Concrete-filled steel tube columns of different cross-sectional shapes under axial compression: A review

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Abstract. This paper presents a review on the axial compression behavior of different cross-sectional shaped concrete-filled steel tube (CFST) columns such as circular, rectangular, square, elliptical, hexagonal, octagonal and round-ended. A discussion on some special shapes like triangular, D-shape, ¼ circular, fan shape etc. is also done in this paper. Confinement offered by the varying cross-sectional shape steel tubes to concrete core, material strength limits and slenderness limits available in different codes of practices and the proposed yield slenderness limits for rectangular, elliptical and octagonal cross-sections are discussed. The failure modes encountered during the axial compression test on CFST columns are mentioned. An analysis on the parameters that influence the behavior of the columns, design equations in the current codes of practice, modifications made on the code design equations, equations proposed on the determination of compressive strength of different cross-sectional shapes of CFST columns is done. Unified formulas for two different cross-sectional shapes and solid and hollow concrete-filled steel tubes are also included. Conclusions are finally made based on the discussion done.

Key words: CFST, cross-sectional shapes, compressive strength.

1. Introduction

Concrete-filled steel tubes (CFSTs) are being used effectively in the construction industry as columns of mid-rise and high rise buildings, in bridge as piers and piles, submarine pipelines, and other engineering structures. CFST are known for their high ductility, high stiffness, greater energy absorption and, greater seismic and fire resistance [1]. Concrete filled steel tube column comprises a concrete core in hollow steel tube with or devoid of additional reinforcement. A concrete-filled steel tube can have either a solid or hollow concrete core. This paper discusses the literatures on steel tubes having solid concrete core without reinforcement.

Steel tubes of circular, rectangular and square are the regularly employed cross-sections in CFST column construction. The square section is considered as an exceptional type of rectangular section. For architectural reasons, hexagonal, octagonal, elliptical and round-ended shapes are used in CFST. The elliptical hollow section has varying radius of curvature around its perimeter [2]. The hexagonal shape can be regular and dual-axisymmetric. The regular hexagonal shape has equal lengths on all sides with an
interior angle of 120° whereas; dual-axisymmetric shape has equal lengths on all sides with four interior angles of 135° and two interior angles of 90° in the opposite directions. The regular shape of hexagonal column has higher load carrying capacity than its dual-axisymmetric shape column and its steel tube shape closely resembles a circular tube [3]. Octagonal hollow section lies anywhere between circular and square hollow section and is used as transmission poles, lattice towers and telegraph towers [4]. Round-ended rectangular column (RRCFST) is a hybrid column of two different shapes. It can resist the impact of running water with its smooth rounded corners and hence using RRCFST columns as piers can reduce the force of running water and increase the life time of the bridge using such piers [5]. Columns with special shapes such as L-shape, T-shape, triangular, fan-shape, D-shape, 1/4 circular, semi-circular, round-ended, rhombic, T-shape, plus shaped, pentagram, and fan-shape are some of the recent additions to the tubular family.

2. Interaction between concrete core and steel tube
The concrete-steel interface is a region where most of the stress transfer takes place in a composite column. The combined action of steel and concrete in this region is integral as it contributes to high strength and ductility of the column. Steel provides lateral confinement to the infill concrete in a passive way and reduces shrinkage of concrete. Circular steel sections are found to provide the strongest confinement compared to rectangular/square, hexagonal and special-shaped sections such as triangular, Fan, D-shaped, 1/4 circular and semi-circular sections. The confinement of the square/rectangular steel tube to the core concrete is strongest at the corners than at the center. The confinement in elliptical CFST column lies between that in rectangular and circular tube and is a function of the aspect ratio of the section [6]. The confinement effect is assumed to be between those of circular and rectangular CFSTs in hexagonal CFST column and the confinement effect is more at the corner regions than at the center of the core concrete [7]. The confinement is greater at the corners and at the mid-point of the core concrete in octagonal CFST columns [8] and is found to be superior to square CFST columns [9]. For round-rectangular CFST columns, the concrete area in the rounded ends of the column has the strongest confinement and that in the straight edge has the weakest confinement [10]. Concrete core in special-shaped (triangular, Fan, D-shaped, 1/4 circular and semi-circular sections) CFST columns are also confined by the steel tube and is similar to square/rectangular hollow section columns [11]. The confined areas of concrete infill by steel under axial compression in different cross-sectional shapes are shown in Figure 1.
Figure 1. Confined and unconfined areas in different cross-sectional shaped CFST columns under axial compression (a) Circular CFST, (b) Square/Rectangular [19], (c) Round-ended rectangular CFST [10], (d) Hexagonal CFST [13], (e) Octagonal CFST [8].

