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The Evolution and Performance of Cold-Formed Steel Built-Up Battened Columns

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Abstract

The cold-formed steel (CFS) built-up battened column represents a transformative and innovative solution in the construction industry due to its versatility, cost-effectiveness, and superior strength-to-weight ratio. In design consideration, chord spacing and batten plates influence the structural performance and stability of the column. The emphasis lies in the design flexibility of built-up battened columns, in which the composite action of several chord members connected by batten plates can enhance axial compressive strength. The batten plate plays a crucial role in preventing buckling and increasing the stability of the column while distributing the load evenly. The batten plates need to be properly designed to ensure stability and reduce buckling failure in the built-up battened column. However, implementing CFS built-up battened columns presents several challenges, including design complexity, connection design, and limited standards and guidelines.

1. The Highlights of Batten's Columns

In recent years, the structural and construction industry has undergone a notable shift in perspective, primarily driven by the introduction and increasing acceptance of cold-formed steel (CFS) as a versatile and cost-effective alternative to traditional building materials. CFS offers a multitude of advantages over hot-rolled steel including a superior strength-to-weight ratio, enhanced design flexibility facilitated by readily attainable varied cross-sectional shapes, exceptional dimensional stability, heightened fire resistance, ease of transport resulting in cost reduction, sustainability, and accelerated construction process [1]. The utilization of CFS in structural systems has witnessed a remarkable evolution, giving rise to innovative configurations such as the built-up battened column. This unique structural element combines experimental and numerical approaches to comprehensively study its behavior, design, and performance under diverse loading conditions. CFS built-up battened column has been a subject of significant research interest in recent years.

One notable advantage of having a wide variety of shapes is that the fabrication details can be primarily customized. This is an example of a built-up structure that can be created using cold-formed steel columns. A built-up battened column is a structural column compromising two or more individual columns (chords) connected by battens plate at different spacing along the length [2]. The column is reinforced only at certain points along its length. This design strengthens the chords and allows the column to function as a single unit, which enhances its capacity to bear heavy loads and withstand lateral forces [3]. When a battened column has two or more chords working together through composite action, it can generate greater axial compressive strength than what each chord component can provide [4]. Furthermore, in situations where seismic activity is a concern, battened steel column members are utilized to provide additional lateral resistance and passive confinement to reinforced concrete (RC) columns that may be defective [5].

In comparison to lacing columns, built-up battened columns offer easier fabrication addition with proper design to achieve the desired axial strength with optimal material and cost efficiency [6]. Moreover, according to the study, the use of cold-formed steel type is easy to form, adding to the ease and convenience of fabricating CFS battened columns. Construction time and cost can be reduced by efficient fabrication and installation of steel battens. Compared to other reinforcement methods, such as concrete encasement or composite materials, CFS built-up battened columns are relatively easier to construct. In addition, built-up battened columns provide design flexibility in terms of shape and appearance, allowing for customizable batten arrangements to achieve desired architectural aesthetics while maintaining structural integrity. Dar [7], suggests that having sufficient transversely spaced chords in battened columns results in superior performance in terms of ultimate strength and stiffness response. This capability of implementing the battened columns enables architects and engineers to create visually appealing structures that meet functional requirements.

Studies have explored various aspects of CFS built-up battened columns, including their behavior under different loading conditions and the influence of different design parameters on their performance. The research aims to improve the understanding of the behavior and design procedures of CFS built-up battened columns through both experimental and numerical investigations. Based on past studies, the steel battened column is suitable to use as a compression member that provides many advantages compared to individual chord members. However, the specific advantage may vary depending on the design, engineering requirements, and construction project context. To ensure the appropriate selection and design of battened columns is recommended to consult with a structural engineer or a professional in the field.

2. The Role of Batten in a Column

CFS built-up battened columns offer numerous benefits over individual chord members, including the ability to provide greater axial compressive strength through the composite action of two or more chord members [4]. When a single chord member cannot withstand higher loads over a longer span, using a battened column as a compression element is a suitable solution [8]. The desired size and thickness of the columns are connected using fasteners, such as stiffeners in the form of batten systems, and connectors like bolts, screws, rivets, and welds. The batten is made from steel such as a thin strip or plate that is attached vertically to two or more chord members as a reinforcement and eventually will enhance the column's strength and stiffness.

