column S2-H2-SHS (34.55 kN) by over 300%. Experimental-to-theoretical ratios ranged from 0.6 to 1.3, validating EN 1993-1-1:2005 with a mean ratio of 1.0. The findings support future design improvements for closed-section CFS battened columns, which differ from conventional shapes due to unique stiffness characteristics and buckling behavior. Limitations include fabrication imperfections and connection variability, which may influence buckling performance.

1. Introduction

During Cold-formed Steel (CFS) built-up battened columns are widely used in steel construction, particularly for slender columns, as they offer enhanced flexural stiffness without significantly increasing the cross-sectional area [1]. The built-up battened columns are composed of two or more individual longitudinal components (Chords), such as angles, channels, or I-sections, which are connected by transverse batten plates [2,3]. The batten plates act as critical structural elements, enabling the composite behavior of the column and enhancing its axial load-carrying capacity [4, 5]. They also provide lateral restraint, thereby improving the column's stability against certain types of buckling. The compressive resistance of a battened column is governed by both the local behavior of the individual chord members and the global response of the assembled column. The internal forces in the batten plates significantly influence the overall stiffness and strength of the

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built-up battened column [6]. While shear deformation is relatively small in solid cross-section columns, it becomes more significant in battened columns due to the flexibility of the batten plates [7]. CFS built-up battened columns have gained prominence as efficient compression members due to their lightweight nature and relatively larger moment of inertia compared to single steel sections [8]. The built-up battened columns can carry higher loads over longer spans, making them ideal for structural applications where a single section is insufficient [3]. Among built-up sections, those using closed sections, such as square or rectangular hollow sections, exhibit superior torsional rigidity compared to open sections, further improving their structural performance under axial loading [1,9,10]. The square hollow sections (SHS) as chords demonstrate superior torsional rigidity and uniform stress distribution, making them ideal for resisting axial compression in slender column applications.

Recent studies have emphasized the importance of batten spacing and connection rigidity in influencing buckling behavior. A study by Li and Young [11] showed that closer batten spacing improves lateral restraint and post-buckling ductility, while excessive spacing leads to premature failure due to reduced stiffness. In their study, experimental and numerical investigations on cold-formed steel (CFS) battened columns composed of stiffened chord components connected by longitudinally spaced batten plates were performed. The study involved 20 full-scale compression tests and 216 finite element simulations to evaluate the effects of member slenderness, transverse chord spacing, and batten spacing on axial strength.

The role of batten plate rigidity in controlling secondary bending effects and shear lag has been highlighted in the study by Sangeetha et al. [12]. This is particularly crucial for thin-walled configurations such as square Hollow Sections (SHS). In the study, an investigation on the behavior of ten cold-formed steel built-up battened box columns consisting of four lipped angles connected by batten plates with varying lengths and cross-sectional dimensions was conducted. The study emphasized that the slenderness of batten plates significantly affects shear deformation and overall buckling behavior. Built-up battened columns have practical relevance in industrial buildings and modular buildings, where long-span and lightweight solutions are essential, and they have the ability to handle heavy axial loads and resist buckling. These columns are used when buckling lengths are large and compression forces are moderate, offering a practical solution for slender structural members. A recent study by Setiawan et al. [13] demonstrated that battened cold-formed steel columns are effective in portal frames up to 24 meters, offering better performance than conventional back-to-back configurations in their study.

Battened columns are not alien to structural engineering; they are well-established, codified, and widely applied in real-world construction. The design of battened built-up columns is explicitly covered in major design standards, including EN 1993-1-1:2005 [14], IS 800:2007 [15], AISC guidelines [16], and design guides such as Steel Buildings in Europe – Part 6 [17], which provide detailed methodologies for battened column design, including buckling length calculations and internal force analysis. Dar et al. [18] emphasized that while closed-section CFS battened columns offer superior torsional resistance and axial strength, their fabrication involves precise alignment of batten plates and chord spacing, which can introduce geometric imperfections and affect performance. The number of fasteners along the column height may introduce geometric imperfections that negatively affect axial performance. These imperfections arise from misalignment, uneven spacing, and manual fastening errors during fabrication. Furthermore, in the case of SHS arrangements, two sides of each chord may remain unconnected to the batten plate; thus, this partial connection is expected to affect shear transfer and reduce composite action. Unlike open-section configurations, such as channels, where design standards like EN 1993-1-1:2005 [14], provide guidance for flange-only connections, the closed geometry of SHS makes it more difficult to achieve full contact between battens and all chord surfaces. This fabrication challenge is not explicitly addressed in existing design codes, underscoring the need for refined provisions tailored to closed-section battened columns. Built-up CFS columns are a cost-effective and scalable solution for modern construction. Rahnavard et al. [19] emphasized the need for optimized fastener design and refined modeling techniques to ensure performance and efficiency. Their parametric study showed that optimizing the number of fasteners per batten panel and batten spacing can significantly improve composite action and axial strength in battened columns composed of two lipped channel sections. Using three rows of fasteners per batten panel was found to be optimal, balancing strength and material usage. This optimization can reduce fabrication effort and cost, making battened columns more economical.

Battened columns are scalable for a wide range of structural applications due to their modular design and inherent adaptability. However, scalability depends on several critical factors, including the effectiveness of composite action, connection rigidity, geometric imperfections, and end conditions. Despite these insights, most existing research focuses on open-section built-up columns, leaving a gap in understanding the behavior of closed-section SHS battened columns under axial loading. Despite their advantages, there remains a significant lack of experimental data and design guidelines for CFS built-up battened columns, particularly those employing square hollow sections [1, 20]. Existing design codes often inadequately address the influence of shear deformation in the chord members, potentially leading to inaccurate strength predictions [1]. Furthermore, the absence of comprehensive experimental studies on CFS battened columns with closed sections limits the advancement of reliable design methodologies [20].

This study specifically addresses the lack of experimental evidence on CFS built-up battened columns fabricated from closed cross-sections, particularly of square hollow sections, SHS, which offer superior torsional rigidity and different buckling behavior. While existing literature has predominantly focused on built-up columns using open sections (e.g., lipped angles, channels). However, the scope of this is limited to closed-section configurations using cold-formed steel under axial compression to investigate their structural behavior, failure modes, and load-carrying capacity, with particular emphasis on the influence of batten spacing. The findings are intended to support the development of refined design recommendations for this specific type of structural element.

2. Methodology

This study employs an experimental study to evaluate the structural behavior, failure modes, and load-carrying capacity of CFS built-up battened columns fabricated using SHS under axial loading. The experimental investigation consists of two key components, which are the tensile coupon test and the full-scale axial compression test. The tensile coupon test is conducted to determine the fundamental material properties of CFS, including yield strength, ultimate tensile strength, and elongation capacity.

The full-scale axial compression test is performed to assess the load-deformation behavior, failure mechanisms, and critical buckling loads of SHS built-up battened columns with steel plates as battens. These tests involve precise load application, displacement monitoring, and strain measurement to capture the structural response accurately. All tests were conducted in a standard indoor laboratory environment at ambient temperature.

