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Review

A Critical Review of Cold-Formed Steel Built-Up Composite Columns with Geopolymer Concrete Infill

Serene Sara Simon, Bidur Kafle and Riyadh Al-Ameri *

School of Engineering, Deakin University, Geelong 3216, Australia; s.sarasimon@deakin.edu.au (S.S.S.); bidur.kafle@deakin.edu.au (B.K.)
* Correspondence: r.alameri@deakin.edu.au

Abstract: Concrete-filled built-up cold-formed steel (CFS) columns offer enhanced load-carrying capacity, improved strength-to-weight ratios, and delayed buckling through providing internal resistance and stiffness due to the concrete infill. Integrating sustainable alternatives like self-compacting geopolymer concrete (SCGC) with low carbon emissions is increasingly favoured for addressing environmental concerns in construction. This review aims to explore the current knowledge regarding CFS built-up composite columns and the performance of SCGC within them. While research on geopolymer concrete-filled steel tubes (GPCFSTs) under various loads has demonstrated high strength and ductility, investigations into built-up sections remain limited. The literature suggests that geopolymer concrete's superior compressive strength, fire resistance, and minimal shrinkage render it highly compatible with steel tubular columns, providing robust load-bearing capacity and gradual post-ultimate strength, attributed to the confinement effect of the outer steel tubes, thereby preventing brittle failure. Additionally, in built-up sections, connector penetration depth and spacing, particularly at the ends, enhances structural performance through composite action in CFS structures. Consequently, understanding the importance of using a sustainable and superior infill like SCGC, the cross-sectional efficiency of CFS sections, and optimal shear connections in built-up CFS columns is crucial. Moreover, there is a potential for developing environmentally sustainable built-up CFS composite columns using SCGC cured at ambient temperatures as infill.

Keywords: cold-formed steel (CFS); geopolymer concrete (GPC); built-up sections; shear connectors

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1. Introduction

Cold-formed steel built-up columns with concrete infill represent an innovative approach in structural engineering, combining the advantages of both materials to create robust and efficient structural elements [1–3]. Research has demonstrated that these columns filled with concrete can carry up to 2.5 times more load than empty built-up columns of the same dimensions [1]. In this construction method, thin-gauge steel sections are fabricated and assembled into built-up configurations, forming columns, beams, or other load-bearing members [2]. Cold-rolled steel sheet (coil) is derived from a cold working process applied to a thick hot-rolled steel sheet, where elongation of steel grains and filling of porosity occur, leading to a strain hardening process that densifies the steel, enhances its strength, and diminishes ductility [4]. A range of grades and shapes like G250, G300, G450, G500, and G550, comprising a channel, lipped channel, Z-section, circular hollow sections (CHSs), a rectangular hollow section (RHS), a hollow flange channel section, and a square hollow section (SHS), are available, facilitating cost-effective and eco-friendly construction designs and methods [5]. These steel sections are then filled with concrete, creating a composite structure with enhanced strength, stiffness, and durability [3]. The concrete infill provides additional mass and resistance to compression, while the steel sections offer flexibility, ease of fabrication [6], and high tensile strength. This combination results in lightweight structures capable of supporting significant loads, making them ideal for various applications in construction, including multi-story buildings, bridges, and industrial facilities [7].

Alternatives to the concrete infill, particularly self-compacting geopolymer concrete (SCGC), offer environmental benefits via utilising industrial by-products and reducing carbon emissions [8]. This innovative material is formulated using geopolymer binders, which replace the cement content in normal concrete and are typically derived from industrial by-products such as fly ash or slag, along with alkaline activators [8,9]. Reducing cement consumption in concrete retards carbon emission pollution tremendously as it is a high-demand binder product in the field of construction. Through optimising particle size distribution, rheology, and viscosity, self-compacting geopolymer concrete achieves excellent workability and flowability while maintaining high mechanical strength and durability, offering significant advantages in construction processes where traditional compaction methods are impractical or labor-intensive [10]. Moreover, there is scope for developing environmentally sustainable built-up CFS composite columns using SCGC cured at ambient temperatures as infill.

The role of shear connectors introduces better capacity due to the anchorage it creates within the infill [1,11,12]. The incorporation of screw connectors in built-up concrete-filled CFS columns enhances structural integrity via facilitating efficient load transfer between steel and concrete components, thereby improving resistance against lateral loads, reducing susceptibility to buckling, and ensuring robust structural performance under varying loading conditions [1,12].

This review contributes to comprehensively assessing the possibility of utilising SCGC as an infill in inventively designed built-up cold-formed steel channel sections. Various factors like the shape of the stiffened steel channel sections, the dimensions of the columns, the bond between steel and infill, and the position, size, and anchorage length of fasteners all advance the performance of the column [3,12,13]. This has been elaborately discussed to qualitatively and quantitatively increase the use of SCGC as an infill in built-up CFS columns, which remains scant. Even though a handful of the literature addresses GPC and CFS built-up columns separately, research that utilises such novel concrete materials along with lightweight built-up steel sections remains scarce. Consideration of these sustainable materials in CFS sections can contribute to more eco-friendly construction practices. CFS built-up sections with SCGC infill offer a cost-effective and sustainable alternative to traditional construction methods, with benefits such as reduced material usage, shorter construction times, and improved seismic performance [12].

2. Conceptual Background

2.1. Cold-Formed Steel Sections as Columns

Cold-formed steel sections offer structural and environmental advantages like low weight, ease of construction, and recyclability [14,15]. CFS open sections are typically manufactured through production techniques including coiling, uncoiling, flattening, and cold-forming or press-braking methods [14]. These adaptable manufacturing processes enable the creation of various commercially available cross-sections with diverse shapes, leading to favourable strength-to-weight ratios [15]. Moreover, these manufacturing processes can be applied to cross-sections crafted from plain steel sheets and other materials. A review of different CFS sections was published, where the authors assessed different CFS sections and found that compression members under axial loading have the potential to buckle about their major axis [14,15]. CFS profiles typically exhibit thin wall thickness and sizeable width-to-thickness ratio (h/t), leading to diminished resistance, and tend to buckle locally under various stresses like flexural bending, axial compression, shear, or bearing [16].

To counteract this inherent susceptibility to buckling, manufacturers have produced highly stiffened sections through incorporating additional folds and stiffeners [16,17]. Research studies in the past few decades have extensively reported investigations on the structural behaviour of CFS plain sections, edge, web, and flange-stiffened sections, and sections with complex stiffeners under various loading conditions [17]. Hancock et al. [18] discussed using high-strength steel to develop new section shapes for CFS structures in Australia. They focused on the behaviour of these stiffened sections, including their advantages and buckling analysis [18]. The development of the direct strength method (DSM) for the design of cold-formed sections is highlighted in the Australian/New Zealand standard AS/NZS 4600:2005 [19], which also introduces new and innovative shapes, such as plain sections, Supa sections, and Diamond Hi-Span (DHS) sections, and emphasises the importance of shear buckling analysis and signature curves for innovative shapes. The critical review by Dai et al. [5] provided an in-depth analysis of the structural behaviour and design approaches for cold-formed built-up members, focusing on columns, beams, and portal frames. The research emphasises the increasing use of cold-formed members in structural engineering due to their advantages, such as low weight, ease of construction, and greater flexibility [5]. It has been observed that CFS sections can better serve as supporting elements in columns along with other materials to form composites, compared to using heavier steel sections all by themselves.