The arching action of the ineffectively confined concrete in rectangular CFST columns occurs in the form of a second-degree parabola with an initial tangent slope of 45° [12]. The confinement effect in hexagonal steel tube is observed in the corner areas and the center area of core concrete (A_{c2}) while, the length of un-constrained areas (A_{c1}) is approximately 3/5b (b is the edge length of concrete core) [13]. 33% of the total area of concrete core is therefore unconfined [3]. For octagonal CFST columns, the length of unconfined area (A_{c1}) is approximately 2/3b (b is the edge length of concrete core) and the effectively confined area (A_{c2}) in octagonal section is nearly 70% of the total cross-sectional area of the octagonal column [8].

3. Materials for CFST columns

3.1 Hollow steel tubes

Mild steel, cold-formed steel and high strength structural steel are the general types of steel used in CFST columns. The stress-strain curve for mild steel is marked by a typical yield plateau. The stress-strain curve of cold-formed steel is rounded and the rounded stress-strain curve is replaced by a straight line for high strength steel.

Tensile coupon test on steel is generally carried out to determine the material characteristics. Coupons are generally obtained from corner, curved and flatter regions of the hollow tubes depending upon the shape of the tube. Width-to-thickness ratio (B/t) and diameter-to-thickness ratio (D/t) of steel plates are widely used to determine the performance of rectangular and circular CFST columns and as a measure to prevent local buckling. Steel strength is taken either in the form of $\frac{\sigma}{f_y}$ or $\frac{E}{f_y}$. ANSI/AISC 360 [14] divides CFT columns into compact, non-compact and slender sections. Table 1 shows the maximum allowable limits on steel tube yield strength and yield slenderness by few design codes.
Table 1. Yield slenderness limits and yield stress limits in hollow steel sections.

| Country | Code | Cross-section Shape | Yield slenderness limits | Yield stress \( f_y \) MPa |
|---------|------|---------------------|--------------------------|--------------------------|
| USA     | ANSI/AISC 360 [14] | Circular | \( \leq 0.15 \left( \frac{E_s}{f_y} \right) \) | \( \leq 525 \) |
|         |       | Rectangular | \( \leq 2.26 \sqrt{\left( \frac{E_s}{f_y} \right)} \) |            |
|         |       | Non-compact/ slender sections | Circular | \( \leq 0.19 \left( \frac{E_s}{f_y} \right) \) |            |
|         |       |         | Rectangular | \( \leq 3 \sqrt{\left( \frac{E_s}{f_y} \right)} \) |            |
| Europe  | EC4 [15] | Circular | \( \leq 90 \left( \frac{235}{f_y} \right) \) | 230 to 460 |
|         |       | Rectangular | \( \leq 42 \sqrt{\left( \frac{235}{f_y} \right)} \) |            |
| Australia | AS 5100-6 [16] | Circular | \( \leq 82 \left( \frac{250}{f_y} \right) \) | 230 to 400 |
|         |       | Rectangular | \( \leq 35 \sqrt{\left( \frac{250}{f_y} \right)} \) |            |
| USA     | ACI 318 [17] | Circular | \( \leq \frac{8}{3} \left( \frac{E_s}{f_y} \right) \) | - |
|         |       | Rectangular | \( \leq 3 \left( \frac{E_s}{f_y} \right) \) |            |

*E_s* - Young’s modulus of steel

3.1.1 Proposed yield slenderness limits and cross-section classification. Hollow steel sections are generally classified between Classes 1-4. Under axial compression, Class 1-3 sections reach their ultimate loads before local buckling and Class 4 sections encounter local buckling before reaching their ultimate loads. Therefore, Class 1-3 sections or non-slender sections have thicker walls than Class 4 sections or slender sections. It is seen from Table 1 that, limits on slenderness in standard codes of practice are found only for circular and rectangular cross-sections. Therefore, due to the lack of code limits, researchers have proposed slenderness limits for the sections such as elliptical and octagonal sections. An extension of the slenderness limit for rectangular section is also included in this section. Design recommendations in rectangular CFST columns for width-to-thickness (h/t) were proposed by Du et al. [18] for EC4, AISC 360, the Chinese code GB 50936 and, by Du et al. [19] for the Chinese code DB 29-57 to extend the code limits to cover high strength steel. Yield slenderness limits on elliptical hollow sections (EHS) were given by Chan and Gardner [20], Teran and Gardner [21] and Zhao and Packer [22]. A new slenderness limit for octagonal cross-section was given by Zhu et al. [4] and, in accordance with EN 1993-1-1, ANSI/AISC 360-16, ASCE/SEI 48-11 and the Direct Strength Method (DSM) incorporated in North American code AISI 100-16 was given by Chen et al. [23]. Table 2 shows the proposed yield slenderness limits for rectangular, elliptical and octagonal hollow sections.
**Table 2.** Proposed yield slenderness limits.