Like any other structural element, the strength and stability of a built-up battened column depend on various factors and design considerations. Buckling is a critical failure mode in column structures, especially in the case of slender columns or columns subjected to high axial loads. Therefore, battened columns, with their enhanced load-carrying capacity due to the use of battens, are well-suited for taller and structurally efficient buildings. The presence of battens on the built-up battened column enhances the structure's resistance to buckling provided that the columns have adequate bracing and lateral support that are essential to prevent buckling and maintain the stability of any column structure.

Batten plates are used as transverse connectors that are composed of two or more similar chords at certain points along the length of chord members to ensure that the column can act as one integral unit [3]. As a result, the steel battened column improves stability by evenly distributing the applied load along its height, enhancing overall structural stability. The additional batten in the steel battened column can be strategically placed to reinforce critical areas of the column at once, which can optimize the use of material. This also leads to efficient material utilization and cost-effectiveness in construction.

CFS sections inherently have low buckling resistance due to their thinner plate [9], however, with the battened column design, buckling resistance can be significantly enhanced. In this context, battens serve as vertical stiffeners that prevent the column from buckling under axial compression loads. They effectively increase the column's effective width, reducing the slenderness ratio and enhancing its ability to resist buckling. Therefore, a CFS battened column can reduce the risk of localized failures and ensure the column can effectively withstand both axial and lateral loads. This highlights the capability of a CFS battened column to minimize the risk of localized failures and ensure the column's effectiveness in withstanding both axial and lateral loads. Additionally, CFS sections offer greater flexibility in terms of cross-sectional shape and size, leading to more efficient design solutions with reduced material redundancy [9].

Under axial load, the column will be subjected to forces along its length and tend to either elongate or compress, whereas flexural load will cause bending and it is possibly caused by uneven loading. In the battened column, the batten will help distribute the axial load more evenly across the chord members in the column. Similarly, for columns subjected to flexural load, the batten will help the chord members to work together reducing the excessive deflection due to bending with the battens' contribution to the column's ability to withstand the bending forces.

The battens also act as vertical stiffeners, preventing the column from buckling under axial compression loads. Simultaneously, they play a pivotal role in enhancing the column's stability by increasing its effective width, thereby reducing the slenderness ratio. This reduction, facilitated by the battened system in the steel column, not only improves the column's ability to resist buckling but also results in a significant enhancement in load-carrying capacity. The battened system effectively reduces the column's effective length, contributing to a more robust and resilient structural design. The capacity of a steel battened column to withstand compressive forces is increased because it offers enough flexural stiffness to prevent buckling without expanding the chord section's cross-sectional area [4].

Constructed by combining multiple individual sections and their arrangement, the batten columns can strategically achieve symmetrical section properties. The use of battened columns results in symmetrical section properties and increased resistance to out-of-plane movement [9]. In typical open sections, the flanges are positioned on opposite sides of the central web of the column, ensuring a symmetrical cross-section about its vertical axis. This symmetrical arrangement effectively increases the section modulus of the column in the plane perpendicular to the web. The balanced geometry of built-up battened columns helps them resist out-of-plane movements symmetrically, contributing to overall stability.

The spacing between battens in a battened column is critical to its structural behavior and aesthetic look. The spacing and thickness of the battens influences the overall lateral stiffness of the built-up battened column. These can be seen from the study by Mahmoud et al. [2], the lateral stiffness of a built-up battened column increases as the thickness of the batten plate increases. However, increasing the spacing between the battens will cause a decrease in lateral stiffness. Closer spacing between battens can result in higher flexural stiffness and less deflection when under loads. This can also improve the moment inertia of the column [2].

The distance of battens should be decided by the column's structural need and requirement to enhance the structural performance. Waheed et al. [10] study the effect of batten spacing of built-up battened columns on the seismic response. This study uses two channels as a chord with an 8 mm thick steel plate as a batten. The distance used varies from 200 mm to 375 mm, with 150 mm and 100 mm distance between the batten at the base and the top of the column. They conclude that the decrease in batten spacing significantly affects the increased ultimate load of a built-up battened column. This demonstrates that a closer batten plate resulted in greater overall stiffness and load-bearing capacity of the columns [10].