2.2. Built-Up CFS Sections as Columns

Built-up CFS columns are gaining popularity in construction due to their technical and economic advantages [11,20]. These columns are formed via connecting individual CFS sections using screws or fasteners to prevent independent buckling, and are commonly used in steel trusses, space frames, and wall studs within light gauge steel framing systems [21]. In their article, Meza et al. [20] focused on two additional complications in built-up members: modelling connectors and contact between constituent parts, and demonstrated that detailed, accurate, and reliable finite element models can provide an excellent means to achieve this. Such sections offer increased load-bearing capacity and torsional stiffness compared with single sections, particularly for doubly symmetric cross-sections like box sections, created through nesting two-lipped or unlipped single channel sections, effectively eliminating eccentricities between shear and gravity centres for improved member stability [3]. While built-up sections have advantages such as ease of transportation, handling, and stacking like single sections, they can be readily assembled on site without altering the manufacturing process, providing significant economic benefits. However, challenges persist, such as local buckling and failure due to excessive local buckling or interaction between local and flexural buckling.

Research has shown that incorporating stiffeners in built-up columns can significantly increase their axial strength [2]. Ananthi et al. [21] investigated the axial strength of built-up CFS unequal angle box columns, showing a 28% increase with stiffeners compared with plain columns, validated through experimental and FE results. Finite element models have been developed and validated to analyse the behaviour of these columns under various conditions, including fire resistance. However, existing design methodologies, such as those outlined in EN1994-1-2 [22], may need modifications to accurately predict these innovative structural elements' fire resistance and load-bearing capacity [11]. Figure 1 presents the various cross-sections of built-up CFSs used by different researchers.

Further research is recommended to optimise the structural performance of built-up CFS columns under different loading scenarios and to explore the potential of artificial intelligence algorithms for strength prediction. Craveiro et al. [23] showed that built-up columns comprising Σ (sigma) profiles provided greater load-bearing capacity, with rectangular closed sections having slightly higher load-bearing capacity than square ones. Yang et al. [24] revealed the impact of screw arrangements on the load-bearing capacity and behaviour of columns under compression. The results indicated that screw arrangements had a significant effect on the load-bearing capacity, with a reduction in screw spacing from 300 mm to 100 mm leading to an increase of up to 11% of capacity. That study's findings provided valuable insights into the behaviour of closed built-up CFS columns with longitudinal stiffeners under compression, offering a comprehensive understanding of their load-bearing capacity, stability limitations, and design code suitability [24]. Hence, built-up sections provide a versatile option for varied cross-sections, thereby exploiting the effectiveness of the shape.

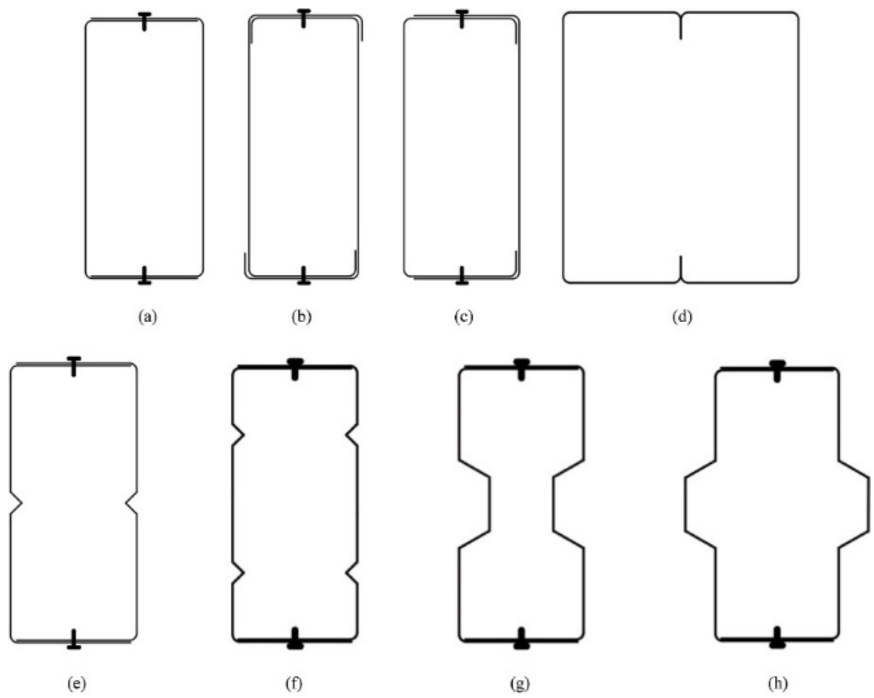

Figure 1. The different ways CFS sections can be placed face-to-face as investigated in Ref. [5]. (**a**–**h**) explaining the different ways the steel sections can be arranged.

2.3. Concrete-Filled Steel Tubular Columns

Concrete-filled steel tube (CFST) columns exhibit excellent load-bearing capacity under compression [25,26]. CFST composite columns are structural elements that combine the advantages of steel and concrete. These columns exhibit high compressive strength, durability, and excellent mechanical properties [25]. Concrete-filled tubular columns, including those made of carbon steel, stainless steel, and FRP, exhibit excellent compression performance due to the confinement effect, high-strength materials, and low elastic modulus of the concrete [26]. The behaviour of CFST columns is influenced by their material properties, confinement effects, and slenderness ratios [27,28]. However, material compatibility to ensure a proper bond between concrete and steel is crucial as the interfacial bond resists the local failure of the materials to form a unified structure.

Additionally, using nanomaterial-based concrete in CFST columns has shown promising results, increasing load capacity and stiffness while improving composite interaction and confinement effects [29]. Studies have shown that the compressive behaviour of CFST columns can be enhanced via using high-strength materials and optimising loading conditions [30]. Techniques like acoustic emission analysis have been employed to quantitatively assess concrete damage during axial compression, providing insights into the different stages of damage evolution in CFST columns [27]. Overall, CFST columns are a popular choice for structural applications due to their robust performance under compression.