| Cross-sectional shape | Author | Code | Yield slenderness limits |
|-----------------------|--------|------|-------------------------|
| Rectangular           | Du et al. [18] | EC4 | \( h/t_e = -12h/b + 62 \) |
|                       |        | AISC 360 | \( h/t_\beta = -0.77h/b + 2.79 \) |
|                       |        | GB50936 | \( h/t_e = -7.5h/b + 65 \) |
| Elliptical [20]       | Gardner and Chan [20] | - | \( \frac{D_{e1}}{t e^2} = 2 \frac{a^2/b}{te} \) |
|                       |        |        | Equivalent circular diameter \( D_{e1} = 2(a^2/b) \) |
|                       | Teran and Gardner [21] | - | \( \frac{D_{e2}}{t e^2} = 2a \left[ 1 + f \left( \frac{a}{b} - 1 \right) \right] \) |
|                       |        |        | Equivalent circular diameter \( D_{e2} = 2a \left[ 1 + f \left( \frac{a}{b} - 1 \right) \right] \) |
|                       |        |        | Coefficient \( f = 1 - 2.3(t/2a)^{0.6} \) |
|                       | Zhao and Packer [22] | - | \( \frac{D_{e3}}{t e} = 2(a-t) \) |
|                       |        |        | Equivalent rectangular hollow section diameter \( D_{e3} = 2(a-t) \) |
| Octagonal [4]         | Zhu et al. [4] | EN 1993-1-1 | \( b/t \leq 29.8 \sqrt{235/f_y} \) |
|                       |        | ANSI/AISC 360-16 | \( b/t \leq 34.1 \sqrt{235/f_y} \) |
|                       |        | ASCE/SEI 48-11 | \( b/t \leq 2.01 x \frac{260}{\sqrt{f_y}} \) |
|                       |        | DSM | \( \lambda_p^d \leq 0.653 \) |

\( \lambda_p \) – overall cross-section slenderness.

### 3.2 Concrete

Different strengths of concretes such as normal strength, high strength and ultrahigh strength concrete (UHSC) are generally filled in the steel tubes. Special concretes like self-compacting concrete (SCC) and lightweight concrete (LWC) are also used as infill in steel tubes. SCC in concrete-filled tubes has become popular due to reduced sound and injuries connected to vibration of concrete, higher workability characteristics, higher load capacity, inherent ductility and toughness [7, 22, 24]. LWC has been used in composite construction for its low thermal conductivity and low specific gravity, reduced self-weight of
the structure [25]. Lightweight CFST was 15.3% and 26% lighter than normal concrete-filled steel tube columns [1, 25]. The methods to increase the compressive strength of CFST columns are to use large cross-sections and to use high-strength materials. Therefore, the use of high-strength steel tubes with yield strength ≥ 460MPa has attracted much attention. High strength materials in CFST can reduce the size of the member. High strength steel of Q345 or above should be combined with C100 or above grade concrete and a steel ratio not less than 20% is recommended by Zhou et al. [33] for UHSC filled steel tube column to ensure sufficient ductility. For special-shaped CFST columns, the designers are recommended to attempt higher steel tube strengths by Wang and Han [11]. It is suggested to limit the use of expansive agent in ultra-high performance concrete filled steel tubes to 12% by Huang et al. [53]. Table 3 gives the limitations on the concrete compressive strengths in different codes of practice.

Table 3. Compressive strength limits specified in codes of practice.

| Code            | Concrete strength (MPa) limits |
|-----------------|-------------------------------|
| ANSI/AISC 360-16 [14] | 21 to 70                     |
| EC4 [15]        | 20 to 50                      |
| AS 5100-6 [16]  | 25 to 65                      |
| ACI [17]        | ≥ 17.2                        |

4. Failure modes

From the literatures it is found that the failure mode that affected the strength of stub and short members was the local buckling or yielding of the steel tube. Overall (half-sine) buckling affected the strength of long or slender members. Intermediate members failed by combined yield, overall buckling and/or local buckling. Buckling of steel tubes followed the failure of concrete core by shear and crushing. Failures like elephant foot buckling, drum-type, crippling in thin tubes were also observed. Weld crack was observed at the corners of certain specimens due to poor ductility of the weld. Hollow steel tubes and concrete-filled steel tubes showed a difference in the orientation of local buckling. Inward and outward buckling was observed in hollow steel tubes whereas CFST column failed by only by outward buckling due to the presence of concrete infill. Figure 2 shows the different failure patterns in CFST columns.
5. Parametric study

5.1. Concrete compressive strength ($f_c$)
Smaller confinement effect was observed in steel tubes filled with high strength concrete irrespective of the shape of the steel tube as the stiffness of the concrete increases with the concrete strength [25, 26, 27]. Increasing the value of compressive strength of concrete increased the bearing capacity of the CFST columns [3, 10, 23, 27, 28, 29]. High strength concrete core in CFST columns contributed to more compression load capacity for thinner tube [27]. Higher concrete strength improves the load bearing capacity of CFST columns especially those with smaller steel ratio [10]. Higher concrete compressive strength and strength of steel tube contributes to moderate improvement in the load carrying capacity of CFST columns filled with UHSC [30].