2.1. Tensile Coupon Test

The tensile coupon test is a standard method for determining the mechanical properties of materials, including yield strength, ultimate tensile strength, elongation, and modulus of elasticity. The process begins with specimen preparation, where materials such as CFS and batten plates are shaped according to ISO 6892-1:2009 [21]. The specimen is designed in a dog-bone shape, with grip ends wider than the test section to ensure a secure hold in the tensile testing machine, prevent slippage, and ensure axial force application without bending. To maintain consistency and reliability, the test specimens feature a reduced cross-sectional area at the center, ensuring that the fracture occurs within the gage length, thereby accurately representing the material behavior under tensile loading. The number of tests is 6 specimens, where 3 specimens are for a chord thickness of 1.6 mm, and three specimens are for a chord thickness of 1.9 mm. Throughout the test, a stress-strain curve is generated, illustrating various material behavior phases, including the elastic region, yield point, ultimate strength, and fracture point.

2.2. Specimen Fabrication and Preparation

All specimens were fabricated using cold-formed steel (CFS) square hollow sections (SHS) and steel batten plates. Cold-formed steel square hollow sections (SHS) were cut to the required heights of 1000 mm and 1500 mm. Batten plates were prepared from steel sheets and cut to the designated size. Referring to Fig. 1, holes were drilled into both the batten plates and chord members using a drilling machine following the design configuration. Rivets were used to connect the batten plates to the chords forming the built-up column assembly as in the figure.

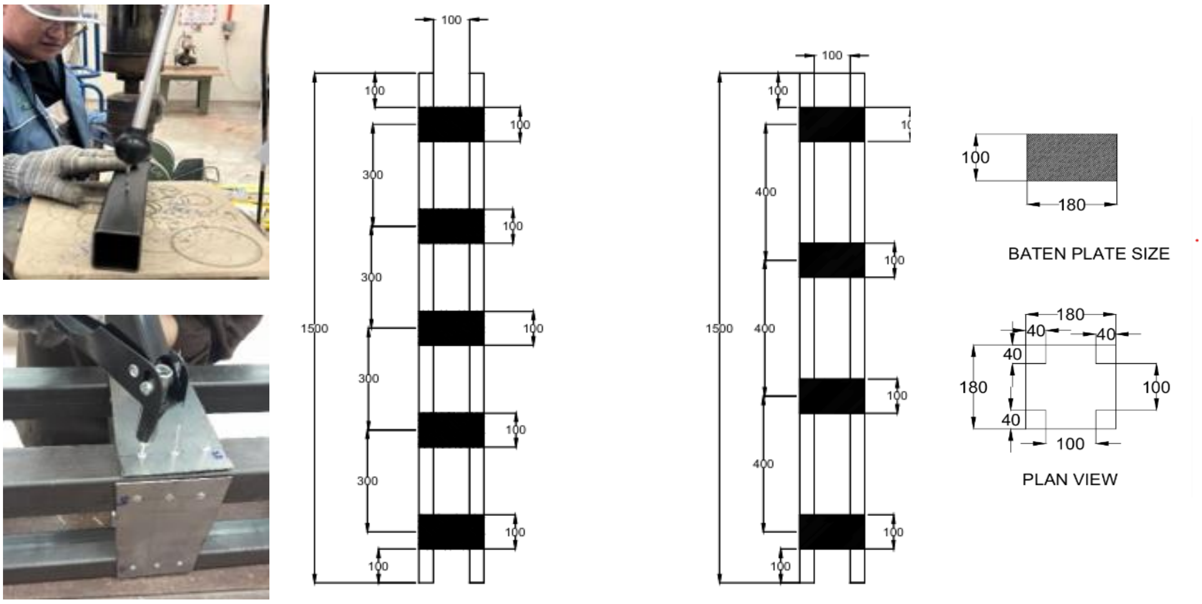


Fig. 1. Specimen fabrication and assembly process

In this study, blind rivets 4.8 mm in diameter with a length of 16 mm were spaced at 30 mm intervals along the batten plate. The rivet spacing was selected based on practical fabrication constraints and standard recommendations to ensure structural integrity. Spacing satisfies the AISI S100-16 requirement that fasteners be spaced at least three times the rivet diameter, and not less than 1.5 times the diameter from the edge. To ensure stability during testing, the top and bottom ends of each column were trimmed to within ±1 mm. Strain gauges were installed at mid-heights of the columns, with the surface cleaned before bonding with glue. The number and placement of strain gauges varied depending on the specimen, with some having four gauges per side and others two on opposite sides. The fabrication was carried out manually using standard workshop tools, including cutting machines and drilling equipment.

2.3 Design and Specification

Various design standards provide guidelines on batten spacing to ensure the structural integrity and composite behavior of CFS built-up battened columns. The AISI S100 stipulates that the slenderness ratio of individual chord components between batten connections should not exceed half the overall member slenderness, to prevent premature local buckling and ensure effective composite action [22]. EN 1993-1-1:2005 [14] Clause 6.4 requires a minimum of three batten connections along the member length and limits the maximum spacing to 70 times the minimum radius of gyration of the chord section, to control local and lateral-torsional buckling [14]. The Indian Standard IS 800:2007 [15] also states that required a minimum of three bays within the column length and restricts the slenderness ratio between batten points to a maximum of 50 or 0.7 times the overall member slenderness, whichever is smaller.

By these standards, this study adopts batten spacing of 300 mm and 400 mm to assess their influence on the structural performance of built-up battened columns fabricated from SHS. These spacings were selected to evaluate the behavior near the limits permitted by EN 1993-1-1:2005 [14], allowing for a focused investigation into the effects of batten spacing on stiffness, load-carrying capacity, and failure modes, as illustrated in Fig.1b. Other batten spacing configurations, including closer or wider spacing, remain outside the scope of this work and may be explored in future studies to develop a more comprehensive understanding. Table 1 shows a specimen configuration for this study. From the table, S2 stands for SHS thickness 1.6 mm, S3 stands for SHS thickness 1.9 mm, H2 stands for column height 1500 mm, SHS stands for single column, and B stands for batten spacing. Each specimen configuration in this study was designed to represent a specific variable, such as thickness, height, or batten spacing, to allow comparison across individual parameters.