Cheng et al. [31] utilised ultra-high-performance concrete-filled steel tube composite columns to exhibit high compressive strength and durability. The findings suggested that increasing steel tube strength and thickness significantly improved the ultimate bearing capacity while reducing the ductility coefficient. Additionally, increasing the concrete strength enhanced the ultimate bearing capacity but decreased the ductility coefficient. Their study also evaluated the contribution of concrete to the overall load-bearing capacity of the composite columns, indicating the significant role of concrete in the load-carrying capacity of the composite columns [31]. CFST composite columns are widely used in construction because they can sustain heavy loads with high performance. They are employed in various applications, such as multi-storied buildings, extended bridges, bridge piers, floodwall structures, and submarine pipeline systems [26–28]. Achieving strain continuity at the steel–concrete interface ensures optimal performance, especially in regions where the materials are not loaded simultaneously [32]. Recent developments in composite columns reported by Shanmugham et al. [33] have highlighted the efficiency of utilising the interactive behaviour of steel and concrete, providing both strength and fire resistance. Outcomes also indicated that an increase in load eccentricity reduced the load-carrying capacity and stability of the columns [33]. The concrete core provides an alkaline environment to the steel tube, thereby protecting the steel from corrosion [34]. The pH of concrete passivates the steel, forming a protective oxide layer on its surface [35]. The concrete acts as a barrier preventing the ingress of corrosive agents such as moisture, chlorides, and carbon dioxide. Hence, ensuring a tight seal between the steel tube and the concrete core is necessary to prevent the entry of corrosive agents [34]. Proper coating and treatment with corrosion-resistant materials further reduce the risk of corrosion [36].

Various novel cross-section profiles, including semi-oval, round-ended oval, elliptical sections, etc., have been developed to cater to the increasing aesthetic and structural requirements of architectural design [13]. CFST, widely studied in civil and structural applications, offers advantages, including high load-carrying capacity, stiffness, energy absorption, and seismic performance due to composite action between the concrete core and steel tube [29]. However, compared with conventional column design, the composite nature of CFST columns requires complex design and analysis to accurately predict their behaviour. Designing CFST structures involves following the guidelines set by the relevant design codes, such as AS/NZS 2327:2017 [37], for composite structures influenced by parameters like cross-section shape, h/t ratio, slenderness ratio (λ), strength, material deformability, restrained lateral expansion of concrete, and local buckling of the steel tube. Ignoring the confinement effect for the CFST column with a slenderness ratio higher than 50 has also been proposed [12]. The degree of end restraint specifically via fixed-end supports increases the column's effective length factor, enhancing its buckling resistance compared with pinned ends [12]. Ensuring continuous load paths through end connections is critical for the effective transfer of forces and maintaining structural stability.

A study conducted by Khan et al. [38] demonstrated the enhanced axial and flexural performance of concrete-filled fibre-reinforced tubes, especially when combined with carbon FRP reinforcing bars, compared with conventional steel–concrete columns. The innovative column carried a 15.8% higher axial load due to the higher confinement provided via the tube, and the specimens with rebars carried a 43.7% higher axial load, as the rebars and tube provided additional confinement [38]. Another innovative column consisting of an inner concrete-filled FRP tube and an outer concrete component showed considerable increases in strength and ductility compared with the plain concrete column [39]. The glass fibre-reinforced CFST showed a reduction in ductility under eccentric axial load. Increasing the eccentricity of the applied axial load reduced the maximum axial load and axial displacement; however, it increased the ultimate axial strain but reduced the ultimate axial stress. Increasing the FRP tube's thickness to an optimised value increases the specimens' flexural strength [40]. Compared with reinforced concrete columns, CFST has proven to be an efficient alternative due to the reduction in steel percentage and the provision of confinement of concrete without the use of formwork. Nevertheless, high-quality construction practices are necessary to prevent issues such as voids within the structures or even improper compaction and segregation.

2.4. Geopolymer Concrete Infilled CFST Columns

Geopolymer concrete in cold-formed steel tubes (CFSTs) represents an innovative construction approach, offering sustainable and durable solutions. Geopolymer concrete utilises industrial by-products like fly ash or slag, reducing carbon emissions compared with traditional Portland cement-based concrete [8,9,41]. The performance of geopolymer concrete, specifically SCGC, is influenced by several factors including mix proportions, activators used, and curing conditions. Rahman. et al. [8] introduced a newly developed SCGC mix without superplasticisers that achieved compressive strengths up to 40 MPa after 28 days of ambient curing, comparable to an M40-grade conventional concrete. Furthermore, using finer binder materials like micro fly ash and solid alkali activators helped achieve self-compacting properties in the geopolymer concrete without the need for superplasticisers [8] (refer to Figure 2). The optimum mix ratio for achieving a superior working performance was identified as a fly ash to slag ratio of 60/40. The study found that varying the water–binder ratio from 0.4 to 0.5 was critical to achieving the right balance between workability, mechanical properties, viscosity, microstructural characteristics, and strength, as higher ratios led to segregation [8,41]. The SCGC was designed to cure under ambient conditions of 23 ± 2 °C, eliminating the need for high-temperature curing typically required for conventional GPC [8]. Additionally, using FRP rebars can further improve the bond strength and capacity of the innovative SCGC and provide a promising sustainable solution to address corrosion issues in reinforced concrete structures [9]. The yield stress and viscosity of SCGC are governed by factors like water–binder ratio and binder composition as well as the utilisation of finer binder materials. The self-compacting nature of this GPC, achieved because of the excellent binder composition and mixing procedure, makes it less viscous yet compact without segregation. Nikemehr et al. [41] presented a detailed review of the addition of recycled concrete aggregate as a 100% replacement for coarse aggregate, potentially paving the way to a much more sustainable alternative.

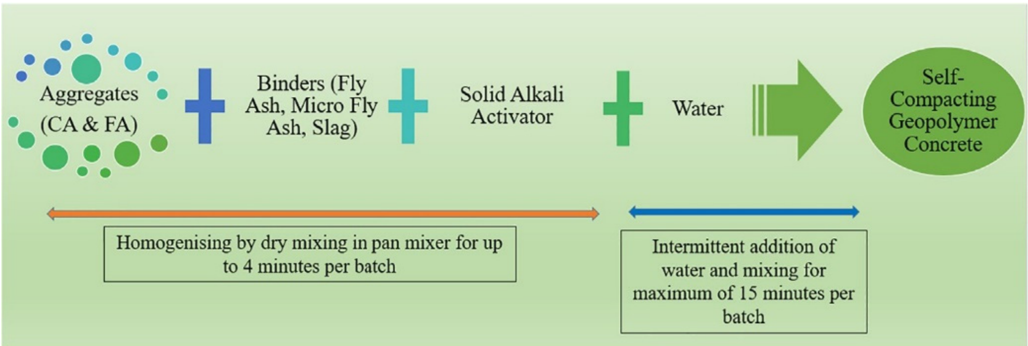

Figure 2. Innovative self-compacting geopolymer mix [8].

In CFST applications, geopolymer concrete is an effective infill material, enhancing the structural performance of steel tubes [42–45]. Gkantou et al. [42] proposed a new composite structural cross-section combining geopolymer concrete-filled aluminium alloy tubes (GCFAT). GCFAT specimens exhibited higher strength and deformation capacity, with an average strength increase ranging from 16.5% to 93.3% for stub columns, and the flexural strength increased from 27.1% to 41.6% for GCFAT beams [42]. Geopolymer concrete-filled stainless steel tubular (GCFSST) columns also exhibited 3–7% higher ultimate strength than CFST [43]. A lower diameter-to-thickness (D/t) ratio of 37.5 resulted in higher ultimate strength than a D/t ratio of 50 for both hollow and concrete-filled tubular columns. Stainless steel tubes as the outer core material improved the load-bearing capacity and ductility of the GCFSST columns compared with mild steel tubes [42,43]. The yield stress of the outer steel tube influenced the behaviour of GCFSST, with a higher yield stress of 517 MPa, showing around 4.5% higher ultimate strength than CFST columns with a yield stress of 282 MPa [43].