Sangeetha et al. [11] examined the behavior of lipped channel main chords under axial compression. Unlipped channels were placed close to each other with a spacing of 19 to 20 mm, and the number of batten plates varied between 0 to 3. The study found that all built-up battened columns had failed due to local buckling, while the column without a batten had failed due to torsional buckling and local buckling. Additionally, the study concluded that the use of batten plates effectively improved the ultimate strength and distortional buckling behavior of the column. Besides that, the effective strength may be reduced due to the large spacing between battens which can cause the batten to be prone to local buckling [11]. To ensure the batten can resist the applied load without buckling or failing prematurely, appropriate batten spacing is necessary. According to Li & Young [12], it is recommended to use the codified values from the North American Specification, which sets an upper limit of 0.5 for the relative slenderness ratio (λ_i/λ_y) for long CFS built-up battened columns. However, for short and medium CFS built-up battened columns, it is considered conservative.

The spacing between battens is the vital key to the structural behavior and aesthetic appearance of CFS built-up battened columns. studies indicate that closer spacing between battens increases flexure stiffness, reduces deflection, and enhances overall load-bearing capacity that needs a proper detailed design based on structural requirements because excessively large spacing may lead to local buckling and reduce the effective strength of the batten. Generally, CFS built-up battened columns represent a robust and versatile structural solution, offering a balance between material efficiency, stability, and load-carrying capacity that needs considering batten spacing in design to contribute to achieving optimal structural performance in various applications.

3. Effect of Chord Spacing

The spacing of the chord in the battened column refers to the horizontal distance between the CFS individual section of the column that acts as the load-bearing element of the column. In the design consideration, chord spacing plays an important role as it directly influences the structural performance and stability of the column. The effect of chord spacing has been experimentally investigated by several researchers and proved that chord spacing has a significant effect on the stability and strength of the built-up battened column. There are several effects and considerations related to chord spacing in CFS built-up battened columns such as buckling modes, stability, slenderness ratio, batten stiffness and connection, load distribution, standard and design consideration, and economic consideration.

Designing columns requires careful consideration of buckling modes and stability, a crucial factor. The spacing of chords plays a crucial role in preventing buckling or minimizing its effects. To ensure the stability and safety of a structure under axial or bending loads, it is important to select the right spacing for the chords which can improve the column's resistance to buckling. Dabaon et al. [13], conducted an experimental study on batten columns consisting of two cold-formed channels that connected back-to-back using batten. The column has various clear back-to-back distances of the channels. The observed modes of failure in the built-up cold-formed steel section battened columns included, flexural buckling, local buckling of flange components (Chords) between connectors, and combined buckling modes. The research findings suggest that the increase in cross-section geometries led to an increase in column stiffness, and the local buckling mode became the governing mode of failure for the behavior of built-up cold-formed steel section battened columns, particularly in specimens with larger back-to-back clear distances.

The lateral buckling resistance of the column was affected by the chord spacing which is if the chord spacing is too large can result in lower lateral buckling capacity due to the reduction of lateral bracing provided by the batten. The lateral loading capacity of a built-up battened column can be enhanced by increasing the chord spacing, which results in an increase in the moment of inertia in the column section. Studies have shown that the ultimate lateral strength of columns improves with an increase in chord spacing, but only for axial loads greater than 45% of the yield load [5]. The column's lateral buckling resistance can decrease if the chord spacing is too large, reducing the lateral bracing provided. It can be concluded that the larger the spacing is, the lower the lateral buckling resistance. On the other hand, the smaller the chord spacing can enhance the column's lateral stability by more frequent bracing along the height.

The proper chord spacing is crucial to ensure stability in the column where the batten helps to resist torsional forces in the column that are caused by eccentric loading or other asymmetrical load conditions. Waheed et al. [14], mention that the increase in the distance of the chord spacing significantly increases the plastic deformation in the column. The study also obtained that the distance between chords increases the strength degradation in the column from the beginning. The increase of chord spacing in the study also significantly increases the initial stiffness of the column. It can be concluded that proper chord spacing will enhance the stability and stiffness of the built-up battened column.

