Effects of Section Properties on Structural Behaviour and Failure Mode of Built-Up CFS Columns

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Abstract. Built-up CFS column is a type of structure that can be classified as an industrialized building system. This column has been widely used in the construction industry. It has relatively lightweight, easy to fabricate and provide efficient installation, thus suitable for the construction with difficulty in accessibility. However, the main issue that arises from the built-up CFS column is its bearing capacity. The ultimate strength and displacement of the built-up CFS column are prominently governed by its section properties such as size and thickness. Therefore, this study intends to investigate the effects of section properties on the structural behaviour and failure mode of built-up CFS columns. The built-up CFS column was modelled in the three-dimensional using WELSIM, taking into account the nonlinearities of geometry, material criterion and contact surface. It was found that the built-up CFS column attains ultimate strength of 53.33 kN to 210.6 kN and displacement around 1.33 mm to 2.98 mm. When the size and thickness of square hollow sections are increased, the ultimate strength increases simultaneously but the displacement shows a decrement trend. Under compression force, it was observed that the built-up CFS column suffers distortional and flexural buckling as well as connector and stiffener failures.

1. Introduction

CFS members are made of cold-formed steel and commonly be applied to the structures with short span such as joists and roof trusses for commercial and industrial buildings [1]. CFS members that fabricated from more than one section and joined together to form a global structure is known as built-up members. The advantages of built-up members are that it creates symmetrical section properties, greater strength and resistance towards out-of-plane movement. Generally, built-up members with the desire size and thickness will be fastened by using stiffener (such as lacings and battens) and connector (such as bolts, screws and rivets) or welds to produce the new assembled shape [2]. Zhang et al. [3] stated that built-up members do offer one of the highest load-bearing capacity-to-weight ratios among several other structural components. The material itself is very workable, hence many shapes can be fabricated easily [4]. One of the famous built-up members is known as the built-up CFS column. This type of structure can be classified as an industrialised building system (IBS).

Built-up CFS column is relatively lightweight, easy to fabricated and provides efficient installation, thus suitable for the construction of building at the site with difficulty inaccessibility. Currently, the
built-up CFS column has become popular in the construction industry due to its cost and sustainability. Despite that, bearing capacity still becomes the main issue that arises from the built-up CFS column. Moreover, CFS members are susceptible to buckling when applied as flexural and compression members [5]. The thin wall of CFS members will undergo local and distortional buckling, hence this issue must be taken seriously in the design stage. For the built-up CFS column, its ultimate strength and displacement are prominently governed by the section properties such as size and thickness. Other than that, fastener flexibility might affect stability. Although there are many previous studies have been done in inspecting the performance of built-up CFS column, the knowledge on the effects of section properties is still limited. Therefore, this study intends to investigate the structural behaviour and failure mode of built-up CFS columns concerning different section properties.

2. Built-up CFS column
Built-up CFS column consists of two or more parallel metallic sections and can be interconnected by lacings or battens. This type of column is widely used to accommodate its function as a primary structure. However, the built-up CFS column suffers from buckling and instability. It may be subjected to local and torsional buckling due to its thin-walled nature [6]. The buckling resistance of the built-up CFS column can be eliminated by the design modification. Young & Chen [7] suggested that web stiffeners can be added to enhance buckling resistance. Currently, there are two basic design methods for built-up CFS column, namely; the effective width method and the direct strength method. These methods are proposed by American Iron Steel Institute (AISI). However, only the effective width method is formally available for CFS members. The effective width method specifies the modified slenderness ratio to take the effect of shear force into account [8]. Meanwhile, the direct strength method incorporates many buckling phenomena into the thin-walled members where the buckling strength can be derived in a function of theoretical elastic buckling load [9]. The specifications for the design of CFS members such as provided by AISI S-100 and EC3 have become the main standard worldwide.

It was revealed that these codes of practices have a very good agreement regarding built-up members subjected to compression load [10]. However, EC3 does have limitations due to the inexistent interaction between the local and global buckling for the built-up CFS column. Besides, the section properties are vital in determining the structural behaviour. Section properties include the thickness, size and shape. Whittle & Ramseyer [11] conducted an experimental study on built-up CFS columns where three different thicknesses of cee channel were adopted. It was revealed that when the thickness of the cee channel is increased, the built-up CFS column can sustain an exceptional axial load and portray an improvement in strength [11]. Musa [12] investigated the structural behaviour of stiffened built-up CFS column that constructed using a combination of square hollow sections and steel plate. It was identified that the thickness of square hollow sections plays a vital role in governing the load-carrying capacity and displacement. In terms of failure mode, Kyvelou [13] found that section instability plays a paramount role. The increase in the slenderness ratio causes the ultimate strength to decrease uniformly [14]. Long and medium columns are prone to flexural buckling about the y-axis, where local buckling occurs when subjected to concentric axial compression for short columns [15].