Table 1. Specimen configuration

Specimen	Height (mm)	Thickness (mm)	Chord Spacing (mm)	Batten Spacing (mm)	Batten plate Thickness (mm)	Number of battens
S2-H2-SHS	1500	1.6	-	-	-	-
S3-H2-SHS	1500	1.9	-	-	-	-
S2-H2-B300	1500	1.6	100	300	1.2	5
S2-H2-B400	1500	1.6	100	400	1.2	4
S3-H2-B300	1500	1.9	100	300	1.2	5
S3-H2-B400	1500	1.9	100	400	1.2	4

2.3 Axial Compression Test

The axial compression test for CFS SHS built-up battened columns is conducted to evaluate their load-carrying capacity, failure modes, and structural behavior under compressive loading. The test specimens are fabricated using SHS members connected by batten plates at 300 mm and 400 mm batten spacing, according to design specifications. The tests are performed using a 1000 kN hydraulic actuator, with each column specimen placed vertically between the upper and lower plates of the testing machine. To replicate realistic structural conditions, a fixed-pinned boundary condition is adopted. This setup induces realistic moments and shear effects in the column. To monitor the column behavior during loading, strain gauges are installed on the chord members near the batten connections to capture shear deformation, which is critical in battened columns due to the relative movement between the chords and the flexibility of batten plates. Additionally, Linear Variable Displacement Transducers (LVDTs) are strategically positioned to measure axial shortening and lateral displacements, while high-precision load cells record the applied axial load throughout the test. The experimental setup is illustrated on Fig. 2.

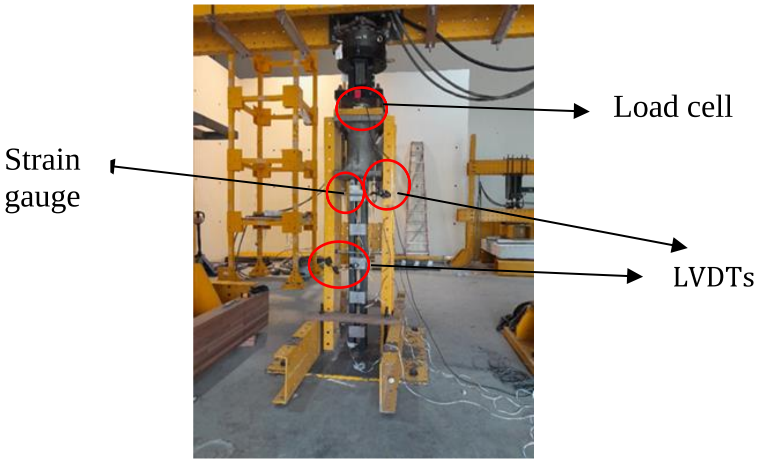


Fig. 2. Testing set-up

2.4 EN 1993-1-1:2005: Existing codified Design Method

CFS built-up battened columns, particularly those fabricated using SHS, are not explicitly addressed in most structural design codes, including EN 1993-1-1:2005 [14], which, while offering detailed guidance for CFS members, lacks specific provisions for battened configurations. Existing guidelines for build-up sections primarily focus on stitched or fastened connections, offering limited insight into battened design, where discrete battens connect the members [19]. This omission challenges accurate prediction of structural behavior, especially regarding the effect of batten sections' properties, buckling interactions, and batten spacing on load distribution. As a result, there is a clear need for experimental studies to evaluate the applicability and effectiveness of current design standards, such as EN 1993-1-1:2005 [14], for CFS built-up battened columns using SHS [19]. Based on the European standard, EN 1993-1-1:2005 [14] under concentric loading, the unfactored column strength (NEC3) is determined using the following formula:

$$N_{EC3} = \frac{\chi A_g f_y}{\gamma_{m1}} \text{ (For class 1,2, and 3)} \qquad N_{EC3} = \frac{\chi A_e f_y}{\gamma_{m1}} \text{ (For class 4)} \tag{1}$$

Where, A_g = gross cross-sectional area for classes 1,2, and 3, A_e = gross cross-sectional area for class 4 that was estimated using Clause 4.4, f_y = yield stress, and χ = the reduction factor, which can be calculated using the formula (2) – (3)

$$\chi = \left(\frac{1}{\varphi + \sqrt{\varphi^2 - \lambda^{-2}}}\right) \, but \, \chi \leq 1.0 \tag{2}$$

$$\varphi = 0.5\left[1 + \alpha\left(\underline{\lambda} - 0.2\right) + \underline{\lambda}^2\right] \tag{3}$$

Where, $\underline{\lambda}$ = the non-dimensional slenderness, which is determined using equation (4)

$$\underline{\lambda} = \sqrt{\frac{A_g f_y}{N_{cr}}} \text{ (For Class 1, 2 and 3)} \qquad \underline{\lambda} = \sqrt{\frac{A_e f_y}{N_{cr}}} \text{ (For Class 4)} \tag{4}$$

Where, α = the imperfection factor and N_{cr} = the elastic critical buckling load. The elastic critical buckling load of the CFS built-up battened column is calculated as a single member by ignoring the shear deformation. The individual chord member of the buckling is ignored, and the length of the buckling is considered and calculated using the formulas (5) and (6)

$$\underline{\lambda} = \frac{L_{cr}}{i} \frac{\sqrt{\frac{A_g}{A_e}}}{\lambda_1} \tag{5}$$

$$\lambda_1 = \pi \sqrt{\frac{E}{F_y}} \tag{6}$$

Based on EN 1993-1-1:2005 [14], the flexural buckling resistance of the CFS built-up battened column about the minor axis was calculated using clause 6.4.3. The non-dimensional equivalent slenderness must be considered for the shear effect between separated chord members.

$$\underline{\lambda}_{eq} = \sqrt{\frac{A_e F_y}{N_{cr,v}}} \tag{7}$$

Where, $N_{cr,v}$ = the critical buckling load of built-up members is calculated using the formula (8)

$$N_{cr,v} = \left(\frac{1}{\frac{1}{N_{cr,e}} + \frac{1}{S_v}}\right) \tag{8}$$

Where, $N_{cr,e}$ = the critical force of the effective built-up battened member that is calculated as shown in the formula (9) – (10)

$$N_{cr,e} = \frac{\pi^2 E I_{eff}}{L^2} \tag{9}$$

$$I_{eff} = 0.5h_0^2 A_{ch} + 2\mu I_{ch} \tag{10}$$

Where, I_{eff}= the effective second moment of the area of built-up members, h_0= the distance between the centroids of the chords, A_{ch}= the cross-sectional area of one chord, μ = the efficiency factor, and I_{ch}= the in-plane second moment of area of one chord. The efficiency factor is in the range of zero and unity, and it depends on the overall slenderness of the CFS built-up battened column, where the shear stiffness is calculated using the formula (11)

$$S_v = \frac{24EI_{ch}}{\alpha^2 \left[1 + \frac{2I_{ch}}{nI_b}\frac{h_0}{\alpha}\right]} \leq \frac{2\pi^2 EI_{ch}}{\alpha^2} \tag{11}$$

Where,α= the distance between the batten plates and I_b= the in-plane second-moment area of one batten plate