5.2. Steel tube thickness ($t$) and Steel yield strength ($f_y$)
The resistance of CFST columns increases with increase in steel yield strength [3, 7, 8, 13, 27]. The performance of concrete-filled steel tubular columns increases by increasing the thickness of steel tube [6, 10, 22, 26, 30].

5.3. Steel ratio ($\alpha$)
Steel ratio is given by the ratio of area of steel to the total area of cross-section. For circular lightweight concrete-filled steel tube columns, low steel ratio showed better strength [32]. Improvement in load bearing capacity of CFST columns can be achieved with high steel ratio, low concrete grade and high strength steel [5, 7, 34].

5.4. Ductility
Ductility is the ability of a structure to maintain deformation beyond the elastic limit at the same time, maintaining a reasonable load carrying capacity until total failure [35]. The ductility index is influenced...
by the cross-section shape of the CFST column [32, 35, 36]. Ductility decreases in CFST columns filled with high strength concrete than steel tubes filled with low strength concrete [7, 8, 10, 13, 19, 28, 37, 39]. Stub columns have shown a higher ductility than that of the long columns. Higher ductility was observed in CFST columns that were shorter, bigger in diameter and filled with low strength concrete than columns with smaller diameters and high strength concrete infill [26]. Increase in steel ratio increases the ductility of CFST columns [8, 32, 34]. Increase in steel tube thickness offers better ductility to the CFST columns [6, 10, 27] and a bigger B/D ratio gives columns with weaker ductility [10]. High-strength steel in CFST columns demonstrates better ductility when lower D/t ratio and lower h/b ratio is used [18]. Ductility increases with increase in yield strength [27]. By applying the load on the concrete core only and by using by using Class 1 steel sections or by adopting higher steel contribution ratio, improvement in ductility and strength of UHSC filled composite columns can be observed [38]. The confinement index should not be taken > 3.0 for square ultra-high performance CFSTs [3]. An axial expansion of 5mm out of the steel tube by the lightweight concrete infill showed the ductile behavior of lightweight concrete-filled steel tubes [1].

5.5. Slenderness ratio
Greater flexibility, larger sideways displacement at the mid-height and lesser stiffness is observed in columns with large slenderness ratio [24, 29, 39].

5.6. Effect of steel fibers
Addition of steel fibers to UHSC increases the shear strength of concrete and the ultimate resistance of the column. Also, for the CFSTs with Class 2 or Class 3 sections, the ductility was improved compared to CFSTs with the plain UHSC [38].

5.7. Strength index
The strength index (SI) is the ratio between the calculated capacity of the column and the actual ultimate load on the column. Higher SI shows a stronger confinement of steel tube to concrete core and a delay in local buckling in the steel tube [30, 39]. SI of CFST columns increase with decrease in the D/t ratio [3]. Change in shape of cross-section decreases the SI [50]. The SI decreases as the width-to-thickness and aspect ratio increases and also the increase of confinement index (ξ) might not contribute to the increase of SI [19]. Slender columns had lower SI than short and intermediate length columns [27]. Increasing the confinement index does not give in high capacity for the rectangular CFST columns with high strength steel and results in the decrease of SI [19]. Use of high-strength steel in rectangular CFT columns showed high bearing capacity, low strength index and weaker confinement with increased D/t ratio and h/b ratio [18]. Parent hot-rolled circular concrete filled specimens showed larger SI values than the cold-formed elliptical CFST specimens [31].

5.8. Width to thickness ratio
The confinement given by the steel tube to concrete core decreased with bigger B/D ratio in round-ended rectangular stub CFST column specimens [10].

5.9. Concrete contribution ratio
Concrete contribution ratio (CCR) is defined as ratio of the ultimate load of the CFST column to the corresponding ultimate load of bare hollow steel tube. As the steel tube thickness decreases, CCR decreases [10]. CCR reduces with increase in width-to-thickness ratio and also with the increase of confinement index [19].
6. Axial load carrying capacity of CFST columns

6.1 Design equations from code of practices

Extensive research and the practical application of CFST construction has lead the way to develop design codes in many countries. Empirical formulae to predict the resistance of different cross-sections to compression from the codes of practice is shown in Table 4 (a) and (b).