3. Design and specifications
The design and specifications of the built-up CFS column are based on an experimental study conducted by Musa [12]. Built-up CFS column consists of three main components, namely square hollow sections as vertical members, steel plate as battens and rivets as connectors. These components are assembled to form the built-up CFS column. The schematic design of the built-up CFS column is shown in Figure 1. Since the section properties become the subject of interest, the detailed section properties of the built-up CFS column is provided in Table 1. Overall, the built-up CFS column has a height of 500 mm where the square hollow sections have the dimension of SHS 19x19, SHS 25x25 and SHS 32x32 with thicknesses ranging from 0.72 mm to 2.2 mm. Meanwhile, the battens have a size of 50 mm depth, 125 mm length and 1.0 mm thickness. The rivets are 4.8 mm in diameter and length of 7 mm.
Figure 1. Schematic design of built-up CFS column, (a) Elevation view, and (b) Plan view.

Table 1. Section properties of built-up CFS column.

| Code | Section Properties | Thickness, t (mm) |
|------|--------------------|-------------------|
|      | Size, B (mm) × H (mm) |                  |
| S1T1 | 0.72               |                   |
| S1T2 | 1.00               |                   |
| S1T3 | 19 × 19            | 1.20              |
| S1T4 | 1.90               |                   |
| S1T5 | 2.20               |                   |
| S2T1 | 0.72               |                   |
| S2T2 | 1.00               |                   |
| S2T3 | 25 × 25            | 1.20              |
| S2T4 | 1.90               |                   |
| S2T5 | 2.20               |                   |
| S3T1 | 0.72               |                   |
| S3T2 | 1.00               |                   |
| S3T3 | 32 × 32            | 1.20              |
| S3T4 | 1.90               |                   |
| S3T5 | 2.20               |                   |

4. Finite element modelling
The built-up CFS column was modelled and simulated using WELSIM, a finite element program. The numerical modelling is based on an explicit analysis considering the nonlinear plasticity. Therefore, the properties such as geometry, material criterion, constraint, loading and contact surface must be defined properly. Built-up CFS column was modelled in three-dimensional and discretized using tetrahedral elements with unstructured mesh. Figure 2 shows the built-up CFS column in the numerical modelling. The size of the mesh was automatically determined by WELSIM using an adaptive refinement method. It was identified that the size of mesh around 10 mm to 50 mm can produce convincing results. On the other hand, the material criterion of the built-up CFS column was derived from a combination of mechanical and hardening properties as tabulated in Table 2 and Table 3. This material criterion ensures that the plastic deformation can be achieved by the built-up CFS column and to avoid the fail-to-convergence condition. Hardening properties in term of multilinear kinematic hardening was used as proposed by Dewangan et al. [16] and Lu et al. [17].

The constraint is specifically used to represent the support and to control the translational. In the numerical modelling, the bottom part of the built-up CFS column was defined as fixed. Therefore, the constraint become true in all x, y and z directions. This restricts the horizontal and vertical movements
as well as induces the reaction forces. On the other hand, the top part of the built-up CFS column was freed. The loading that shall be imposed to the built-up CFS column must be able to imitate the compression force. Therefore, a concentrated applied force in the downward direction was applied at the top part of the built-up CFS column. The pattern of compression force is a force-time history at the speed rate of 4.17 kN/minute with 15 sub-steps within a second. Meanwhile, the bond mechanism between battens to square hollow sections as well as rivets to battens and square hollow sections must be provided using a contact surface. In the numerical modelling, the perfect bonded was employed as a contact surface. It is requiring the definition of master and target geometries. Thus, the body of rivets was selected as the master geometries while the interface of battens to square hollow sections was defined as target geometries. In this condition, no sliding and separation between geometries are allowed.

![Figure 2](image-url). The geometry of built-up CFS column, (a) Three-dimensional model, and (b) Discretization using tetrahedral elements.

| Mechanical Properties | Value  |
|-----------------------|--------|
| Density, \( \rho \) (kg/m³) | 7850   |
| Young’s Modulus, \( E \) (GPa) | 186    |
| Poisson’s Ratio, \( \nu \) | 0.29   |
| Bulk Modulus, \( G \) (GPa) | 148    |
| Shear Modulus, \( S \) (GPa) | 72     |
| Yield Strength, \( \sigma_y \) (MPa) | 350    |
| Ultimate Strength, \( \sigma_u \) (MPa) | 420    |

| Plastic Strain, \( \dot{\varepsilon}_p \) | True Stress, \( \sigma \) (MPa) |
|------------------------------------------|-------------------------------|
| 0.0000                                   | 0                             |
| 0.0029                                   | 350.46                        |
| 0.0505                                   | 350.46                        |
| 0.1078                                   | 395.37                        |
| 0.1928                                   | 420.75                        |
| 0.2208                                   | 420.75                        |
5. Results and discussion

Figure 3 shows a comparison of strength-displacement profile and stress-strain curve between the numerical modelling and the experimental study. For the strength-displacement profile, the numerical modelling does provide a similar curve when compared with the experimental study. The ultimate strength obtained from the numerical modelling is lower than the experimental study. The percentage difference is around 7.75%. Likewise, the displacement obtained from the numerical modelling is slightly lower than in the experimental study. The percentage difference is about 2.64%. Based on this assessment, it can be upheld that numerical modelling can provide very convincing results.