3. Results and Discussion

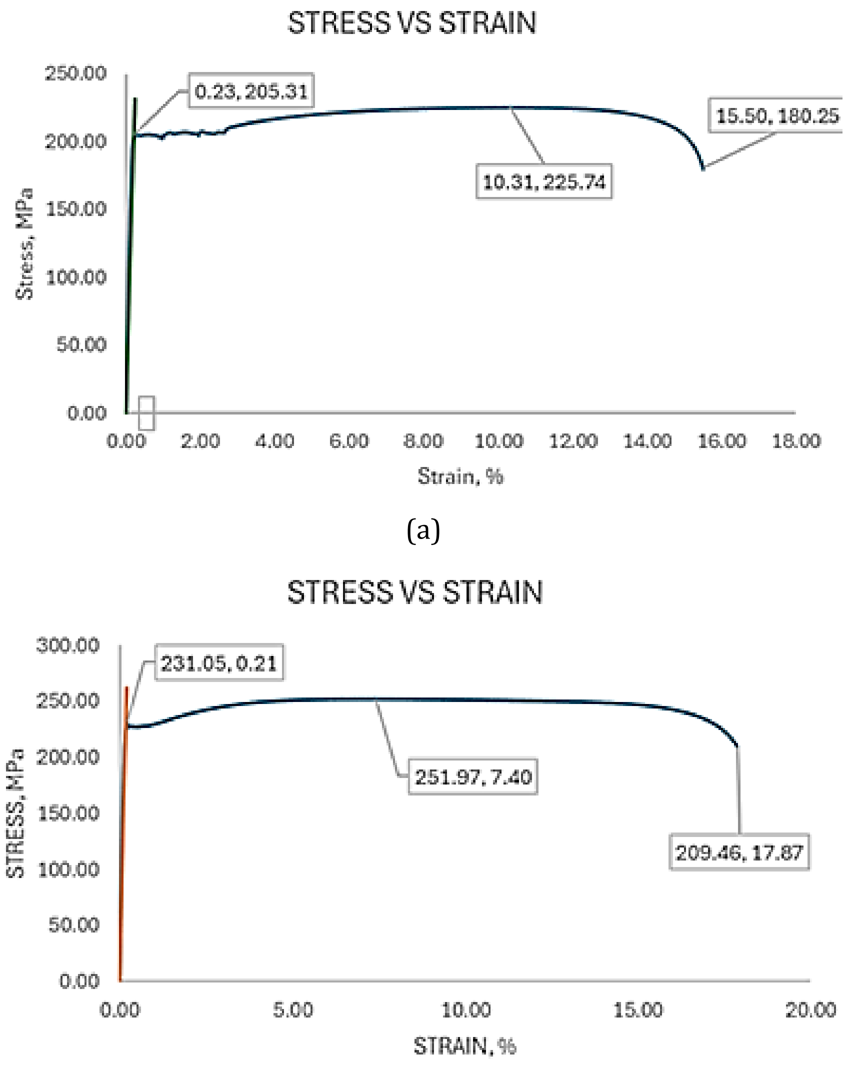
3.1 Stress-Strain Curve

The tensile coupon test results in Table 2 for the 1.6 mm and 1.9 mm thick specimens indicate variations in their mechanical properties, as evidenced by the stress-strain curves and the data presented above. The 1.9 mm specimen exhibits higher yield strength with a value of 231 MPa and an ultimate tensile strength value of 252 MPa compared to the 1.6 mm specimen with a value of 205 MPa and 226 MPa, respectively, indicating that increasing thickness enhances material strength. Additionally, the modulus of elasticity is significantly higher for the 1.9 mm specimen with a value of 1277 MPa, compared to 1028 MPa for the 1.6 mm specimen, indicating improved stiffness and resistance to deformation. However, both materials exhibit a similar tensile-to-yield strength ratio with a value range from 1.09 to 1.10, implying that the strain hardening behavior remains relatively consistent regardless of thickness.

Table 2. Tensile coupon test results

Result		
Thickness, mm	1.6	1.9
Yield Strength, MPa	205	231
Strain, %	0.23	0.21
Ultimate Strength, MPa	226	252
Strain, %	10	7.4
Tensile/ Yield Strength Ratio	1.10	1.09
Fracture Strength, MPa	180	209
Elongation, %	16	17.9
Modulus Of Elasticity, MPa	1028	1277

The stress-strain curves in Fig. 3 show that both specimens undergo an initial elastic phase followed by yielding and strain hardening before eventual fracture. The 1.9 mm specimen has a lower strain at yield with a value of 0.21 % and an ultimate strength value of 7.4% compared to the 1.6 mm specimen with a value of 0.23% and 10%, respectively, showing a reduction in ductility with increased thickness. However, the elongation at fracture is 17.9% compared to 16%, respectively, showing that both materials retain significant deformation capacity before failure. The higher fracture strength is 209 MPa for a 1.9 mm thick specimen compared to 180 MPa for a 1.6 mm thick specimen, indicating improved resistance to final rupture for the thicker specimen. These findings indicate that while increasing thickness enhances strength and stiffness, it slightly reduces ductility, which may influence structural behavior under different loading conditions.



(a)

(b)

Fig. 3. (a) Stress-strain curve of 1.6 mm thick coupon test and (b) 1.9 mm thick coupon test

3.2 Failure Modes, Load-Carrying Capacity

The graph in Fig. 4 presents the load-bearing capacities of different column configurations, highlighting the influence of section type, thickness, and batten spacing on structural performance under axial compression. A single SHS column with a thickness of 1.9 mm (S3-H2-SHS) carries a higher load compared to a 1.6 mm thick SHS column (S2-H2-SHS), demonstrating that increasing the thickness from 1.6 mm to 1.9 mm enhances the load-carrying capacity. This improvement aligns with the differences in yield strength observed in the tensile test results. The results also indicated that a single SHS column battened column consists of four individual SHS columns interconnected to function as a single structural unit, thereby enhancing axial strength and overall stability. The findings emphasize the effectiveness of battened configurations in improving structural performance.

For CFS built-up battened columns, S3-H2-B300 and S2-H2-B400 exhibited the highest load-bearing capacities, reaching 250.13 kN and 263.95 kN, respectively. While both thickness and batten spacing contribute to the performance of the batten columns, it is important to note that technical disruption occurred during the loading process of S3-H2-B400. This may have affected its structural response and contributed to the reduction in axial capacity compared to S3-H2-B300 and S2-H2-B400.