ANSI/AISC 360 gives the formula to calculate the axial load carrying capacity of columns on the basis of compact, non-compact and, slender section that considers the critical buckling stress $f_{cr}$. For non-compact sections, the plastic strength $P_p$ and the yield strength $P_y$ of the composite section are considered.

For compact sections, the compression capacity of the section is equal to the plastic strength of the composite section. The advantage of the effect of confinement provided by the circular steel tube is considered in the European code EC4 by applying an enhancement factor $\eta_c$ and the reduction in the yield strength of the steel tube with diameter $D$, due to the lateral expansion of concrete is considered by applying the reduction factor $\eta_a$. The relative slenderness $\lambda$, elastic critical force $N_{cr}$, effective flexural stiffness (EI)$_{eff}$ and the plastic resistance of the composite section to compressive normal force $N_{pl,Rk}$ are calculated as shown in Table 4. The Australian standard AS 5100-6 has similar formula as EC4 for calculating the compressive resistance of circular section under axial compression and uses the capacity factors $\varnothing, \varnothing_c$. A single equation is used in ACI 318-11 for calculating the compressive load carrying capacity of circular and rectangular sections. In the following equations, area of steel, area of concrete, strength of steel, strength of concrete, second moments of area of the steel and the concrete are denoted by $A_s, A_c, f_y, f_c, I_s$ and $I_c$ respectively.

Table 4. Design equations from codes for compressive load carrying capacity of CFST columns.

| Code                      | Cross-section shape | Equation for axial load ($N_u$) carrying capacity of CFST column |
|---------------------------|---------------------|-----------------------------------------------------------------|
| ANSI/AISC 360 (2005) [14] | Circular            | $N_u = A_s f_y + 0.95A_c f_c$                                   |
|                           | Compact             | $N_u = P_p - \left[ P_p - P_y / (\lambda_r - \lambda_p) \right] (\lambda - \lambda_p)^2$ |
|                           | Non-compact         | $\lambda_p = 0.15E_s / f_y, \lambda_r = 0.19E_s / f_y$         |
|                           | Slender             | $N_u = A_s f_{cr} + 0.7A_c f_c$                                 |
|                           | $f_{cr} = 0.72 f_y \left( \frac{D}{t} \right) \left( \frac{f_y}{E_s} \right)^{0.21^{-1}}$ |
|                           | Rectangular         | $N_u = A_s f_y + 0.85A_c f_c$                                  |
|                           | Compact             | $N_u = P_p - \left[ P_p - P_y / (\lambda_r - \lambda_p) \right] (\lambda - \lambda_p)^2$ |
|                           | Non-compact         | $P_y = A_s f_y + 0.7A_c f_c$                                   |
6.2 Validation of the design equations from codes

EC4 gave reasonable predictions for axial load carrying capacity of circular CFST columns [1, 25, 26, 27, 51, 52, 53]. Also, it is suggested by Xiong et al. [38] that for circular CFST columns filled with UHSC or when Class 3 sections are not used, the confinement effect in EC4 should be ignored. Calculated results using design equations in EC4 were closer to experimental results of rectangular and square [26, 35, 27, 58], elliptical [6, 22, 24], hexagonal [7, 32], octagonal [32], triangular [32] and special-shaped [50] CFST columns subjected to axial compression. The South African code SANS 10162-1 and the Japanese code AIJ also gave satisfactory predictions for axially loaded circular CFST columns [26, 54].

The Chinese code DBJ /T13-51-2010 can be used to compute the compression strengths of square and rectangular [52, 54], hexagonal [7] and special-shaped [50] CFST columns. The compression strength of rectangular CFST columns can be calculated using the codes ACI 318 [54, 57] and GB 4142-2000 [54]. The code ANSI/AISC 360 predicts well for circular [27] and elliptical [55] CFST columns under axial compression.