Geopolymer concrete (GPC)'s high compressive strength, excellent fire resistance, and low shrinkage make it well suited for CFST columns. Geopolymer concrete-filled steel tube (GPCFST) specimens demonstrated high load-bearing capacity and gradual post-ultimate strength degradation without brittle failure due to the confinement provided by the outer steel tubes [44]. Kanwal et al. [46] found that increasing the NaOH molarity improved the compressive strength and ductility of GPC and that confining GPC in CFRP or GFRP tubes further enhanced these properties, as confinement provided the best performance. The finite element model accurately predicted the behaviour of GPCFST structures under different loading conditions. Parametric studies revealed that increasing steel grades, decreasing section slenderness (B/t or D/t ratios), and decreasing member slenderness

(L/r ratios) improved the resistance to compression and bending [45], providing structurally efficient, sustainable, durable members with a low carbon footprint [42]. Through incorporating geopolymer concrete, CFST structures can achieve enhanced load-carrying capacity, improved durability, and reduced environmental impact, thus aligning with modern construction trends towards sustainability and efficiency.

Consequently, the effects of utilising recycled brick aggregate (RBA) in GPCFST with varied aggregate replacement ratios, cross-section shape (circular vs square), and the slenderness ratios on the failure modes, load-deformation response, bearing capacity, and strain development were studied [47,48]. The bearing capacity decreased with increasing brick aggregate replacement ratio and slenderness ratio, while the ductility improved with higher brick aggregate content [47]. Parametric analysis showed that the stability coefficient decreased with increasing slenderness ratio, steel yield strength, and concrete strength, but it was less affected by the steel ratio [47,48]. The ductility index ranged between 11–42% for 100% RBA replacement for the different grades of concrete. Compared with specimens without RBA, a 100% RBA replacement can reduce the ultimate strength by about 30% and 20% for concrete grades C45 and C65, respectively [48]. Investigation of the behaviour of GPCFST columns with geopolymer concrete made from other waste materials like copper slag, metakaolin, or silica fumes could be explored. GPCFST columns exhibited better fire resistance than conventional CFST columns, especially when using heat-cured geopolymer concrete [44]. Circular specimens performed better than square ones due to the higher confinement effect [45]. The results showed that as the diameter of the column decreased, the deformation increased while the stress increased. The deformation and stress increased as the column's length increased [49]. Ahmad et al. [50] reported the compressive strength, longitudinal reinforcement ratio, and confinement ratio on the P-M interaction behaviour. It was found that all these parameters linearly increased the load and moment capacities of the columns. The compressive strength of GPC, longitudinal reinforcement ratio, and confinement ratio were identified as the key parameters that significantly influenced the behaviour of FRP-reinforced GPC-filled FRP tube columns [50].

Design formulae have been proposed to predict the strength of GPCFST cross-sections, showing reasonable accuracy and consistency compared with experimental results. The design approaches in EN 1994-1-1 [22], AS/NZS 2327 [37], and AISI-S100-16 [51] for conventional concrete-filled steel tubes provided conservative strength predictions for GPCFST structures, underestimating the ultimate loads by 6–25% on average [45]. Designers are reluctant to specify geopolymer concrete in structural applications due to the non-availability of real-site case studies or performance data, hindering its acceptance in the construction industry. However, in regards to sustainability and low carbon emissions, the superior compliance of GPC over that of concrete can provide better scope for constructing built-up sections.

3. Area of Research Focus

Combining steel and concrete in a section results in composite action, where the two materials work together to resist applied loads [1]. The steel provides tensile strength and flexibility, while the concrete provides compressive strength and stability [2]. This synergistic interaction leads to efficient load transfer and enhanced structural performance.

3.1. Composite Action

The composite action of concrete and steel tubular sections, such as concrete-filled steel tube (CFST) columns and double composite sections, offers numerous advantages. CFST columns exhibit high strength, ductility, and stiffness due to the combination of steel's properties of tension and bending resistance with concrete's compressive strength [52]. Incorporating concrete into steel tubes delays local buckling, enhancing overall section stiffness. Double-composite bridge sections improve structural efficiency via effectively distributing forces, reducing steel usage, and enhancing dynamic response for high-speed rail bridges [53]. The bond strength between steel and concrete in CFST sections can be significantly improved through incorporating rectangular flutes on the steel tube, enhancing overall performance [54]. These findings highlight composite action's benefits and the potential enhancements it can provide in concrete and steel tubular sections. A composite solution increased the load-bearing capacity of CFS columns, demonstrating the advantage of combining steel and concrete in mitigating local buckling phenomena and increasing load-bearing capacity [12]. Concrete-filled columns exhibit superior structural performance compared with hollow columns, with increased strength and stiffness.

Kumar et al. [55] conducted an experiment on rectangular and square hollow structural steel with and without infill under compression and flexure, and the results obtained from the experimental work demonstrated the effect of composite action in building a better structural component. Kenarangi et al. [56] investigated the composite action between steel casing and concrete shafts in foundations, showing that the existing friction coefficient was able to develop a composite strength exceeding theoretical calculations. The concrete infill effectively delayed local buckling of the steel section, allowing the development of higher compressive stress in the steel. The concrete not only increased the overall stiffness and load-bearing capacity of the column but also provided internal restraint against the inward buckling of the steel section [7]. This composite action allowed the steel to achieve higher stress levels before buckling, improving the column's strength [1]. Another study on steel-reinforced concrete-filled steel tubular (SRCFST) columns found that they exhibited high strength and fire resistance due to composite action enhancing cyclic performance, with circular cross-sections showing superior behaviour [57]. The composite action between steel tubular sections and concrete enhanced load-carrying capacity by 32%, with factors like slenderness ratio influencing strength and ductility indices in CFST columns [58]. However, these studies also pointed out that current design codes may not accurately predict the strength of these composite columns, indicating a need for code improvements to account for the composite action more effectively [7,12].

3.2. *Profile of Built-Up Sections*

Using different cross-sectional steel profiles for concrete-filled CFS built-up section stub columns is essential for determining structural behaviour, particularly the buckling resistance of the columns under compressive loads [2]. Various cross-sectional configurations, such as face-to-face connected channel sections, web-stiffened and lipped channel profiles, and corrugated web columns, have been investigated to examine their structural behaviour under various loading conditions (Figure 3) [1–3]. Studies have shown that the arrangement of the sections to form varied profiles, thickness, and hollow ratios significantly impacts the flexural and load-carrying capacity of the built-up CFS sections [12]. Additionally, infill materials in CFS sections have been proposed to enhance buckling resistance and increase load capacity by up to 40% [59]. Studies have focused on investigating the flexural performance of composite columns with different cross-sectional configurations, such as C-sections filled with concrete material containing varied lightweight recycled aggregates [60].