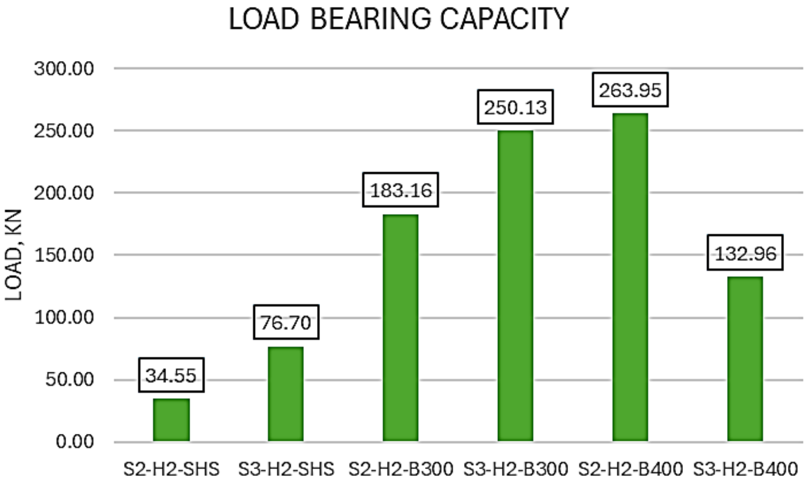


Fig. 4. Load-bearing capacity of the columns

Increases in batten spacing may not necessarily enhance the performance, as it leads to a higher slenderness ratio and reduces the lateral restraint provided by the battens, potentially causing premature instability. While batten provides lateral support, excessive spacing between battens may reduce the overall stiffness of the built-up battened columns, allow greater lateral displacement and twisting under axial compression. However, as evidenced in the case of S2-H2-B300 and S2-H2-B400, the trend suggested that a spacing of 400 mm may not yet be considered excessive, as S2-H2-B400 still achieved a high peak load, indicating that performance is highly dependent on section thickness and connection rigidity

The influence of thickness is evident in the improved load-carrying capacity of S3-H2-B300 compared to its thinner counterpart, S2-H2-B300. However, this trend is not clearly confirmed in the case of S3-H2-B400 due to the aforementioned disruption. An analytical assessment using EN 1993-1-1:2005 [14] was conducted to further evaluate these observations, as discussed in Section 3.6. In general, these findings suggest that both section thickness and batten spacing significantly influence the load-bearing capacity of built-up battened columns.

3.3 Load-Lateral Displacement Responses

The graph in Fig. 5 illustrates the lateral stability and strength behavior of CFS with different configurations and batten spacing, where the thickness of SHS is 1.6 mm. The S2-H2-SHS exhibits low load capacity and gradual buckling behavior, reflecting its slenderness and susceptibility to global buckling without lateral support. In contrast, the built-up battened columns, S2-H2-B400 and S2-H2-B300, showed significantly higher load capacities and stiffer responses, confirming the effectiveness of the battened configuration in enhancing column strength and stability [4]. Notably, both S2-H2-B400 and S2-H2-B300 achieve high peak loads but experience sharp drops after peak, indicating sudden post-buckling failure likely due to insufficient intermediate restraint from batten spacing. This suggests that while closer batten spacing may enhance peak strength, it does not necessarily improve ductility in thin-walled configurations. A truly stable post-peak behavior would indicate improved lateral restraint and more ductile buckling behavior [19]. Overall, the graph shows that battened columns significantly outperform single SHS columns in axial load capacity and lateral stability, with batten spacing being a critical factor in post-buckling performance.

Fig. 6 shows the graph of load Vs lateral displacement of the SHS single column and built-up battened column that was fabricated using SHS with 1.9 mm thickness. The S3-H2-SHS specimen shows low strength and early lateral displacement, indicating susceptibility to global buckling. In contrast, the built-up battened column specimens show dramatic improvements in load capacity and ductility. S3-H2-B300 achieves the highest peak load and exhibits a sharp rise and gradual post-peak softening, signifying strong confinement and effective batten restraint due to closer batten spacing. Despite the technical disruption, S3-H2-B400 still demonstrated notable strength, though its performance was lower than expected with more extended lateral displacement, suggesting increased flexibility and delayed failure. In general, batten columns highlight the effectiveness of the battened systems and the critical influence of batten spacing on both peak strength and post-buckling behavior [5].

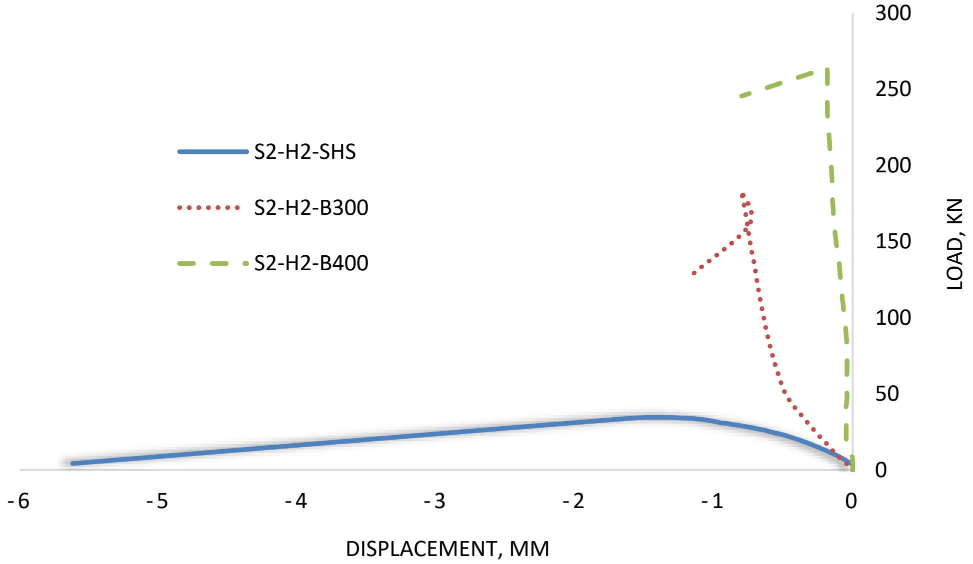


Fig. 5. Load vs lateral displacement for single column and built-up battened column with a thickness of 1.6 mm

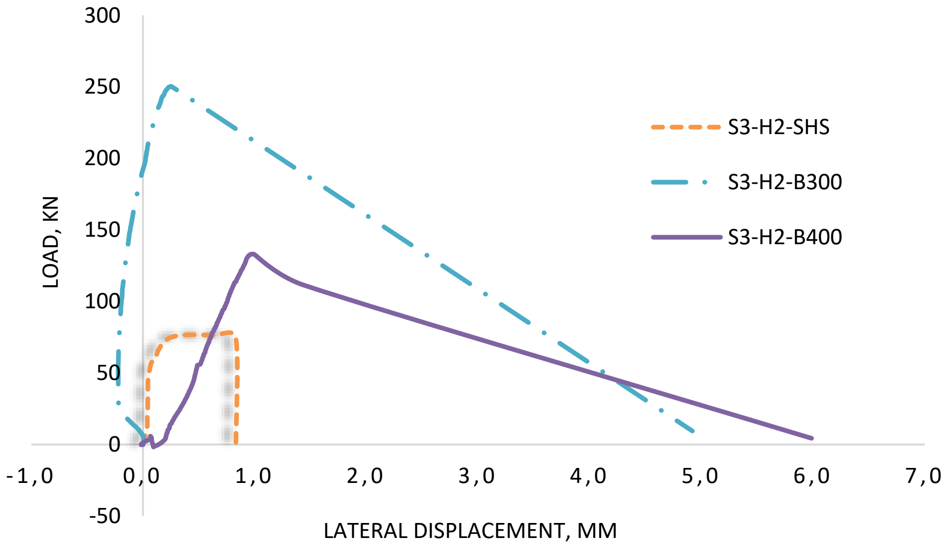


Fig. 6. Load vs lateral displacement for single column and built-up battened column with a thickness of 1.9 mm

The load and lateral displacement graph in Fig. 7 shows that both section thickness and batten spacing significantly influence structural performance. S3-H2-B300, constructed with a thicker section, demonstrates higher load capacity and better lateral stability compared to the thinner sections of S2-H2-B300 and S2-H2-B400. Considering the results of these three columns, thicker columns generally outperform thinner ones, and a batten spacing of 400 mm still appears to enhance lateral stiffness and load resistance. Notably, S3-H2-B300 shows the best overall performance, combining high load capacity with stable displacement behavior. In contrast, S2-H2-B400 demonstrates reduced performance, highlighting the sensitivity of thin-walled built-up sections to increased batten spacing and the associated risk of buckling [23].