6.3 Design equations modified and proposed

Apart from the equations given in codes, equations were also proposed by researchers. A summary of the equations proposed for concrete-filled steel tubes of different cross-sectional shapes are shown in Table 5 (a), (b) and (c). For circular stub CFST columns, Lu and Zhao [41] proposed modified equations for the design codes AIJ (Japanese), ACI, AS, AISC, EC4, DL/T (Chinese) and Han et al. [59]. Equations were proposed by Ding et al. [40] to predict the ultimate capacity \( N_u \) or ultimate strength \( f_{sc,u} \) of centrally loaded circular CFT stub column, by Xue et al. [43] to calculate the ultimate load capacity of circular CFST stub columns with de-bonding \( N_{ud} \) given as the product of ultimate load capacity of specimens without debonding \( N_u \) and debonding reduction factor \( K_d \), by Wang et al. [45] for the axial bearing capacity of circular CFT that considered the size effect. For lightweight concrete-filled steel tube columns,

| ANSI/AISC 360 (2005) [14] | Rectangular Slender | \( N_u = A_s f_{cr} + 0.7 A_c f_c \) |
|---------------------------|----------------------|-------------------------------------|
|                           | \( f_{cr} = 0.9 E_s (B/t)^2 \) |
| EN1994-1-1 (2004) [15]    | Circular             | \( N_u = \eta_a A_s f_y + A_c f_c \) |
|                           | \( \eta_a = 0.25(3 + 2\lambda) \leq 1.0 \) |
|                           | \( \eta_c = 4.9 - 18.5\lambda + 17\lambda^2 \geq 0 \) |
|                           | \( \lambda = \left( \frac{N_{pl,ke}}{N_{pl,kr}} \right)^{1/2} \) |
|                           | \( N_{pl,ke} = A_s f_y + 0.85 A_c f_c \) |
|                           | \( N_{cr} = \pi^2 (EI)_{eff} / L^2 \) |
| AS 5100-6 (2004) [16]     | Rectangular          | \( N_u = \emptyset A_s f_x + \emptyset A_c f_x' \) |
|                           | \( \emptyset = 0.9, \emptyset_c = 0.6 \) |
|                           | Circular             | \( N_u = \emptyset A_s f_y + \emptyset A_c f_c \left( 1 + \frac{\eta_s f_y}{D f_c} \right) \) |
| ACI 318-11 (2011) [17]    | Circular and Rectangular | \( N_u = A_s f_y + 0.85 A_c f_c \) |
equations were proposed by Zhongqiu et al. [42] and Fu et al. [44] by considering a coefficient of lateral deformation $\nu$ and a lateral pressure coefficient $k$.

Using the principle of superposition, new equation was proposed by Ding et al. [28] for calculating the ultimate bearing capacity axially-loaded square CFT stub columns with a confinement factor 1.2, Ding et al. [13] for ultimate strength of hexagonal CFT stub column with a confinement factor 1.3, Ding et al. [8] for the ultimate load bearing capacity of axially loaded octagonal CFT stub columns with a confinement factor of 1.5.

The axial compressive bearing capacity of the square ultra-high performance CFST short columns was proposed by Yan et al. [30]. The limitations in DB 29-57 was extended using a new method proposed by Du et al. [19] to include steel grade 460 MPa in designing rectangular CFT columns. The axial load carrying capacity of the elliptical CFST stub columns was proposed by Uenaka [46] and the re-estimations $(N_{rest-A}, N_{rest-B})$ were calculated with concrete strength induced by two confined stress in larger and smaller directions $c\sigma_{cbA}$, $c\sigma_{cbB}$ respectively. To design regular hexagonal CFST short columns in compression with internal angle $\theta = 120^\circ$, an equation was proposed by Hassanein et al. [3]. A new formula for lateral confinement pressure $f_{pl}$ was also proposed. Equations for round-ended rectangular CFST stub and short columns were proposed by Faxing et al. [10] and Hassanein and Patel [5] respectively. Unified formulas to predict the axial load bearing capacity for circular hollow and solid concrete-filled steel tube columns, and for circle and polygon CFST columns under axial compression were proposed by Yu et al. [47] and Yu et al. [48] respectively. A simple superposition model to predict the ultimate strength for both circular and rectangular CFST stub columns under axial compression was given by Wang et al. [49].

Table 5. Equations proposed by various researchers for different cross-sectional shapes.