Furthermore, the influence of corrugated web thickness, connection types, shear connection degree, and steel beam height on the overall behaviour of composite floor structures has been examined, highlighting the significant impact of connection types and shear connection degree on system behaviour [61]. Meza et al. [62] described a comprehensive experimental program in which built-up CFS stub columns with four different cross-sectional geometries were investigated, and the experiments revealed a significant amount of restraint within the buckling due to the cross-sectional stiffeners and connector spacing having a pronounced effect on the observed buckling mode. These studies collectively contribute valuable insights into the performance of different cross sections in built-up CFS-concrete composite sections [62]. These findings highlight the importance of considering different cross-sectional designs and materials to optimise the performance of built-up CFS sections in structural applications.

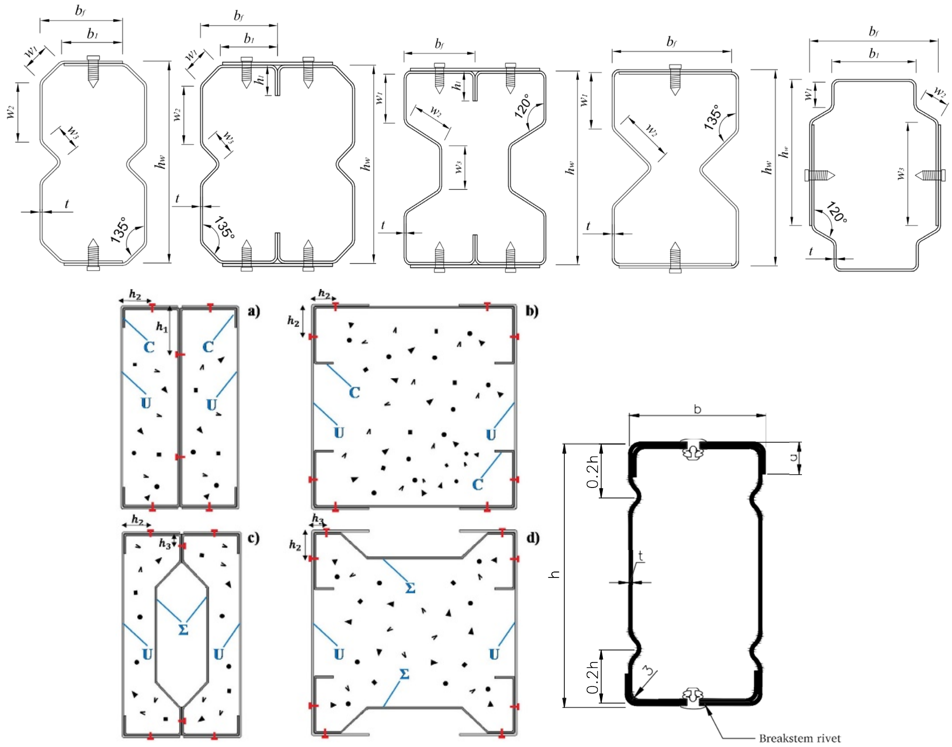

Figure 3. The various ross-sectional profiles investigated by different researchers [1–3,7,11,12,23].

CFS built-up closed sections, including nested/box channel members, have become more popular as compression members. The advantage of nested channel (NC) members is that they can be easily made of two commercially available single-lipped channel members using screw fasteners [6]. Chen et al. used five types of CFS built-up sections of various shapes and made via press braking. The reason for the utilisation of such specific cross-sectional profiles was not detailed. Still, the study mentioned that a pair of identical open sections were built up to form a closed section using self-tapping screws and connected using steel strips where necessary [2].

In contrast, Rahnavard et al. [1,12] provided more detailed information about the specific cross-sectional profiles used in their study. The authors investigated the compressive behaviour of innovative concrete-filled closed built-up CFS columns using three different CFS profiles: (a) C-shaped profiles, which are conventional in CFS construction and typically have a rectangular cross-section with a hollow centre; (b) U-shaped profiles, which are similar to C-shaped profiles but with a U-shaped cross section and which can also be used to form closed sections when combined with other profiles; (c) Σ-shaped profiles which are less common and have a more complex geometry that includes additional folds or bends that can increase the structural stability and load resistance. These profiles were assembled in built-up sections and filled with lightweight concrete (Figure 3). Four different cross-section shapes were tested: a rectangular built-up cross section comprising two C-shaped profiles fastened back-to-back and two U-shaped profiles (Figure 3a); a square built-up cross-section consisting of two C-shaped and two U-shaped profiles (Figure 3b); a rectangular built-up cross-section with two Σ-shaped profiles fastened back-to-back and two U-shaped profiles (Figure 3c); a square built-up cross-section with two Σ-shaped and two U-shaped profiles (Figure 3d).

Teoh et al. [3,7] considered another cross-section with two nesting asymmetric lipped CFS channel sections, front-to-front, connected along the longitudinal flanges using aluminium break-stem rivets. The effective cross-sectional areas were also evaluated for buckling load prediction, showing that the analytical predictions agreed with the experimental results when the steel's effective cross-section area and specific buckling curves were considered. The reliability analysis performed in the study resulted in a more reliable design methodology that considered the effective cross-sectional area of CFS profiles [1]. Studies have shown that the axial compressive capacity of composite CFS–engineered cementitious composite (ECC) columns can be significantly enhanced, up to 2.79 times that of bare CFS columns, via incorporating thin layers of ECC into the design [63].

3.3. Slenderness Ratio

The slenderness ratio plays a crucial role in the behaviour of CFS concrete-filled composite columns. Sheta et al. [64] reported that composite columns with higher slenderness ratios tended to fail through overall buckling. In comparison, those with lower slenderness ratios failed due to localised buckling and crushing of the concrete infill. The axial behaviour of composite columns with high-strength CFS and ECC showed enhanced compressive capacities, ductility, and toughness, with slenderness ratios between 10.08 and 13.86 [64]. More et al. [63] conducted axial compression tests on 24 columns, including three hollow steel columns and 21 composite columns, and three distinct slenderness ratios were developed (λ = 20, 40, and 70). The slenderness ratio significantly influenced the failure mode of CFS–concrete composite columns, with low ratios (λ = 20 and 40) failing due to local buckling and the high ratio (λ = 70) failing through overall buckling [63]. Salim et al. [65] conducted an experimental and numerical investigation to estimate the slenderness ratio of concrete-filled multi-skin steel tubes (CFMSTs) under axial load, and a new equation was suggested for the predicted slender limit of a composite column with a varying number of steel tubes. Stub column specimens infilled with lower-strength concrete demonstrated relatively ductile behaviour. In contrast, those infilled with higher-strength concrete showed a brittle response, particularly specimens with a larger section slenderness ratio [3].