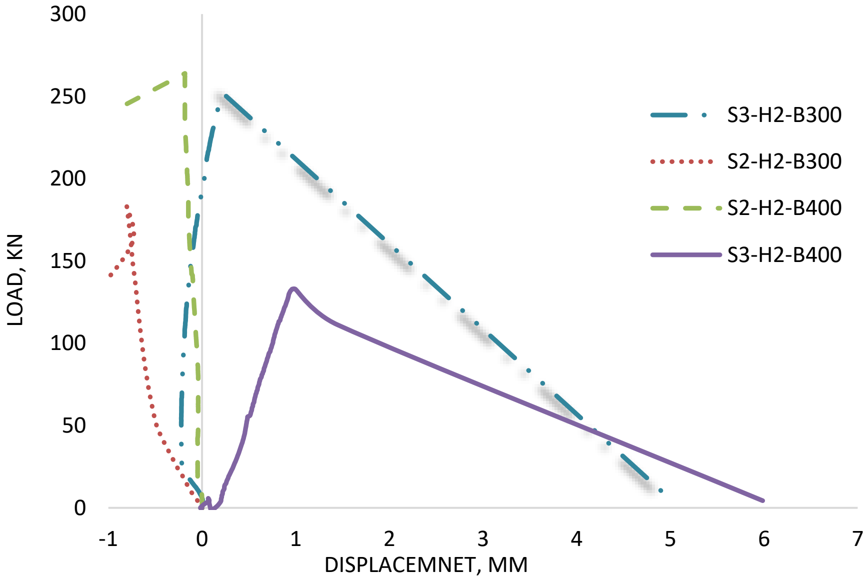


Fig. 7. Load vs lateral displacement for built-up battened column with batten spacing of 300 mm and 400 mm

The analysis of load versus lateral displacement reveals that built-up battened columns significantly outperform single SHS columns in both strength and lateral stability, with thicker sections and closer batten spacing yielding the best performance. Thickness and batten spacing confirm the critical role of batten-column configuration. Future studies should explore optimal battens pacing, geometries, spacing-to-depth ratios, and the impact of connection rigidity on the buckling behavior of built-up CFS columns under various loading conditions. The post buckling response provides the insight of structural resilience. From these figures, a more ductile post-peak response with a gradual decline can be observed for thicker specimens.

3.4 Failure Modes

Fig. 8 to Fig. 13 show the failure conditions of all columns in this study involving single and built-up battened columns subjected to axial compression loading. From these figures, single SHS columns, S2-H2-SHS and S3-H2-SHS, exhibit global buckling failure characterized by noticeable lateral deformation along the column length and local buckling as shown in Fig. 8 and Fig.9. As these columns undergo overall buckling, they will bend laterally, which causes non-uniform stress distribution across the cross-section. This will lead to higher compressive stress experienced in certain regions, and the localized stress will eventually trigger local buckling. The S3-H2-SHS column appears to have slightly higher resistance to deformation compared to S2-H2-SHS, indicating that increased thickness improves buckling resistance. However, both specimens still experience significant overall buckling failure, showing the limitations of using a single SHS under compression without additional lateral restraints.

For the built-up battened columns, S2-H2-B300 and S3-H2-B300, localized buckling and deformation are concentrated near the end batten connections, as shown in Fig. 10 and Fig. 11. This indicates that while the battens effectively restrained global buckling, they could not entirely prevent local distortions. In contrast, the S2-H2-B400 and S3-H2-B400 columns, shown in Fig. 12 and Fig. 13, exhibit more severe deformation and plate detachment, particularly at mid-height. This behavior is expected due to the reduction in lateral restraint effectiveness as the batten spacing increases. From the observation, the occurrence of batten plate detachment was after the column failed and slipped during testing.

This study provides evidence of the physical detachment of battens in both specimens with wider batten spacing: S2-H2-B400 and S3-H2-B400. Although the results for S3-H2-B400 may have been influenced by technical disruption, the findings show that wider batten spacing compromises structural performance and contributes to detachment. Rahnavard et al. [24] demonstrated that connection rigidity and fastener layout play a critical role in maintaining composite behavior in cold-formed steel battened columns.

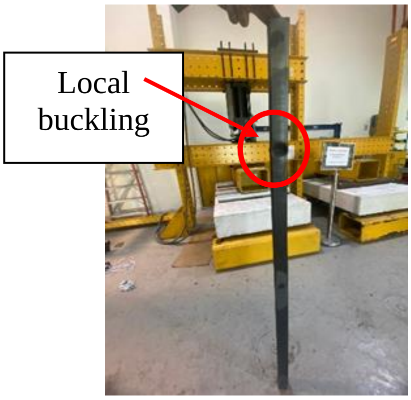


Fig. 8. Failure modes for a single SHS column of S2-H2-SHS

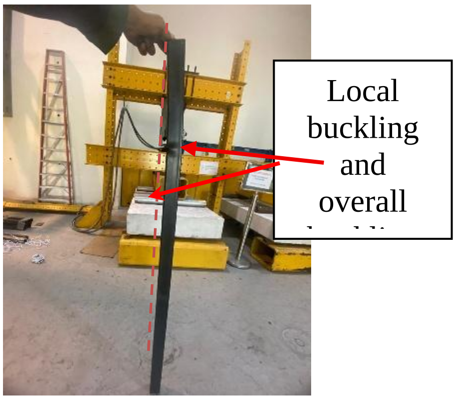


Fig. 9. Failure modes for a single SHS column of S3-H2-SHS

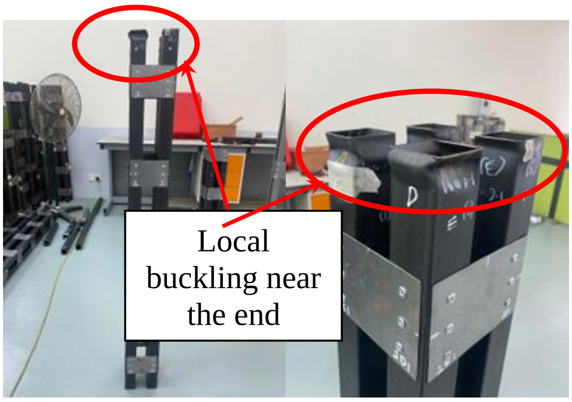


Fig. 10. Failure modes for specimen CFS built-up battened column with SHS of S2-H2-B300