Abarasu [4] also examined the compression behavior of CFS built-up battened columns made of four-lipped angles, emphasizing the impact of member, chord, and plate slenderness on the column’s behavior. According to the study, the built-up battened column’s axial compression capacity is greatly influenced by the chord slenderness ratio, with lower chord slenderness converting into higher axial compression resistance. The CFS built-up battened column’s axial compression resistance is also slenderness ratios. The behavior and strength of the CFS built-up battened columns made of four-lipped angles under axial compression were determined in large part by these slenderness ratios. Proper spacing helps control the slenderness ratio, which is crucial for determining the critical buckling load and the column’s resistance to buckling.

Additionally, connection detail such as screw spacing for built-up battened columns also plays a crucial role in the behavior and performance of CFS built-up battened columns. Proper connection detail helps in transferring load effectively between individual chords, helps optimize the design, and improves load carrying capacity at once can reduce the risk of premature failure, enhancing the overall strength of the assembled members. Ting et al. [15] observed the effect of screw spacing for CFS built-up battened columns, for short and intermediate columns showing that the strength was significantly dependent on the number of screws while doubling the screw spacing resulted in a reduction in strength by 5% to 15%. It is because the increasing screw spacing made fewer fasteners along the length of the channel section, and the reduction in the number of connections resulted in decreased load transfer efficiency between the individual chords. This emphasizes the significance of optimizing screw spacing and connection detail to maintain the desired strength and performance and maintain the stability of the CFS built-up battened column.

However, the spacing between chords in the built-up battened column depends on various factors which include the material and size of the batten, the design load on the column, and the desired level of reinforcement. A proper batten spacing ensures adequate lateral bracing and connection detail prevent buckling modes that can compromise the column’s stability. Generally, the spacing of the chord is designed to achieve the optimal balance between structural efficiency, load-bearing capacity, and aesthetic consideration, which causes the variation in the chord spacing on the built-up battened column.

4. Built-Up Battened Column Behavior

The CFS built-up battened columns are composed of two or more chords that are joined at the flange of the main chord using a batten plate, forming a composite column. Due to the thin-walled nature of the CFS section, the behavior of CFS can be complex and highly susceptible to structural instabilities such as local buckling, Euler buckling, and distortional buckling. The single chord sections, particularly for open steel sections like channels, have relatively low torsional rigidity. This is due to the lack of material in certain regions, which can result in lower torsional rigidity. In contrast, closed-section chords, with a more uniform distribution of material, generally possess higher torsional rigidity. Torsional rigidity is associated with material properties, cross-section shape, and dimension [16]. Various factors affect the behavior of CFS built-up battened columns, including material properties, geometry, and boundary conditions.

In the context of slender columns (high λ), the torsional rigidity becomes an important consideration as they are more prone to torsional buckling. The slenderness ratio significantly affects the behavior of a column, especially for Cold-Formed Steel (CFS) sections which are prone to buckling due to their thinness. A study conducted by Adil Dar et al. [6], observed that the axial performance of a built-up battened column consisting of two plain channels showed that the failure mode gradually transitions from local buckling to flexural buckling as the slenderness of the short column increases. The stud column failure mode primarily experiences local buckling at the chord, and the long column fails through flexural buckling with local buckling half-waves at mid-height, while the intermediate column experiences the maximum local and flexural buckling due to the complex thin-walled behavior.

Manikandan et al. [17], studied the impact of battens, revealing that the load-bearing capacity and stiffness of CFS built-up columns increase as the number of batten plates. The direct stiffness of the flange also increases, leading to a higher strength for the elevated section. By adding extra stiffness to the column and distributing the applied load, battening can lower the risk of local buckling in the column. Other than that, the connection between the chord and the batten plate may affect how the CFS built-up battened column behaves overall. It is crucial to have the right connection design to guarantee the integrity of the column. It may also have an impact on the built-up battened column's overall stability and strength. Dai et al. [18] indicated that, in comparison to a single CFS section, the structural performance of a CFS built-up battened column can be influenced by the quantity and spacing of the screws. When the screw spacing is doubled, the axial strength is decreased by 5% to 10% for the intermediate column. The back-to-back built-up battened column's slenderness ratio determines the screw spacing's effect. It is indicated that the number of fasteners affects the load-bearing capacity of the built-up battened column.