| Cross-section | Author | Year | Proposed equation on ultimate bearing capacity of axially loaded columns $(N_u)$ |
|---------------|--------|------|--------------------------------------------------------------------------------|
| Circular      | Lu and Zhao [41] | 2010 | $N_u = f_{cyl,100} a A_c + 1.4 f_y A_s$ (for AIJ) |
|               |        |      | $N_u = f_{cyl,150} b A_c + 1.47 f_y A_s$ (for ACI, AISC, AS) |
|               |        |      | $N_u = \left( 1 + 1.8 \frac{f_y}{f_{cyl,150}} \right) f_{cyl,150} + f_y A_s$ (for EC4) |
|               |        |      | $N_u = (1.3 + 1.1 \xi^c) f_{pl} (A_s + A_c)$ (for DL/T and Han et al.[59]) |
|               | Ding et al.[40] | 2011 | $N_u = f_y A_c (1 + 1.7 \xi), f_{sz,u} = (1 + \rho)(1 + 1.7 \xi) f_c, \xi = \frac{A_s}{A_c}$ |
|               | Zhongqiu et al. [42] | 2011 | $N_u = 1.35 (f_y A_s + f_y A_c)$ |
|               | Xue et al.[43] | 2012 | $N_D = K_0 N_u$ |
|               |        |      | $K_D = \begin{cases} 1 - \alpha_1 R_d \\ 1.015 - 0.3 \alpha_1 - 0.05 R_d \end{cases}$ $\begin{cases} (0 \leq R_d \leq 0.3) \\ (0.3 \leq R_d \leq 1) \end{cases}$ |
|               |        |      | $\alpha_1 = \begin{cases} 0.25 \xi + 0.25 \\ 0.625 \end{cases}$ $\begin{cases} (0.6 \leq \xi \leq 1.5) \\ (1.5 \leq \xi) \end{cases}$ |
|               | Fu et al. [44] | 2015 | $N_u = f_y A_s + f_c A_c + (2 k t v f_y / D), \nu = 0.5, k = 3.4$ |
|               | Wang et al.[45] | 2016 | $N_u = A_f f_{sz} + A_c f_{cc}$ |
|               |        |      | Strength of the confined concrete $f_{cc} = f_{cd} + K^d f_r$ |
| Shape             | Reference                  | Year | Equation                                                                 |
|-------------------|----------------------------|------|--------------------------------------------------------------------------|
| Rectangular/Square| Ding et al. [28]            | 2014 | \( N_u = A_c f_c + 1.2 A_s f_y \)                                        |
|                   | Du et al. [19]              | 2016 | \( N_u = f_y A_s + (1 + k) f_c A_c \) Augmentation factor \( k = 0.5668 - 0.0039 h / \sqrt{f_y / 235} \) |
|                   | Yan et al. [30]             | 2019 | \( N_u = A_c (0.89 f_y) + \frac{1}{2} \left( \frac{3 f_c}{b} \times \frac{2 t}{b - 2 t} \times 0.19 f_y \right)^{0.72} f_y \) |
| Elliptical        | Uenaka [46]                 | 2014 | \( N_u = 1.46 (A_c f'_c + A_s f_y) \)                                   |
|                   |                            |      | \( N_{rest-a} = A_c \sigma_{cBA} + A_s f_y \)                           |
|                   |                            |      | \( N_{rest-b} = A_c \sigma_{cBB} + A_s f_y \)                           |
|                   |                            |      | \( \sigma_{cBA} = f'_c + k \frac{t}{a - t} \sigma_{dA} \)               |
|                   |                            |      | \( \sigma_{cBB} = f'_c + k \frac{t}{b - t} \sigma_{dB} \)               |
| Hexagon (Regular) | Ding et al. [13]            | 2016 | \( N_u = f_c A_c + 1.3 f_s A_s \), \( A_c = \frac{3 \sqrt{3} b^2}{2} \), \( A_s = 6 b t \) |
| Octagon           | Hassanein et al. [3]        | 2017 | \( f_{rp} = \begin{cases} 0.0491703 - 0.0007943 \frac{B + D}{2 t} & \text{for } 17 \leq \frac{B + D}{2 t} < 63 \\ 0.0065311 - 0.0000044 \frac{B + D}{2 t} & \text{for } 17 \leq \frac{B + D}{2 t} \leq 63 \end{cases} \) |

\( f_{cyl,100} \), \( f_{cyl,150} \) – concrete cylindrical compressive strength in MPa.
\( \alpha \) - confinement factor.
\( k \) – varies with \( l_0 \).
| Round-Rectangular | Faxing et al. [10] | 2015 | $N_u = A_c f_c [1 + (0.8 + 0.9D/B)\xi]$ |
|-------------------|-------------------|///// |                                |
|                   | Hassanein and Patel [5] | 2018 | $N_u = f_y A_{s,RE}^i + \left( \gamma_c f_{c}^i + 4.1 f_{rp}^i \right) A_{C,RE}^i + f_y A_{s,RP,eff}^i + \gamma_c f_{c}^i A_{C,RP}^i$ |
|                   |                   |      | $\gamma_c = 1.458(D/c)^{-0.1} (0.9 \leq \gamma_c \leq 1.10)$ |
|                   |                   |      | Confinement pressure $f_{c}^i = \left\{ \begin{array}{ll} 0.7(v_p^k - v_p^l) \frac{2t}{D - 2t} f_{xy} & \text{for } \frac{D}{t} \leq 47 \\ \left(0.006241 - 0.0000357 \frac{D}{t} \right) f_{xy} & \text{for } \frac{D}{t} > 47 \end{array} \right.$ |

*B, *D – Thickness and length of hexagon, width and thickness of round-rectangular column.