On the other hand, the stress-strain curve from the numerical modelling has a similar path as the multilinear kinematic hardening. The stress-strain curve from the numerical modelling reaches the elastic-plastic region and strain hardening, but unable to form softening phase. This indicates that the built-up CFS column undergoes failure when it reaches the yield stress. As the stress-strain curve has a negative gradient of tangent modulus, the numerical modelling is terminated.

![Graph](image)

**Figure 3.** Comparison between numerical modelling and experimental study – (a) Strength-displacement profile, and (b) Stress-strain curve.

Figure 4 shows the effects of thickness on the ultimate strength of the built-up CFS column. It can be noticed that the thickness contributes significantly to the increment of ultimate strength. As the thickness increases, the ultimate strength of the built-up CFS column increases as well. This finding is similar to that observed by Muhammad Noor [18] and Lin [19], where the column’s percentage of axial capacity become more conservative as the member thickness become thicker. It is no doubt that thickness is one of the section properties that will affect the structural behaviour and performance of built-up CFS columns. Although the ultimate strength of the built-up CFS column may be influenced by other factors such as buckling, the thickness gives a major impact on the moment of inertia and stiffness.
Figure 5 shows the displacement against the thickness of the built-up CFS column. The relation between the displacement and thickness is represented by a gradually negative gradient. Regardless of the size of square hollow sections, it can be observed that the increase in thickness will lead to the decrement of displacement. However, this trend is only true for the built-up CFS column with SHS 19x19 and SHS 32x32. For SHS 25x25, it can be seen that few thicknesses especially 1.2 mm and 2.2 mm have a bit higher values than their precedent and does not contribute to the smooth decrement of displacement. The finding for SHS 25x25 is likely contradicted to the previous experimental study by Kesawan et al. [20], which mentioned that the increment of web thickness will reduce the axial displacement of the hollow flange column.

\[
P_{ul} = -10.571t^2 + 58.126t + 17.574
\]

\[
P_{ul} = -13.11t^2 + 89.773t + 5.3397
\]

\[
P_{ul} = -2.6695t^2 + 88.671t + 23.383
\]

Figure 4. Ultimate strength versus to thickness.

The initial failure mode of the built-up CFS column is indicated by the yielding behaviour before it experiences a total collapse. It is noticeable that the built-up CFS column is less susceptible to buckling when the size getting larger. Similarly, the thickness tends to cause a lesser rate as it becomes thicker. According to Whittle & Ramseyer [11], the larger geometry of the structure has less buckling. Figure 6 shows the failure mode of the built-up CFS column. The failure mode may be localised or globalised across size and thickness. It can be observed that the built-up CFS column with SHS 19x19 suffers from distortional buckling throughout the whole length. Besides, there is stiffener failure occurs at the top and bottom parts of the built-up CFS column. Most built-up CFS columns with thickness 0.72 mm experience connector failure as the rivets stretched out from the battens and square hollow sections. On the other hand, SHS 25x25 and SHS 32x32 cause the built-up CFS column to experience the flexural buckling at the mid-height. Flexural buckling is always initiated at the member with a lower chord width-to-thick ratio [20]. In the numerical modelling, there is no appearance of lobe and bulging mechanisms as observed by Musa [12].

Figure 5. Displacement versus thickness.
6. Conclusion

Generally, this study is conducted to investigate the effect of section properties in terms of size and thickness. The numerical modelling was conducted using WELSIM, a finite element program. The effects of section properties in terms of the ultimate strength and displacement were quantitatively measured through the relationships of ultimate strength and displacement in corresponds to the thickness. Moreover, the failure mode was observed visually. It was found that the ultimate strength of the built-up CFS column getting stronger as the size becomes larger. Similarly, the thickness gave a favourable agreement. On the other hand, the displacement of the built-up CFS column shows a decrement trend when the size and thickness getting bigger and thicker. In terms of failure mode, it was found that the built-up CFS column suffers distortional and flexural buckling as well as connector and stiffener failures.
7. References

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Acknowledgements
The authors would like to thanks the Civil and Structural Engineering Branch, Jabatan Kerja Raya Malaysia for their continuous assistance and support.