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A unified formulation for circle and polygon concrete-filled steel tube columns under axial compression

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ABSTRACT

Current design practice of concrete-filled steel tube (CFST) columns uses different formulas for different section profiles to predict the axial load bearing capacity. It has always been a challenge and practically important issue for researchers and design engineers who want to find a unified formula that can be used in the design of the columns with various sections, including solid, hollow, circular and polygonal sections. This has been driven by modern design requirements for continuous optimization of structures in terms of not only the use of materials, but also the topology of structural components. This paper extends the authors' previous work [1] on a unified formulation of the axial load bearing capacity for circular hollow and solid CFST columns to, now, including hollow and solid CFST columns with regular polygonal sections. This is done by taking a circular section as a special case of a polygonal one. Finally, a unified formula is proposed for calculating the axial load bearing capacity of solid and hollow CFST columns with either circular or polygonal sections. In addition, laboratory tests on hollow circular and square CFST long columns are reported. These results are useful addition to the very limited open literature on testing these columns, and are also as a part of the validation process of the proposed analytical formulas.

1. Introduction

A concrete-filled steel tube (CFST) column is formed by filling a steel tube with concrete. According to the form of the cross-section, CFST columns can be divided into different groups, such as circular, square and octagon CFST columns. The cross sections of these columns can be either solid or hollow. A solid concrete-filled steel tube (S-CFST) column is formed by pouring wet concrete into the entire space enclosed by the steel tube, and a hollow concrete-filled steel tube (H-CFST) one is formed by pouring concrete into a steel tube using the centrifugal method. Fig. 1-1 shows some of the commonly used cross sections of the concrete-filled steel tube columns.

Axial load bearing capacity of a CFST column is an important and fundamental design parameter in construction engineering. Extensive research on solid CFST columns has been conducted either experimentally or analytically. Comprehensive research monographs have been published by Zhong [2], Han [3], Zhao et al. [4], Zha [5], and Chiaki [6]. There are also many published research papers on experimental studies of solid circular [7–9], elliptical [10], octagonal [11–13] and square CFST [14–18] columns. Numerical simulations also played an important role in studying the behavior of solid CFST columns under axial compression [19–22] and eccentric loading [23,24]. Practical design formulas were proposed and adopted in, for example, CECS 254:2009 [25] for hollow, Eurocode 4 [26] for solid and Han [3] for circular and square solid CFST columns.

From the above, it can be concluded that most of the research in the last few decades focused only on solid CFST columns. Different design formulas and procedures were recommended for columns with different section profiles. This is not ideal for modern structural design where structural, material, architectural, aesthetic and environmental parameters are all designed in a continuous manner to achieve the best possible design. The modern procedure requires a continuous change of all design parameters, including section profiles of the CFST columns. It is obvious that a unified formulation for the calculation of axial load bearing capacity of CFST columns with various section profiles will benefit both analytically and computationally the overall design process. Fortunately, obtaining a unified design solution for all the sections shown in Fig. 1 is possible since (a) materially, the difference between a solid and a hollow section is the hollow ratio and a solid section can be viewed as a special hollow section with a hollow ratio of zero and (b) geometrically, the difference between a circular and a regular polygonal section is the number of sides and a circular section

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Notations

f_{sc}	combined strength of CFST
φ_{sc}	stability factor of CFST
N_0	strength bearing capacity of CFST, $N_0 = f_{sc}A_{sc}$
N_u	load bearing capacity of CFST, $N_0 = \varphi_{sc}N_0 = \varphi_{sc}f_{sc}A_{sc}$
η	enhanced confining coefficient
η_c	enhanced confining coefficient for circular section
$\eta_{c,s}$	enhanced confining coefficient for circular solid section
A_s, A_c, A_k	area of steel, concrete and hollow, respectively
A_{sc}	area of CFST section, $A_{sc} = A_s + A_c$
Ω	solid ratio, $\Omega = A_c/(A_c + A_k)$
ψ	hollow ratio, $\psi = A_k/(A_c + A_k) = 1 - \Omega$
β	ratio of steel area, $\beta = A_s/(A_s + A_c)$
α	steel ratio, $\alpha = A_s/A_c$
α_{sc}	solid steel ratio, $\alpha_{sc} = A_s/(A_c + A_k)$
I_s, I_c	moment of inertia of steel, concrete, respectively
I_{sc}	composite moment of inertia, $I_{sc} = I_s + I_c$
f_{ck}, f_y	characteristic strength of concrete and steel, respectively
ξ_{sc}	solid confining coefficient, $\xi_{sc} = \alpha_{sc}f_y/f_{ck}$
ξ	confining coefficient, $\xi = \alpha f_y/f_{ck}$
E_c, E_s	elastic modulus of concrete and steel, respectively
E_{sc}	composite bending modulus, $E_{sc} = (E_cI_c + E_sI_s)/I_{sc}$
k_e	confinement effectiveness coefficient, $k_e = k_hk_n$
k_h	hollow confinement effectiveness coefficient
k_n	polygon confinement effectiveness coefficient
n	edge number, for circular cross section, take infinity
K	initial imperfection coefficient
K_c	initial imperfection coefficient for circular CFST
L_0	effective length of column
λ	slenderness ratio, $\lambda = L_0/\sqrt{I_{sc}/A_{sc}}$
$\bar{\lambda}_{sc}$	non-dimensional slenderness ratio, $\bar{\lambda}_{sc} = \lambda/\pi \cdot \sqrt{f_{sc}/E_{sc}} = L_0/\pi\sqrt{N_0/(E_{sc}I_{sc})}$