3.4. Connections

Various studies have explored different connection methods to enhance the performance of such composite systems. Research has shown that innovative splice connection concepts for CFS built-up columns can facilitate quick erection processes and ensure uniform force distribution [66]. Selvaraj et al. [66] used the same size and shape of geometry as the CFS built-up column and enabled a quick erection process. Additionally, investigations into shear connections, such as bolts and composite dowel rib connectors, have highlighted the importance of balancing stiffness and ductility in achieving optimal performance [1,67]. Ćurković et al. [67] investigated two types of shear connections suitable for the proposed composite solution. The results of FE simulations indicated that a solution with bolts ensured higher shear connection stiffness compared with tubular sections, reducing its ductility [67].

Meza et al. [20] focused on two additional complications in built-up members: modelling connectors and contact between constituent parts. They demonstrated that detailed, accurate, and reliable finite element models provide an excellent means to achieve this. Overall, the effectiveness of connections significantly influences the structural integrity and performance of CFS-built-up concrete-filled composite columns. The type of connection between steel beam elements and the degree of shear connection significantly impact the behaviour of lightweight, CFS–concrete composite floor beams [68]. Chen et al. [2] conducted a test campaign concerning the behaviour of concrete-filled CFS built-up section stub columns, where a pair of identical open sections were built up to form a closed section using discrete self-tapping screws. The authors suggested that the penetration of the connectors did not contribute to the composite action of the column. Rahnavard. et al. [1,12] performed tests to prove that connectors of longer lengths (depth ~ 45 mm) impacted the composite action of steel concrete columns.

Various assembling approaches, such as welds, bolts, or self-tapping screws, can be adapted to build up two or more individual open sections into a closed section. Built-up closed sections generally possess superior behaviour in terms of structural stability and load resistance compared with the original open sections. The anchorage length of a bolt in concrete significantly impacts its load capacity and behaviour. Increasing the anchorage length can improve the connection's maximum strength and enhance the connection's initial stiffness up to a specific limit [1]. The load capacity of anchor bolts depends on factors such as diameter, embedment length, alignment, and bond between the steel and concrete [2]. The behaviour of glass fibre-reinforced polymer (GFRP) bolts also shows that as the anchorage length increases, the pull load on the bolt and the decay rate of axial stress along the anchoring length gradually rise. Hosseinpour et al. [69] conducted shear loading tests to study the anchorage length of bolts and found that the shear performance increased with the anchorage length. On the other hand, the depth and diameter of bolts and the strength of bolts increased the capacity to only a specific limit, beyond which it affected the concrete around the bolts in a brittle manner [70]. Therefore, the anchorage length of bolts in concrete is an important parameter to consider to ensure the desired load capacity and behaviour of the connection.

3.5. Applications

CFS built-up concrete-filled composite columns offer various applications in structural engineering. These columns exhibit enhanced strength, ductility, and cost-effectiveness [1,2,70]. They are suitable for earthquake-resistant structures due to their high moment-resisting capacity and ductility [13]. Using innovative built-up concrete-filled CFS columns provides a reliable structural solution, as analytical predictions align well with experimental results when considering effective cross-sectional areas and buckling curves [12]. Additionally, incorporating fibre-reinforced concrete in composite columns significantly improves their load-carrying capacity, ductility, and energy absorption capabilities, outperforming conventional columns [8]. These versatile composite columns offer a sustainable and efficient option for various construction scenarios, making them a valuable choice in modern structural design and construction practices. Infilling concrete in the closed sections has been proven to be an effective approach to retard local buckling via providing internal restraint for inward buckling as well as increasing structural stiffness. Furthermore, formworks are not required for concrete casting [25–28].

Hoisting weight poses a significant restriction in modular design and construction. Maintaining consistent column sizes throughout buildings is critical for inter-module connection details in modular construction. If bare steel columns are used, thicker and larger sections are required for high-rise modular buildings, resulting in higher costs and reduced leasable floor space [1]. Lightweight composite columns can mitigate hoisting weight and maintain column sizes [3]. Adopting composite columns in modular construction further reduces hoisting weight, as the infill concrete can be cast in situ and separated from the module weight [12]. The versatility of CFS products allows exploration of new alternatives, for instance, concrete-filled CFS built-up columns with different geometric shapes using commercially available CFS profiles, which can also be beneficial for retrofitting purposes as strengthening solutions in critical areas of buildings [2]. Additionally, the fire resistance of composite columns, such as steel profiles partially encased in concrete, is notably better than that of unprotected steel columns, with the composite columns exhibiting superior behaviour under fire conditions [11].

3.6. Design Considerations

These findings underscore the need for improved design predictions to ensure accurate and reliable compressive strength assessments for concrete-filled CFS built-up section columns [2]. The ultimate compressive loads obtained from experimental results were compared with predictions from existing design codes to evaluate the applicability of relevant international codified provisions [1–3], including Eurocode (EC4) [22], Australia/New Zealand Standard (AS/NZS 2327) [37], and American Specification (AISI-S100-16) [51]. Additionally, numerical simulations were performed and calibrated against the experimental results to evaluate the validity of current design codes. Rahnavard et al. [1,12] found that the analytical predictions according to the EN 1994-1-1 [22] were conservative for square concrete-filled CFS columns and unconservative for rectangular sections. Various codal provisions for CFS columns with and without infill are listed in Table 1 and should be used for the detailed design of such columns. Modifications need to be adopted to replicate the same concept with a built-up section filled with SCGC.

Table 1. Design Standards for CFS columns with and without infill.

Design Standards	Investigation	Equations
AISI-S100-16 [51] and AS/NZS 4600 [19]	Design guidelines recommended for cold-formed built-up steel columns using the direct strength method (DSM)	■ $\overline{P} = \{Pd\ or\ Pa\} = \{\Phi cPn\ \ or\ \frac{Pn}{\Omega c}\},$ ■ $Pn = min\ \{Nce, Ncl, Ncd\}$ ■ $Nce = \begin{cases} \left(0.658^{\lambda_c^2}\right) Ny, & \lambda c \leq 1.5 \\ \left(\frac{0.877}{\lambda_c^2}\right) Ny, & \lambda c > 1.5 \end{cases}$ ■ $Ncl = \begin{cases} Nce, & \lambda l \leq 0.776 \\ \left[1 - 0.15\left(\frac{Nol}{Nce}\right)^{0.4}\right]\left(\frac{Nol}{Nce}\right)^{0.4} Nce, & \lambda l > 0.776 \end{cases}$ ■ $Ncd = \begin{cases} Ny, & \lambda d \leq 0.561 \\ \left[1 - 0.25\left(\frac{Nod}{Ny}\right)^{0.6}\right]\left(\frac{Nod}{Ny}\right)^{0.6} Ny, & \lambda d > 0.561 \end{cases}$ ■ Where $\lambda c = \sqrt{Ny/Noc}, \lambda l = \sqrt{Nce/Nol}, \lambda d = \sqrt{Ny/Nod}$ note: λ refers to the slenderness ratio of global, local, and distortional buckling, P refers to the design loads and N refers to the working loads
AS/NZS 2327 [37]	Design recommendation for steel–concrete composite columns	• Contribution of steel: $as = \frac{\phi Asfy}{Ns,Rd}$ • $0.2 < as < 0.9$ • Design buckling load: $N_{s,Rd} = k_f A_s f_y + A_c f_c + A_{sd} f_{sd}$; corresponding to area and yield strength • Since there is no reinforcement, design load: $N_{s,\ Rd} = k_f A_s f_y + A_c f_c$ • Form factor: $k_f = \frac{\lambda ep}{\lambda e} \leq 1$ (plastic/elastic) • Slenderness ratio $\lambda_e = \frac{h}{t}\sqrt{\frac{fy}{250}}$