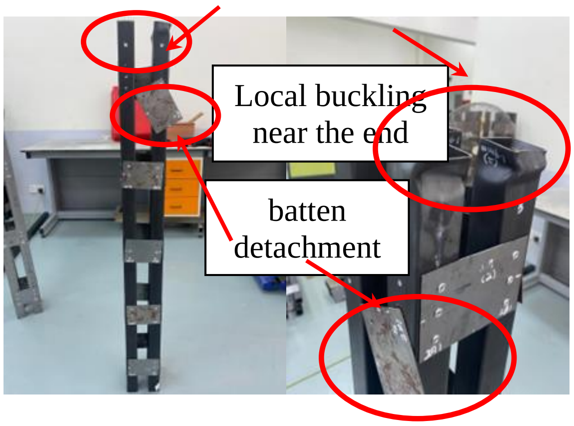


Fig. 11. Failure modes for specimen CFS built-up battened column with SHS of S3-H2-B300

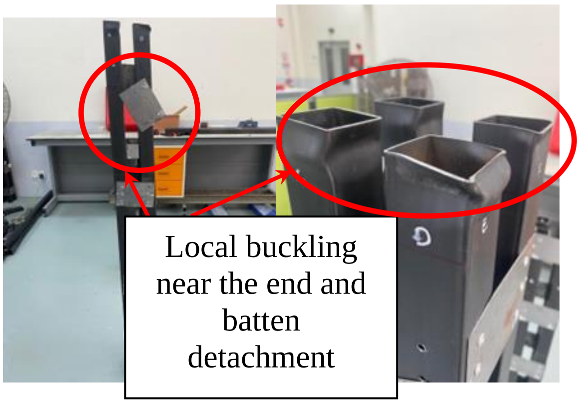


Fig. 12. Failure modes for specimen CFS built-up battened column with SHS of S2-H2-B400

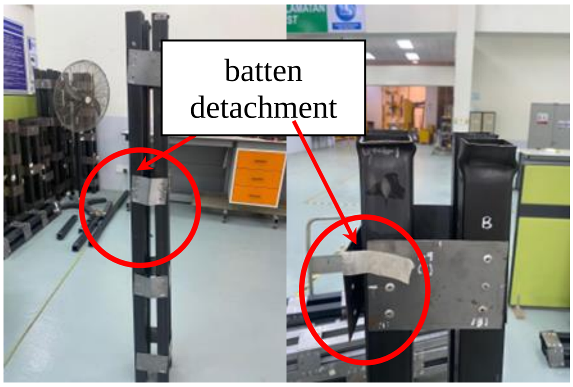


Fig. 13. Failure modes for specimen CFS built-up battened column with SHS of S3-H2-B400

The increased lever arm between chords reduces the effectiveness of battens in transferring shear forces and increases the risk of local buckling, as flanges and webs become less restrained. It is also expected that the thickness alone does not necessarily improve strength if batten spacing is too large. These findings emphasize the importance of optimizing both batten spacing and section thickness to achieve a balance between load-carrying capacity and overall stability in built-up battened columns [16, 18]. In general, the discrepancy between experimental and analytical predictions further highlights the need for refined design provisions tailored to closed section battened columns

3.6 Validation

The result obtained from the experimental data is validated with the existing design method from EN1993-1-1:2005 [14]. Table 3 presents the value of maximum load capacity from experimental study and analytical calculation.

Table 3. Maximum load capacity from experimental data vs manual calculation

Specimen	Maximum axial load		P_{TEST} / P_{EN}
	P_{TEST} (kN)	P_{EN} (kN)	
S2-H2-SHS	34.55	50.8	0.68
S3-H2-SHS	76.70	59.2	1.30
S2-H2-B300	183.16	203	0.90
S2-H2-B400	250.13	203	1.23
S3-H2-B300	263.95	237	1.11
S3-H2-B400	132.96	237	0.56
Mean			1.0
Standard deviation			0.3

The findings show that built-up battened columns generally achieve experimental axial loads close to or exceeding the theoretical calculation, with ratios ranging from 0.68 to 1.30. The highest discrepancy with the value of 0.56 occurred in the S3-H2-B400 specimen was expected due to technical disruption during the testing progress. In contrast, single SHS columns like S2-H2-SHS showed lower performance with the ratio value of 0.68, likely due to higher slenderness and lack of lateral support. The mean experimental-to-theoretical calculation ratio is 1.0, indicating that the EN 1993-1-1:2005 [14] design rule aligns well with experimental data on average. However, some values deviate significantly, suggesting potential limitations in the theoretical calculations for certain geometries or spacing. However, the standard deviation of 0.3 is notable among specimens, suggesting that factors such as thickness, batten spacing, and local buckling behavior significantly influence load capacity and should be carefully considered in design for future study.

EN 1993-1-1 [14] provides general design rules for steel columns under axial compression, including built-up members. However, when applied to cold-formed steel (CFS) battened columns made from closed sections like Square Hollow Sections (SHS), some adjustments and careful interpretation are needed due to differences in geometry and structural behavior. There are several limitations when using EN 1993-1-1 [14] for SHS battened columns. EN 1993-1-1 [14] Clause 6.4.3 mainly covers built-up columns made from open sections and stitched connections. It provides little guidance for battened columns using closed sections like SHS. The SHS members usually have only two sides connected to the batten plates. This reduces how well the forces are transferred between the chords and battens, which weakens the overall structural action. EN 1993-1-1 [14] does not clearly explain how to handle this partial connection.

For all specimen cases, particularly S3-H2-B400, replication was not performed solely due to resource constraints but based on engineering judgment corroborated by consistent analytical predictions. Based on the EN 1993-1-1:2005 [14] analysis, the predicted axial capacity for S3-H2-B400 was 237 kN, while the experimental result was only 132.96 kN, yielding a P_{TEST}/P_{EN} ratio of approximately 0.56 compared to other specimens, which showed ratios ranging from 0.68 to 1.3, this result is significantly lower. The results from the EN 1993-1-1:2005 [14] analysis was aligned well with other specimens, and the deviation observed in S3-H2-B400 is considered an isolated anomaly likely caused by technical disruption during testing and replication was not pursued, as the analytical model provided sufficient validation for this configuration. While replication would enhance statistical reliability, resource constraints limited the scope of this study, and another evaluation was made based on the analytical analysis.

Fabrication imperfections can result from misalignment and uneven spacing between components. These imperfections may affect buckling behavior but are not considered in the code. However, the experimental results in this study show that EN 1993-1-1 [14] gives a reasonable estimate of axial strength, with an average test-to-prediction ratio of 1.0. However, the variation in suggests that more specific design rules are needed for SHS battened columns to improve accuracy and reliability.