The advancement of research and engineering practice in structural engineering is critical, particularly in CFS built-up battened columns, because it enables more exact codes and standards. CFS built-up battened column must be designed following applicable codes and standards, taking into account a variety of parameters such as load combination, safety margin, and environmental conditions. The CFS built-up battened column behavior, structural integrity, and overall performance are not solely determined by a single CFS section but also by the chord-batten plate connection. The behavior of the built-up battened column constructed from the CFS section is determined by a variety of parameters, including design, dimension, material qualities, and loading conditions.

The CFS built-up battened columns are made of two or more chords by joining them at the flange of the main chord using a batten plate to form a composite column. The thin-walled nature of the CFS section, the behavior of CFS can be complicated and highly susceptible to structural instabilities, including local buckling, Euler buckling, and distortional buckling [19]. The single chord sections have relatively low torsional rigidity, making them weak in twisting compared to doubly symmetric sections. This causes the built-up battened column to exhibit a unique buckling behavior that is not comprehensively addressed in current codes. There are various factors affecting the behavior of CFS built-up battened columns, including material properties, geometry, and boundary conditions.

The slenderness of the column affects the behavior of the built-up battened column. Since the CFS section is prone to buckling due to its thinness the slenderness of the column is important for consideration during the design stage. Adil Dar et al. [6] observed that the axial performance of a built-up battened column consisting of two plain channels showed that the failure mode gradually transitions from local buckling to flexural buckling as the slenderness of the short column increases. The study observed that the stud column failure mood is mainly local buckling at the chord same as for the short column. However, the long column failed by flexural buckling with local buckling half-waves at mid-height, while the intermediate column experienced the maximum local and flexural buckling due to the complex thin-walled behavior.

Besides that, the addition of batten in the CFS built-up column can enhance the load-bearing capacity and strength of the column compared to CFS single sections. Manikandan et al. [17] studied the impact of battens and found that the load-bearing capacity and stiffness of CFS built-up columns increase as the number of batten plates increases. Additionally, the direct stiffness of the flange also increases, leading to a higher strength for the elevated section. The use of batten can help distribute the applied load and provide additional stiffness to the column reducing the local buckling risk.

In conclusion, CFS built-up battened columns composed of two or more chords joined by a batten plate show a complex structural behavior influenced by various factors. The thin-walled nature of the CFS section makes them susceptible to instabilities such as local buckling, Euler Buckling, and distortional buckling. The evolution of research and engineering practice in structural engineering is so important, especially in CFS built-up battened columns because it can establish the codes and standards that are more precise. It is essential to design CFS built-up battened columns that refer to appropriate codes and standards that consider various factors including load combination, safety margin, and environmental condition. The behavior, structural integrity, and overall performance of CFS built-up battened columns depend not only on individual chords but also on the connection between the chord and batten plate, emphasizing the importance of comprehensive design practices and ongoing research in this field.

5. Numerical and Experimental Study of CFS Built-Up Battened Column

An extensive study on CFS built-up battened columns has been conducted using both experimental and numerical approaches. The study aims to comprehensively understand the structural behavior, design, and performance of these columns under various loading conditions. The investigation covers a range of experiments and numerical simulations to gain a thorough understanding of the topic. Several studies have contributed significantly to this research of CFS built-up battened columns, also providing valuable insights into the behavior and design of cold-formed steel built-up battened columns.

Numerical analysis and design of CFS built-up open section column with longitudinal stiffeners were carried out in a paper by Zhang & Young [20]. The purpose of the study was to look at how edge and web stiffeners affected the way CFS built-up battened open-section columns performed. A Finite Element Analysis (FEA) was performed to model the behavior of columns with built-up sections. Additionally, the study used the FEM to conform to the ultimate loads found in the experiments to create and validate a finite element model (FEM) for forecasting the behavior of structural parts non-linear FEM is utilized. Most researchers used FEM to predict the ultimate load and failure modes of cold-formed steel built-up battened columns and verify FEM with the experimental result. When compared to the test result, nonlinear 3D FEM was also utilized to analyze the strength and buckling behavior of the CFS built-up battened column while taking into account nonlinear material properties, initial geometry imperfections, and boundary conditions. This showed that the models accurately captured the intricate buckling behavior of the CFS built-up battened columns [21].