The comparison with current design predictions according to the EN 1994-1-1 [22] also revealed that the predictions agreed with the test results when considering the specific contributions of steel and concrete and effective cross-sectional areas [1]. Modifications were also proposed to determine the effective area more accurately, considering the overlapping effect of the steel plates and the confinement provided by the concrete infill. The suggested prediction was obtained based on a reliability analysis, evaluating the safety of the design prediction [1,12]. In their tests on short columns, the authors also indicated a close agreement between the experimental tests and finite element models regarding deformation and load-bearing capacity, suggesting the reliability of these techniques for future parametric studies [12].

3.7. Methodology Adopted

This section reviews key methodologies adopted by researchers on integrating lightweight CFS framing concrete infill, utilising shear connectors to enable composite action and optimising the structural performance through innovative column designs and analytical modelling complemented with experimental investigation. A detailed, elaborate parameter listing is given in Table 2. Chen et al. [2] worked with five types of CFS built-up sections infilled with concrete of three different grades (C40, C80, and C120). The test program investigated the compressive behaviour of these columns, presenting details of material properties tests, stub column tests, compressive strength, axial load-shortening histories, load–strain responses, and failure modes. In other research conducted by Teoh et al. [3], an experimental investigation of lightweight aggregate concrete-filled cold-formed built-up box section (CFBBS) stub columns under axial compression was conducted. The study included a series of 32 CFBBS stub columns of different cross-section sizes infilled with three grades of lightweight aggregate concrete and bare CFBBS stub columns. The mechanical behaviours were analysed and reported, including failure modes, ultimate compressive load, and load–end shortening relationship. The structural performances were examined and compared through a set of performance indices, namely, concrete contribution ratio (CCR), strength index (SI), and ductility index (DI) [7]. Extensive strain analysis was performed to study the composite action of the CFBBS with concrete infill. Table 2 presents the various parameters that different researchers have considered.

Table 2. Specifications of parameters considered in various research.

Author	Individual Section (mm)	Composite Section (mm)	Thickness (mm)	Lips (mm)	Length (mm)	Intermediate Fastener Spacing (mm)	End Fastener Spacing (mm)	Diameter of Fastener (mm)	Depth of Penetration (mm)
Rahnavard et al. [12]	153 × 43, 150 × 43	Sq—153 × 153 Rec—153 × 89	1.5	20	1050	237.5	50	6.3	45
Rahnavard et al. [1]	153 × 43, 150 × 43	Sq—153 × 153 Rec—153 × 89	1.5	20	3000	362.5	50	6.3	45
Chen et al. [2]	-	100 × 41, 98 × 32, 86 × 54, 75 × 70	0.48, 0.6, 0.75, 1.0, 1.2	12, 15	300	100	20	4.8	12.5
Teoh et al. [7]	102 × 51	105 × 51	1.0	12	500, 650, 1000, 1300, 1500	235, 207, 243, 254, 245	15	4.76	NA
	75 × 40	78 × 41		8					
Teoh et al. [3]	102 × 51	105 × 51	0.6, 0.75, 1.0	12	300	90	15	4.76	NA
	75 × 40	78 × 41		8	230	67			

Teoh et al. [3,7], in another paper, presented an experimental investigation of the flexural buckling behaviour and resistance of innovative self-compacting lightweight concrete (LWSCC)-filled cold-formed built-up box section (CFBBS) columns, classifying these as slender columns with length as long as 1 m. The study involved a series of sixteen LWSCC-filled CFBBS columns and four reference hollow columns tested under pin-ended boundary conditions. The experimental investigation scrutinised the specimens' failure modes, deformation developments, lateral deflection distribution, flexural buckling resistance, and load–end shortening relationships, considering the effects of parameters and the associated coupling effects. The dominant failure modes observed were local buckling or interaction between local and flexural buckling [3,7]. The overlapping of plates in the built-up sections did not alleviate the premature local buckling inherent in CFS. The concrete infill enhanced the load-carrying capacity and delayed the local buckling of the CFBBS. The lightweight aggregate concrete-filled CFBBS exhibited higher ultimate loads than the hollow sections [7]. Strain analysis revealed that the concrete infill provided confinement of the steel sections, with the degree of confinement increasing with higher concrete strength. The concrete infill also prevented the inward local buckling of the steel walls [3].

Rahnavard et al. [1,11,12,23] focused on four distinct configurations of concrete-filled CFS columns and documented the test setup, load-bearing capacity, load–deformation behaviour, and failure modes. The study also investigated the buckling behaviour of the steel components and the mitigation of local buckling caused by concrete supporting thin-walled plates. The investigation involved testing twelve concrete-filled CFS built-up slender composite columns under concentric axial load, revealing the tested columns' axial behaviour and failure modes [1,12]. The study also included a detailed description of the experimental setup, material properties, and test configurations, along with the geometric details of the concrete-filled CFS composite columns [1,11,12]. The results included axial capacity, lateral deformations, strain gauge readings, and numerical modelling [1,12]. In another paper, Rahnavard et al. [12] studied experimental and numerical analyses of the same cross sections, comparing the numerical results with the predictions of EN 1994-1-1 [22]. The composite columns, comprising different combinations of C-shaped and U-shaped profiles, were filled with lightweight concrete and were as long as 3 m, classified as slender columns. The effect of fastener depth influenced the bearing capacity of the columns, which was not noticed in other studies as the penetration depth was relatively small [1,12]. Composite solutions are suitable to prevent local buckling phenomena, allowing the total capacity of steel to be more effectively exploited, leading to optimal material consumption and enabling the use of high-strength CFS [1,11,12]. Table 3 presents the details of steel contributions and buckling loads obtained from experiments in all the studies indicated.

Table 3. The contribution of steel and experimental buckling load.