4. Conclusions

This study investigated the structural behavior, failure modes, and axial load-carrying capacity of Cold-Formed Steel (CFS) built-up battened columns using square hollow sections (SHS) under axial compression. The research focused on evaluating the impact of batten spacing and section thickness on performance, addressing the limitations of current design provisions, and contributing to the understanding of closed-section CFS columns. The study concludes that:

- Built-up battened columns demonstrated significantly higher axial load capacities and improved buckling resistance compared to single SHS columns. The inclusion of batten plates provides effective lateral restraint, reducing global buckling susceptibility and enabling composite action between individual SHS components.
- Batten spacing was found to critically influence column behavior. A 300 mm batten spacing yielding superior performance in terms of both strength and post-buckling stability. In contrast, wider spacing led to reduced axial capacity and increased vulnerability to local distortions and batten plate detachment, particularly in thicker sections.
- Single SHS primarily failed by global buckling while, built-up battened columns exhibited a combination of failure mechanisms, including local buckling at chord members and batten plate detachment, especially at larger batten spacing. These variations emphasize the importance of lateral restraint continuity.
- The experimental results generally aligned with predictions from EN 1993-1-1:2005 [14], with a mean test-to-prediction ratio of 1.0. However, discrepancies highlight the sensitivity of performance to geometric and connection parameters, underscoring the need for refined design provisions specifically for CFS built-up battened columns with SHS.

In practical applications, these columns show potential for lightweight, industrial, and mid-rise to high-rise structures, offering efficient load-carrying capacity. Nevertheless, challenges remain, including fabrication costs, connection detailing and limitations on batten spacing during construction.

Future research should investigate the effects of varying batten thickness to develop more robust, code-compliant design guidelines and to expand the application of CFS built-up battened columns in modern structures.

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References

[1] Anbarasu M. Behaviour of cold-formed steel built-up battened columns composed of four lipped angles: Tests and numerical validation. Adv Struct Eng. 2020;23(1):51-64. https://doi.org/10.1177/1369433219865696

[2] Hashemi BH, Jafari MA. Experimental evaluation of cyclic behavior of batten columns. J Constr Steel Res. 2012; 78:88-96. https://doi.org/10.1016/j.jcsr.2012.06.014

[3] Anbarasu M, Kanagarasu K, Sukumar S. Investigation on the behaviour and strength of cold-formed steel web stiffened built-up battened columns. Mater Struct. 2015;48(12):4029-38. https://doi.org/10.1617/s11527-014-0463-8

[4] Sarkar S, Sahoo DR. Effect of chord configuration and spacing on cyclic flexural response of built-up columns. Int J Steel Struct. 2016;16(2):441-53. https://doi.org/10.1007/s13296-016-6015-z

[5] Dar AR. Cold-formed steel composite columns: axial strength and deformation response. Innov Infrastruct Solut. 2021;6(4):1-8. https://doi.org/10.1007/s41062-021-00593-y

[6] Paiva F, Henriques J, Barros CR. Comparative study of built-up members subjected to compression loads, by the EC3-1 and AISC 360-05. In: Proceedings of the November Conference. 2014. p. 1-7.
[7] Pieczka P, Iwicki P. Axial capacity of steel built-up battened columns. Mod Trends Res Steel Alumin Compos Struct. 2021; 235:442-8. https://doi.org/10.1201/9781003132134-57
[8] Waheed A, Vafaei M, Alih SC, Ullah R. Experimental and numerical investigations on the seismic response of built-up battened columns. J Constr Steel Res. 2020; 174:106370. https://doi.org/10.1016/j.jcsr.2020.106296
[9] El Aghoury MA, Salem AH, Hanna MT, Amoush EA. Ultimate capacity of battened columns composed of four equal slender angles. Thin Walled Struct. 2013; 63:175-85. https://doi.org/10.1016/j.tws.2012.07.019
[10] Cui J, Wang R, Zhao H, Hou CC, Hu W. Built-up battened steel columns under impact loading: Experimental and numerical analysis. J Constr Steel Res. 2021; 179:106515. https://doi.org/10.1016/j.jcsr.2020.106515
[11] Li QY, Young B. Experimental and numerical studies on cold-formed steel battened columns. Eng Struct. 2023; 288:117465. https://doi.org/10.1016/j.engstruct.2023.116110
[12] Sangeetha P, Shanmugapriya M, Manjula R, Vijay AP, Sooraj K. Study the effect of intermediate and closer stiffener on the behaviour of cold-formed steel lipped channel section under axial compression. J Mater Eng Struct. 2022;9(1):1-10.
[13] Setiawan J, Bayuaji R, Rohman MA. Influence of built-up cold-formed steel columns battened for long-span portal frame. Int J Struct Civil Eng Res. 2024;13(2):140-5. https://doi.org/10.18178/ijscer.13.2.52-56
[14] CEN. EN 1993-1-1:2005 - Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings. Brussels: European Committee for Standardization; 2005
[15] Bureau of Indian Standards (BIS). IS 800:2007 - General Construction in Steel - Code of Practice. New Delhi: BIS; 2007.
[16] CTICM, SCI. Detailed Design of Built-up Columns (Part 6). In: Steel Buildings in Europe - Single-Storey Steel Buildings. ArcelorMittal, Peiner Träger, and Corus; 2010
[17] CTICM, SCI. Steel Buildings in Europe - Part 6: Detailed Design of Built-up Columns. Luxembourg: European Convention for Constructional Steelwork (ECCS); 2010. 56 p.
[18] Dar MA, Anbarasu M. Nonlinear compression behaviour of thin-walled battened columns. In: Anbarasu M, editor. Advances in Structural Engineering. Singapore: Springer; 2020. p. 379-88. https://doi.org/10.1007/978-981-19-9390-9_35
[19] Rahnavard R, Craveiro HD, Simões RA. Design of cold-formed steel battened built-up columns. In: Proceedings of the Cold-Formed Steel Research Consortium Colloquium; 2022 Oct 17-19; United States. p. 1-12.
[20] El Aghoury MA, Salem AH, Hanna MT, Amoush EA. Computed strength of uni-axially loaded battened columns composed of four cold formed angles. In: Structural Stability Research Council Annual Stability Conference; 2012. p. 387-98.
[21] ISO. ISO 6892-1:2009 - Metallic materials - Tensile testing - Part 1: Method of test at room temperature. Geneva: International Organization for Standardization; 2009.
[22] American Iron and Steel Institute (AISI). AISI S100-16 (2020) - North American Specification for the Design of Cold-Formed Steel Structural Members. Washington, DC: AISI; 2020.
[23] Waheed A, Vafaei M, Alih SC, Ullah R. Effect of battens' spacing on the cyclic response of built-up columns. Thin Walled Struct. 2022; 172:108862. https://doi.org/10.1016/j.tws.2021.108862
[24] Rahnavard R, Craveiro HD, Laím L, Simões RA, Napolitano R. Numerical investigation on the composite action of cold-formed steel built-up battened columns. Thin Walled Struct. 2021; 162:107553. https://doi.org/10.1016/j.tws.2021.107553