can be viewed as a special polygonal section with an infinite number of sides.

On the basis of the aforementioned special cases, this paper attempts to extend the axial load bearing capacity formula of a circular CFST column to the columns with polygonal sections, and a unified formula is finally obtained for both hollow and solid circular and polygonal sections.

2. Unified formulation of the strength for circle and polygon CFST columns

2.1. Simplification of the unified formula for circular sections

A unified formula for both solid and hollow sections was proposed in Ref. [1] to predict the strength of a CFST column through decomposition of the elastic deformation of a circular concrete filled steel tube into a uniaxial compression and a plane strain problem. Displacement compatibility and the solution of thick-walled cylinder were then introduced to derive the strength formula that is applicable for both solid and hollow circular sections. The formula was validated by experimental results, and is shown below [1]:

$$f_{sc} = (1 + \eta_c)[(1 - \beta)f_{ck} + \beta f_y] \tag{2-1a}$$

in which

$$\eta_c = \frac{\Omega\xi_{sc}}{\left[2.0\Omega + 0.05\xi_{sc} + \left(0.2\frac{f_{ck}}{f_y} - 0.05\right)\xi_{sc}\Omega\right](\Omega + \xi_{sc})} \tag{2-1b}$$

where η_c is the enhanced confining coefficient for circular section; β is the ratio of steel area; Ω is the solid ratio; and ξ_{sc} is the solid confining coefficient. The definitions of all the symbols are list in the notations.

From the definitions of the confining coefficient ξ, solid ratio Ω and solid confining coefficient ξ_{sc}, one has

$$\xi_{sc} = \Omega\xi \tag{2-2}$$

Inserting Eq. (2-2) into Eq. (2-1b) yields:

$$\eta_c = k \times 0.5\frac{\xi}{1 + \xi} \tag{2-3a}$$

where

$$k = \frac{2}{2 + 0.2\alpha_{sc} + 0.05\alpha_{sc}\frac{f_y}{f_{ck}}\left(\frac{1}{\Omega} - 1\right)} \tag{2-3b}$$

In engineering practice, the most commonly used steel varies from Q235 to Q420, and the concrete grade from C30 to C80. The values of f_y/f_{ck}, therefore, is somewhere between 4.7 and 20.9.

For solid CFST columns, the steel ratio α_{sc} is between 0.04 and 0.2, and $\Omega = 1$. Approximately, the enhanced confining coefficient for a solid circular section is then:

$$\eta_{c,s} = \frac{2}{2 + 0.2\alpha_{sc}} \times 0.5\frac{\xi}{1 + \xi} \approx 0.5\frac{\xi}{1 + \xi} \tag{2-4}$$

The relationship between the coefficient k and the solid ratio Ω in Eq. (2-3b) is shown by Fig. 2-1.

Further numerical tests show that, for any combination of the parameters, k is always smaller than Ω. Thus, by assuming,

$$k = \Omega = 1 - \psi \tag{2-5}$$

a simplified Eq. (2-3) can be obtained, which leads always to a conservative design. It will be seen later that this approximation does not affect significantly the accuracy of the predictions.

Eq. (2-3a) now becomes:

$$\eta_c = 0.5\frac{\xi}{1 + \xi}\Omega = \Omega \times \eta_{c,s} \tag{2-6}$$

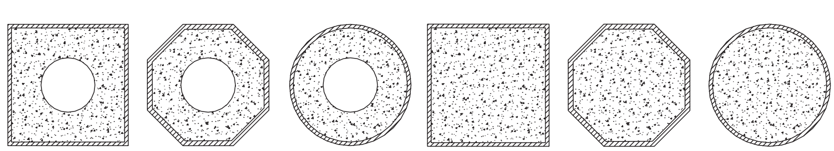

Fig. 1-1. Common section types of CFSTs.