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A unified method for calculating fire resistance of solid and hollow concrete-filled steel tube columns based on average temperature

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ABSTRACT

This paper presents a new method for calculating fire resistance of axially loaded Concrete-Filled Steel Tube (CFST) columns with different section profiles, including circular and polygonal sections that can be solid and hollow. The uniqueness of this new method is that the fire resistance is calculated on the basis of the average temperature of the columns' cross-sections. This is done by taking the bearing capacity of a CFST column at room temperature as a special case of the bearing capacity of the same column at the start of a fire. The equivalent strength and equivalent elastic modulus in relation to the average temperature of steel and concrete are investigated, and a unified method of calculation is proposed, by which the calculation of fire resistance of a CFST column can be divided into two steps, i.e. (a) calculation of the equivalent strength and elastic modulus of steel and concrete at elevated temperature based on the average temperature, and (b) calculation of fire resistance using the formulas at room temperature by replacing the equivalent material strength and elastic modulus at elevated temperature. The two sets of formulas for calculating fire resistance of CFST columns are given by combining the unified method, respectively, with Eurocode 4 and the authors' previous work. The proposed formulas and procedure are validated through comparisons with the experimental results of a number of solid and hollow CFST columns with circular and square sections.

1. Introduction

Fire resistance of Concrete-Filled Steel Tube (CFST) column is one of the most important factors that must be taken into account in the design process of modern building structures. For example, structural fire design is now required by Eurocode 4 [1], DBJ13-51 [2], ASCE/SFPE 29-99 [3] and ACI 216 [4]. There are many different forms of CFST columns characterized by their cross sectional profiles, as shown in Fig. 1 [5]. The hollow ones are normally formed by pouring concrete into the steel tubes using the centrifugal method.

Extensive research has been published on experimental studies of solid CFST columns [6–12], bar-reinforced CFST columns [13,14], concrete-filled double skin tube columns [15,16], and rectangular CFST columns exposed to fire [17,18] under axial or eccentrically compression. There are also limited published work on experimental study of hollow CFST columns subjected to fire, e.g., the work done by Yu [19] and Blaževičius and Kvedaras [20]. Since fire experiments are complex and expensive, numerical simulations have played an important role in studying fire resistance of the CFST columns [21–28]. There are also some analytical formulas proposed by, e.g., Kodur [29] who conducted parametric analysis through experiments and numerical calculations, and proposed formulas for calculating fire resistance time of solid circular and square CFST columns using a regression analysis. On the basis of Eurocode 4 [1], and Wang and Kodur [30] developed an approach for evaluating squash load and rigidity of solid CFST columns at elevated temperature. The formulas were developed for columns with "standard" steel and concrete strength; Wang [31] presented a method for both protected and unprotected circular CFST columns, which required interpolations to obtain their squash loads and rigidities; Li et al. [32] proposed a formula for bearing capacity of solid circular CFST columns under fire on the basis of a parametric analysis and regression; Han et al. [8] calculated strength index of circular and square solid CFST columns based on the results of parametric and experimental studies, and proposed also a formula for calculating the thickness of fireproof; Tan and Tang [33] applied the "Rankine method" to the

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Nomenclature

N_0, $N_{0,T}$	cross-sectional plastic resistance to axial compression of CFST column at room and elevated temperature, respectively
φ_{sc}, $\varphi_{sc,T}$	stability factor of CFST column at room and elevated temperature, respectively
N_u, $N_{u,T}$	ultimate capacity of CFST column at room and elevated temperature, respectively
A_s, A_c, A_k	area of steel, concrete and hollow, respectively
ψ	hollow ratio, $\psi = A_k/(A_c + A_k)$
$\bar{L}$	equivalent thickness of concrete, $\bar{L} = \sqrt{(A_c + A_k)/\pi} - \sqrt{A_k/\pi}$
$\bar{d}$	equivalent thickness of steel, $\bar{d} = \sqrt{(A_c + A_k + A_s)/\pi} - \sqrt{(A_c + A_k)/\pi}$
n	number of edges, (infinite for circular cross section)
I_s, I_c	moment of inertia of steel, concrete, respectively
L_0	effective length of column
f_{ck}, $f_{ck,T}$	Prism compressive strength of concrete at room and elevated temperature, respectively
f_c, $f_{c,T}$	cylinder strength of concrete at room and elevated temperature, respectively
f_y, $f_{y,T}$	characteristic strength of steel at room and elevated temperature, respectively
E_c, $E_{c,T}$	elastic modulus of concrete at room and elevated temperature, respectively
E_s, $E_{s,T}$	elastic modulus of steel at room and elevated temperature, respectively
$(EI)_{sc}$, $(EI)_{sc,T}$	flexural stiffness of CFST column at room and elevated temperature, respectively
ξ_T	confining coefficient at elevated temperature, $\xi_T = A_s f_{y,\bar{T}_s}/A_c \bar{f}_{ck,\bar{T}_c}$
k_e	confinement effectiveness coefficient
η_T	enhanced confining coefficient at elevated temperature
$\bar{\lambda}_{sc,T}$	non-dimensional slenderness ratio at elevated temperature
$\bar{T}_s, \bar{T}_c$	average temperature of steel tube and concrete core, respectively
$k_{s,T}$, $k_{Es,T}$	reduction factor of strength and elastic modulus of steel, respectively
$k_{c,T}$, $k_{Ec,T}$	reduction factor of strength and elastic modulus of concrete, respectively
$\bar{k}_{c,T}, \bar{k}_{Ec,T}$	equivalent reduction factor of strength and elastic modulus of concrete, respectively
$f_{y,\bar{T}_s}, E_{s,\bar{T}_s}$	equivalent strength and elastic modulus of steel tube at $\bar{T}_s$, respectively
$\bar{f}_{ck,\bar{T}_c}, \bar{E}_{c,\bar{T}_c}$	equivalent strength and elastic modulus of concrete core at $\bar{T}_c$, respectively