$a_{A,RE}$ - steel tube cross-sectional area in the round-ended column.

$b_{A,RE}$ - concrete cross-sectional area in the round-ended column.

$c_{A,RP,eff}$ - steel effective cross-sectional area in the rectangular shape of the round-ended column.

$\lambda_{C,RP}$ – concrete cross-sectional area in the rectangular shape of the round-ended column.

$\nu_p$ - Poisson’s ratio of steel tube filled with concrete.

$\nu_c$ - Poisson’s ratio of steel tube devoid of concrete.

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| Solid and hollow CFST | Yu et al. [47] | 2010 | $N_u = \left(1 + 0.5k_n \frac{L}{\xi} \right) (f_y A_s + f_c A_c) \cdot f_{sc} = (1 + \eta_2) \left(1 - \beta \right) f_c + \beta f_y$ |
|-----------------------|--------------|///// |                                |
|                       |                |      | $\eta_2 = \frac{\Omega \xi_{sc}}{\left[2.0\Omega + 0.05 \xi_{sc} + \left(0.2 \frac{f_c}{f_y} - 0.05 \right) \xi_{sc} \Omega \right] \left(\Omega + \xi_{sc} \right)^{1/2}}$ |
|                       |                |      | Steel area ratio $\beta = A_s / (A_s + A_c)$, solid ratio $\Omega = A_c / (A_c + A_s)$ |

$\Omega$ - Capacity factors: $\phi = 0.83, \phi_c = 0.78$ |

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| Circle and polygon | Yu et al. [48] | 2013 | $N_u = \varphi_{sc} N_0$ |
|--------------------|--------------|///// |                                |
|                    | $\varphi_{sc} = \frac{1}{2 \lambda_{sc}^2} \left( \lambda_{sc}^2 + K \lambda_{sc} + 1 - \sqrt{\lambda_{sc}^2 + K \lambda_{sc} + 1}^2 - 4 \lambda_{sc}^2 \right)$ |
|                    | $K = 0.25 - 0.09 k_c$ |
|                    | Normalized slenderness ratio $\bar{\lambda}_{sc} = \frac{k_n}{\pi} \left( \frac{N_0}{E_{se,sc}} \right)^{1/2}$ |
|                    | $E_{se,sc} = E_s I_c + E_c I_s$, $N_0 = (1 + \eta)(f_y A_s + f_c A_c)$ |
|                    | $\eta = 0.5 k_n \frac{L_c}{\xi}$, $\xi = A_s f_y / A_c f_c$ |
|                    | Confinement effectiveness coefficient $k_c$ $k_c = \left(1 - \psi^{\eta} \right)^{\left(\eta^2 - 4 \right) / \left(1 - \psi \right)^2}$ |
|                    | $\psi = 1 - \Omega$ |

$\eta$ - enhanced confining coefficient.
7. Conclusion

The circular hollow steel sections show enhanced confinement to the concrete core than any other cross-sectional shaped hollow sections. Cross-sectional shapes like rectangular, square, hexagonal, octagonal and other special-shaped CFST columns have the strongest confinement at their corners and at the center. The round-ended CFST column shows the strongest confinement in the round ends. Large size CFST columns show weaker confinement effect. Composite action is stronger in slender CFST columns than stocky ones. Confinement is effective in steel tubes filled with normal strength concrete than high strength concrete-filled steel tubes. On the other hand, bearing capacity of the CFST columns increases with increase in compressive strength of concrete. High strength concrete in thicker tubes with high yield strength offers greater confinement effect. Codes should revise their limits on concrete compressive strength and steel yield strength due to the emerging use of high strength and ultra-high strength materials in construction.

CFST columns with lightweight concrete infill are highly prone to local buckling than CFST columns with normal strength concrete infill. The failure mode of CFST columns is not influenced by the aggregate type used in the infill concrete. When lightweight concrete-filled steel tube columns are used in structures, the design confinement factor should not be less than 1.0 to provide enough constraint to the concrete. When ultra-high strength concrete is used in CFST, a careful match of the steel tube grade to the concrete strength should be done. The bond strength between the steel tube and ultra-high performance core concrete increases with the use of an expansive agent.

The ultimate load capacity values increases with the increment of steel wall thickness. Thicker tubes offer greater confinement which enhances the resistance of the composite section. Specimens with pointed ends have lower ductility than round specimens. Ductility decreases with increase in steel grade. Ductility in ultra-high strength concrete filled steel tubes can be improved by adding a minimum of 1% of steel fibers. Slenderness ratio should be small to achieve greater stiffness in CFST columns. EC4 is found to give closer predictions to experimental results of CFST columns of different shapes considered in this paper.

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