Experimental studies are essential in determining the factors that influence the performance of CFS built-up battened columns and their structural response. Several tests were conducted to investigate the behavior, capacity, and failure mode of built-up battened columns. These tests focused on the connector spacing and contact between individual components to determine the overall performance of the columns. The experiments revealed how these factors influence the structural response of CFS built-up battened columns, which helps inform design practices and enhances the knowledge base. The experimental results contribute significantly to the understanding of the subject [22]. Waheed et al. [10] carried out an experimental and numerical study on the seismic response of built-up battened columns, highlighting the significance of variables like chord spacing, axial force, batten spacing, and thickness that affect the performance and failure modes of built-up battened columns. The middle column of the single-story multi-span building was reconstructed in the study's full-scale built-up battened column, which was tested under quasi-static cyclic loading. Additionally, ABAQUS software was utilized for numerical analysis aimed at determining the impact of different parameters on the cyclic response of the battened column.

Additionally, understanding the composite behavior of built-up battened columns is crucial to enhanced load-bearing capacity by understanding how the composite action between individual chords to the overall load-bearing capacity, improved structural efficiency leading to more cost-effective and sustainable designs, safety and reliability to reducing the risk of structural failure and design optimization to develop more accurate design methodology and guidelines for the construction of CFS built-up battened column. The study by Rahnavard et al. [23], focuses on the composite action in CFS built-up battened column with experimental data collection, in which a large set of experimental results from literature is gathered to calibrate numerical models and validate the finding related to the buckling behavior, while the numerical result is compared with analytical prediction based on established codes and specifications such as Eurocode and the North American Specification (NAS) to validate the accuracy of the numerical models and assess the adequacy of existing design standard.

Furthermore, the improvement of the design procedure is needed to optimize the design and develop a more accurate design and standard. Anbarasu & Dar [24] presented a numerical study on the behavior and design of CFS built-up battened columns comprising lipped angle sections to contribute to the improvement of design procedures for CFS built-up battened columns, providing insight into their structural behavior and axial resistance. The study used a numerical model to predict the behavior of the CFS built-up battened column and validated against experimental results with the parametric study on the key parameters affecting the behavior of the CFS built-up battened column to ensure their reliability. The study highlights the importance of considering key parameters and their interaction in the design and assessment of CFS built-up battened columns for improvement of structural performance and safety.

Parametric studies are instrumental for understanding the performance of CFS built-up battened columns by systematically exploring the impact of various parameters, optimizing design, improving efficiency, and addressing challenges associated with material selection, buckling behavior, connection details, and environmental factors. Lu et al. [25] , used a parametric study to investigate the structural response and ultimate strength of CFS built-up battened columns with varying key parameters. The study used a key parametric variation of cross-sectional dimensions to understand how changes in the geometry of the section affect the buckling resistance and overall strength of the column, thickness variation to investigate the impact of material thickness on the structural performance, length variation to investigate how column length influence buckling modes, interaction, and overall structural response and local, distortional and overall slenderness to capture the full spectrum of buckling modes and interactions for the study. Through the parametric study involving variation in cross-sectional dimension, thickness, and length, the researcher sought to comprehensively analyze the structural behavior of CFS built-up I-sections under different loading conditions.

In conclusion, extensive research on CFS built-up battened columns has been conducted through a combination of experimental and numerical approaches. The numerical method mainly FEA and FEM have been employed to simulate and predict the behavior of CFS built-up battened columns and used to capture complex buckling behavior, validate against the experimental result, and present a more precise structural response. Experimental studies have focused on determining factors influencing the performance of CFS built-up battened columns. The results from experiments not only inform design practices but also contribute to an improved knowledge base. Based on the study not only offers the advancement of knowledge of CFS built-up battened columns but also offers valuable insight into the optimized design procedures, enhancement of structural performance, and the development of accurate design methodologies and guidelines for the construction of CFS built-up battened columns.