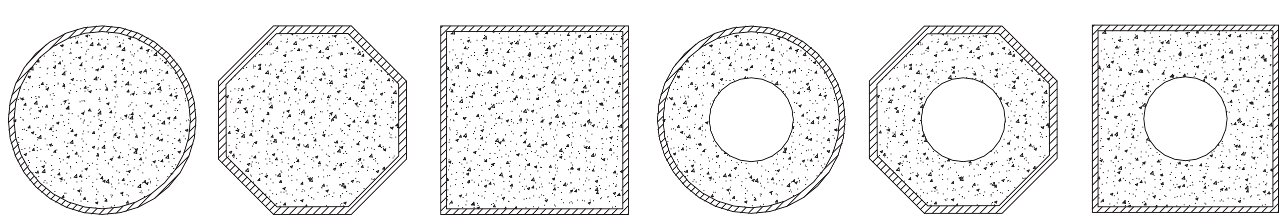
analysis of reinforced and plain solid CFST columns at elevated temperature; Espinos et al. [34] presented a simple calculation method for evaluating fire resistance of circular solid CFST columns based on Eurocode 4, where the concept of equivalent temperature was adopted. The method is suitable for circular cross sections with a diameter of 139.7–508 mm, normal strength concrete C20/25–C40/C50, and a fire resistance time within 2 h. Detailed and more comprehensive review on current methods for calculating fire resistance of CFST columns can be found from Zhao et al. [35], Rush et al. [36] and Espinos et al. [34]. It can be seen from the above literature review that there has been extensive research on fire-resistance of solid CFST columns. In most, if not all, of the research, it has been always the case that different formulas were proposed for different section profiles to predict their axial load bearing capacity or fire resistance time. It was also noticed the research on hollow CFST columns is relatively rare.

This paper attempts to unify the solution procedure by taking (a) a solid CFST column as a special case of a hollow one, and (b) the bearing capacity of a column at room temperature as a special case of the bearing capacity of the same column under fire at time $t = 0$. Consequently, the analysis of the bearing capacity of a column at room and room temperatures for solid and hollow CFST columns becomes a continuous and integrated process of calculation. To this end, a new method is developed for computing fire resistance on the basis of introducing the concept of *average* temperature. Theoretical and finite element analysis are combined with Eurocode 4 and the unified formula proposed by Yu et al. [5], resulting in, respectively, two sets of formulas for calculating fire resistance of solid and hollow CFST columns. The formulas are validated through comparisons with existing experimental results of the columns with circular and square sections.

2. Unified method for CFST columns under fire based on average temperature

2.1. General plastic limit analysis for CFST columns under fire

Eurocode 4 [1] uses the plastic limit method to calculate fire resistance of composite columns, without considering the confinement effect and any partial factors of the materials. The discrete form of plastic resistance and flexural stiffness of a cross-section are calculated by dividing the composite cross-section into a number of sub-areas, calculating the resistance and stiffness of each of the sub-areas and then taking the sum. This process can also be expressed by the following integrations:



(a) Solid circular (b) Solid octagonal (c) Solid square (d) Hollow circular (e) Hollowoctagonal (f) Hollow square

Fig. 1. Common section profiles of CFSTs [5].