Author	Specimen	Area of Steel (mm^2)	Area of Concrete (mm^2)	Area of Composite Column (mm^2)	Percentage of Steel (%)	Yield Strength (MPa)	Buckling Load (kN)	Contribution of Steel (a_s)
Rahnavard et al. [11,12]	R-2C+2U (3)	1485	12,121.5	13,606.5	10.91	306.81	704.12	0.6
	S-2C+2U (3)	1485	21,720	23,205	6.40	306.81	976.72	0.4
	R-2Σ+2U (3)	1540	8912.8	10,452.8	14.73	306.81	603.63	0.7
	S-2Σ+2U (3)	1540	18,307.1	19,847.1	7.76	306.81	856.96	0.5
Chen et al. [2]	AT0.75-C120	299	7657	7956	3.76	550	994.8	0.1
	C80	302	7784	8086	3.73	550	607.8	0.2
	C40	302	7733	8035	3.76	550	338.5	0.4
	AT1.2-C120	511	7879	8390	6.09	500	1041.8	0.2
	C80	509	7783	8292	6.14	500	707.9	0.3
	C40	514	7742	8256	6.23	500	402.3	0.6
	BT0.75-C120	261	4572	4833	5.40	550	605.3	0.2
	C80	259	4441	4700	5.51	550	358.6	0.4
	C40	261	4655	4916	5.31	550	221.5	0.6
	BT1.2-C120	420	4973	5393	7.79	500	619.8	0.3
	C80	423	4874	5297	7.99	500	465.3	0.4
	C40	423	4971	5394	7.84	500	320.5	0.6
	CT0.6-C120	216	4878	5094	4.24	550	571.7	0.2
	C80	215	4870	5085	4.23	550	375.5	0.3
	C40	214	4827	5041	4.25	550	229.9	0.5
	CT1.0-C120	412	4565	4977	8.28	500	536.6	0.3
	C80	417	4585	5002	8.34	500	405.9	0.5
	C40	417	4577	4994	8.35	500	340.6	0.6
	CT1.2-C120	505	4547	5052	10.00	500	625.9	0.4
	C80	506	4577	5083	9.95	500	484.6	0.5
	C40	499	4560	5059	9.86	500	415	0.5
	DT1.0-C120	411	3847	4258	9.65	500	580.6	0.3
	C80	409	3856	4265	9.59	500	345.1	0.5
	C40	413	3879	4292	9.62	500	294.7	0.6
	ET0.48-C120	210	5914	6124	3.43	550	718.9	0.1
	C80	210	5957	6167	3.41	550	502.5	0.2
	C40	211	5902	6113	3.45	550	205.8	0.5
	ET1.0-C120	418	5911	6329	6.60	500	791.3	0.2
	C80	409	5998	6407	6.38	500	511	0.4
	C40	410	5828	6238	6.57	500	281.1	0.7
Teoh et al. [3,7]	102 × 51 × 1-LC20	434.3	4366	4800.3	9.05	550	323.7	0.7
	LC30	434.3	4366	4800.3	9.05	550	337.5	0.6
	LC40	434.3	4366	4800.3	9.05	550	449.8	0.5
	75 × 40 × 1-LC20	323.7	2536	2859.7	11.32	550	246.4	0.7
	LC30	323.7	2536	2859.7	11.32	550	250.3	0.6
	LC40	323.7	2536	2859.7	11.32	550	282.2	0.6
	75 × 40 × 0.75-LC20	246.4	2536	2782.4	8.86	550	185.7	0.7
	LC30	246.4	2536	2782.4	8.86	550	171.8	0.7
	LC40	246.4	2536	2782.4	8.86	550	262.1	0.5
	75 × 40 × 0.6-LC20	197.9	2536	2733.9	7.24	550	168.4	0.6
	LC30	197.9	2536	2733.9	7.24	550	175.5	0.6
	LC40	197.9	2536	2733.9	7.24	550	234.9	0.4

4. Discussions and Suggestions for Future Research

This study provides valuable insights into the influence of concrete infill strength and section slenderness on structural performance. The performance of composite action between steel and concrete contributes to understanding the structural behaviour of lightweight aggregate concrete infill and its potential applications in lightweight and modular construction. Table 3 focuses on the buckling loads obtained for various column sections when the authors used different configurations. Also, the contribution of steel, when increased, eventually improved the performance of these columns. Research on the effects of mid, end, and edge stiffeners, which contribute to the utilisation of various cross sections, requires additional information to enable exploration of the potential of built-up CFS columns.

Improvements in compressive strength were noticed with the effects of fasteners and the spacing between them. The necessity of using fasteners considering parameters like diameter, penetration depth, and the effects of spacing (both intermediate and end) influenced the capacity of the column to yield accurate strength predictions. However, there is scope for studying the influence of fasteners that provide shear resistance between concrete and steel and can yield additional strength via creating a composite action.

The concrete infill was able to delay the occurrence of local buckling in built-up columns and improved the longitudinal strain development, increasing its material utilisation. The value of the steel–concrete ratio (a_s) influenced the concrete infill strength, and a higher concrete infill strength and a larger h/t ratio led to higher capacity. Using geopolymer concrete instead of conventional concrete for built-up CFS-concrete composite columns offers a promising avenue for enhancing structural efficiency, sustainability, and durability. Through this innovative approach, we can harness the superior mechanical properties and environmental benefits of geopolymer concrete while capitalising on the inherent advantages of steel–concrete composite systems.

Through incorporating geopolymer concrete, we can reduce the carbon footprint, enhance structural performance, and contribute to the evolution of sustainable construction practices. This review underscores the potential of geopolymer concrete to revolutionise the design and construction of built-up CFS-concrete composite columns, paving the way for a more resilient and eco-friendly built environment.

5. Conclusions

Against the background of the advantages and widespread use of conventional concrete-filled steel tubular columns, a new technique utilizing built-up steel sections instead of tubular sections has emerged. This research delved into the extensive experimental and numerical investigations of the flexural and axial behaviour of concrete-filled built-up CFS sections to evaluate the effectiveness of engineering design codes in predicting the buckling resistance of such columns. This paper reports the load-carrying capacities, load–deformation behaviours, and buckling modes of the tested columns to compare the numerical results and propose a tailored approach for governing the productive cross-sectional areas of CFS columns. This study indicates that the composite action of steel and concrete obtained with the inclusion of screw fasteners to connect the steel sections to form a built-up section embedded deep in the concrete significantly enhances the load-bearing extent of the column. The experimental campaign demonstrated that the performance of the composite columns was influenced by the concrete infill, with the contribution of the steel part as well as the fasteners demonstrating the advantage of the composite solution in mitigating local buckling phenomena and increasing bearing capacity.

However, maximising its potential requires innovative approaches and the best of these involve combining it with GPC to form a composite section. This combination has the potential to revolutionise column design in construction, offering enhanced strength, durability, and sustainability. Comprehensively, researchers have presented valuable experimental data and validated numerical models relating to the structural capabilities of concrete-filled CFS built-up columns, highlighting their potential as efficient composite systems that can be alternated with GPC. The research emphasises the growing adoption of built-up cold-formed members within structural engineering, attributing this trend to their benefits such as reduced weight, simplified construction, enhanced flexibility, and their sustainable nature as well as their incorporation of a carbon-neutral sustainable concrete material. The findings assert that modifying the structural elements of composite columns can potentially influence design standards and construction practices in the industry.

In conclusion, employing SCGC as an infill in concrete-filled built-up CFS columns presents a compelling solution, offering enhanced structural performance, improved construction efficiency, and sustainable building practices. Through combining the superior flowability and self-compacting nature of SCGC with the inherent strength and versatility of CFS, this innovative approach not only ensures optimal load transfer and structural integrity but also contributes to the reduction of carbon footprint and overall environmental impact, thereby fostering the advancement of resilient and eco-friendly construction methodologies.

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