6. Current Challenges in Implementing CFS Built-Up Battened Column

Implementing CFS built-up battened column presents various challenges that researchers have been addressing, such as the complexity of design, the material behavior, the connection design, buckling issues, the code and standard compliance, and limited research and guidelines. The thinness of the CFS section compared to hot-rolled steel presents unique failure modes and deformation issues, making built-up battened columns less used in the construction industry. The batten in the built-up battened column plays a crucial role because it helps overcome instability and enhance load-bearing capacity while reducing the risk of local buckling. However, determining the optimal spacing of batten, size of battens, and optimal spacing of chords for optimal performance for CFS built-up battened columns.

It is a big challenge to design built-up battened column-composed CFS due to the inherent complexity, especially the need to consider the need to combine different CFSs and address issues such as local buckling. In the study Cui et al. [26] , the battened column with a built-up design that utilizes a CFS angle section and batten plate is susceptible to local buckling failure mode during impact loading because of its open cross-section. The battened column with a built-up design that utilizes a CFS angle section and batten plate is susceptible to local buckling failure mode during impact loading because of its open cross-section. A thorough understanding of these complexities is vital to creating a safe and efficient design while navigating the challenges inherent in cold-formed steel construction.

According to Rahnavard et al. [16], even though CFS has many advantages over hot-rolled steel, specific design instructions are rarely available in the available design codes. Cold-formed steel exhibits different material properties compared to hot-rolled steel and is more sensitive to local buckling. The EN 1993-1-3 does not provide explicit guidance on built-up battened columns. Design codes rarely provide guidelines for cold-formed steel due to its unique material properties and sensitivity to local buckling. Laím et al. [27] also highlighted that the complex and highly nonlinear constraint from CFS built-up battened column design is a great challenge to determine the optimum and minimum weight of the CFS section to achieve a specific performance target. When designing a built-up battened column, it is important to consider various factors like the slenderness of the member, effective length, batten spacing, chord spacing, and buckling behavior. These elements can make the design more complicated.

Li & Young [12] battened columns mainly focus on unstiffened and edge-stiffened angles and channels as chord members where local buckling is observed for relatively short columns. The standards for Cold-Formed Steel (CFS) include a modified approach to account for the effect of residual stresses on column strength. The standards for Cold-Formed Steel (CFS) include a modified slenderness ratio that considers the relative deformation between different components of columns made up of built-up sections. However, this ratio is only applied to compression members that are assembled using two sections in contact. The material behavior of cold-formed steel (CFS) compression members, which are made up of individual cold-formed sections connected by transverse connector elements, is more complex than that of CFS built-up section compression members made up of components in contact. It is crucial to understand and predict the material behavior of the column under different loading conditions to ensure its structural integrity. Additionally, the connection between individual cold-formed sections is an important factor to consider.

Other than that, the connection between individual cold-formed sections is the crucial key that needs to be properly designed. Since the use of CFS in built-up battened columns has become more popular, understanding the behavior and performance of the connection is crucial. The easiness and simplicity of installation, and self-drilling screw connections are preferred compared to the other types of connection [28]. It becomes important to design a connection strong enough during the design stage to transfer loads effectively and rigid enough to maintain stability. The study by Georgieva et al. [29] also highlighted that the use of bolts as a connection of the

CFS section can ease the assembly, and the flexibility of the fastener needs to be considered during the design stage since it can affect the stability and strength of the CFS section.

Several disadvantages of CFS will cause unique failure modes and deformation that are caused by the thin section of CFS. The thinness of CFS over hot-rolled steel provides different behaviors and different failure modes that affect the stability of the column [30]. The instability of the CFS section can be overcome by the addition of the batten. Load-bearing capacity can also be enhanced due to the additional batten in the built-up battened column and at once reduce the risk of local buckling since the cold-formed steel column is susceptible to buckling, especially in slender sections. It is crucial to design proper spacing and size of battens for optimal performance in CFS built-up battened columns.

Implementing cold-formed steel built-up battened columns can be challenging due to the lack of explicit coverage for built-up battened columns in the cold-formed steel design standards. It is also mentioned in the study by Waheed et al. [14], that the current design standards do not offer specific guidelines for the design of built-up columns, particularly concerning seismic design. They only specify the limit for the spacing connector to counteract the buckling of individual chords. Ensuring that the design meets the necessary building codes and standards to guarantee safety and compliance can be quite a challenge.

Comprehensive research and guidelines on the specific configuration and application of CFS built-up battened columns are lacking. More research is needed to establish accurate and reliable design approaches, particularly to understand the composite action between the individual chords [17]. There is a lack of comprehensive research and guidelines for the configuration and application of CFS built-up battened columns. Further research is required to establish accurate and reliable design approaches, particularly in the composite action of a built-up battened column [11]. It shows that comprehensive research is needed to develop an accurate standard and detailed design while considering safety features. The designers may need to rely on empirical data and experience, which can lead to uncertainty in design.

In conclusion, the application of CFS built-up battened columns faces several challenges, ranging from design complexity to material behavior, connection design, buckling issues, code and standard compliance, and a lack of extensive research and guidelines. Existing research has mostly focused on certain types of chord members, leaving gaps in understanding the behavior of CFS battened columns, mainly that involving transverse connector elements. The development of reliable equations and methodologies is critical for gaining a better understanding of the composite action between individual chord sections and batten plates, which will help to formulate a precise standard and comprehensive design that prioritizes safety features. Overall, overcoming this challenge will be crucial for increasing the implementation and performance of CFS built-up battened columns in structural engineering.

7. Conclusions

This study examines the benefits of built-up battened columns, the function of battens in these columns, the impact of chord spacing, the methodology used to construct them, and the challenges in implementing CFS built-up battened columns. Several studies on CFS built-up battened columns have been reviewed, leading to a conclusion.:

1. The built-up battened column offers a few advantages due to the use of a batten plate to assemble two or more CFS sections to form a built-up column. Using battens can improve the load-bearing capacity of a column and increase its stiffness. This is because the battens help the chord members act as a single unit, reducing the risk of local and torsional buckling failure modes. The use of a batten also can enhance the stability of the column because the batten can distribute the applied load equally along the height of the column.
2. The spacing of batten plates has a significant impact on the overall stiffness and stability of the built-up battened column. The closer the spacing between the batten plates, the greater the overall stiffness and load-bearing capacity of the column. Using batten plates also effectively improves the ultimate strength and distortional buckling behavior of the built-up battened column. Therefore, the spacing of batten plates is a vital factor that determines the structural behavior and aesthetic appearance of CFS built-up battened columns.
3. The spacing between each section of the CFS column, known as chord spacing, plays a crucial role in its structural performance and stability. Chord spacing is very important to prevent buckling and minimize its effect. The spacing of the chord should be designed properly to ensure the stability of the built-up battened column and ensure that the batten plate can help resist the torsional force in the column.
4. The built-up battened column can display a distinct buckling behavior that is not fully covered in existing codes because of the thin-walled design of the individual CFS section. The slenderness of the column has a significant impact on its behavior, and as the slenderness increases, the column's failure mode changes gradually from local buckling to flexural buckling.
5. There are various challenges faced while implementing CFS built-up battened columns. These include the complexity of the design, the behavior of the material exhibited in the CFS section, connection

design, buckling issues, code and standard compliance, and limited research and guidelines. However, the CFS built-up battened column has been evolving, attracting many researchers to study it and develop accurate standards and detailed designs.

The use of battens in the CFS built-up battened column can improve its load-bearing capacity, stability, and overall performance while reducing the risk of buckling failure. Although there have been advancements in understanding the behavior and design of CFS built-up battened columns, accurately predicting their axial strengths and ensuring their safety under various loading conditions still remain a challenge. Further research Is required to refine design guidelines, improve the applicability of existing methods, and address specific issues such as column behavior under fire conditions and the influence of composite action on their structural response.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***experimental studies and data collection:*** *N F Jainudin,* ***numerical analysis and finite element modeling:*** *N Jamaluddin;* ***literature review and theoretical framework:*** *Zainorizuan Mohd Jaini,* ***design and optimization:*** *Hakim S.J.S,* ***project management and manuscript:*** *Noridah Mohamad. All authors reviewed the results and approved the final version of the manuscript*

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