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A unified interaction equation for strength and global stability of solid and hollow concrete-filled steel tube columns under room and elevated temperatures

Min Yu [a], Haoming Xu [a], Jianqiao Ye [a,b,*], Yin Chi [a,*]

[a] School of Civil Engineering, Wuhan University, Wuhan 430072, China
[b] Department of Engineering, Lancaster University, Lancaster LA1 4YR, UK

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ABSTRACT

On the basis of plastic limit analysis, this paper proposes a novel, simple and unified interaction equation (N-M) for Concrete-filled Steel Tube (CFST) columns subjected to combined compression and bending. A unique feature of the new N-M equation is that the single equation is valid for a range of columns that can be solid, hollow, circular, polygonal, short or long. The single equation can also apply to columns under both room and elevated temperatures. Validations against independent laboratory test, analytical and numerical results are carried out to assess the accuracy and applicability of the equation. The new equation agrees well with most of the results used in the comparisons. It can be concluded that the simple and unified equation can be used in practical design with sufficient accuracy.

1. Introduction

Consideration of fire resistance is one of the most important design aspects in designing un-protected load bearing structural members, such as concrete filled steel tube (CFST) columns. On the basis of experiments and numerical simulations, various design formulas have been proposed in the last few decades for estimating fire resistance of CFST columns. The approaches to derive these formulas have great impact on their accuracy and applicability, as, in most cases, the formulas were developed from a numerical fitting process through parametric regression.

CFST columns are normally designed for supporting axial compression. However, a CFST column may also support significant bending caused by uneven distribution of stresses over its cross-section. Extensive research has been carried out mainly for columns subjected to compression, as briefly reviewed below.

Design formulas for calculating load bearing capacity and fire resistance time of CFST columns were developed on the basis of experimental and numerical studies by, e.g., Kodur [1–3] who conducted extensive parametric analysis and proposed formulas for estimating fire resistance time of solid circular and square CFST columns under axial load. Using Eurocode 4 [4], Wang and Kodur [5] developed an approach for evaluating squash load and rigidity of solid CFST columns at elevated temperature. Li et al. [6] proposed a formula for calculating bearing capacity of solid circular CFST columns under fire on the basis of parametric analysis and regression; Han et al. [7, 8] calculated strength index of circular and rectangular solid CFST columns based on the results of parametric and experimental studies, and proposed also a formula for calculating thickness of fireproof materials. Tan and Tang [9] applied Rankine method to analyze reinforced and plain solid CFST columns at elevated temperature; Using an average temperature approach, Yu et al. [10] proposed a unified approach for calculating fire resistance of solid and hollow CFST columns having circular and polygonal cross sections; Espinos et al. [11, 12] presented a simple calculation method for evaluating fire resistance of circular and elliptical solid CFST columns under axial load based on Eurocode 4 [4], where the concept of equivalent temperature was adopted. He and Zhong [13] used finite element analysis to calculate thickness of fireproof materials of CFST columns. Yin and Zha [14] adopted the limit analysis method in the study of fire performance of CFST columns under axial load; and Chung et al. [15] used a similar numerical method in the study of fire performance of square CFST columns under eccentric compression.

From the above review and to the authors' best knowledge, the current calculation formulas were all developed individually for specific section profiles and separate sets of design equations have to be used for columns subjected to room and elevated temperatures. These formulas are normally lengthy and complex, requiring introduction of many modification factors from empirical studies. In this paper, a much simple design formula is proposed for plastic limit analysis of

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* Corresponding authors.
E-mail addresses: j.ye2@lancaster.ac.uk, (J. Ye), yin.chi@whu.edu.cn (Y. Chi).

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solid and hollow CFST columns that can be circular and polygonal and are subjected to combined axial compression, bending and elevated temperature. We first present the N-M interaction curves of various CFST sections by the limit analysis method, from which a unified N-M equation for short CFST columns under combined loads is proposed and verified by comparing with the numerical results from full plastic limit analyses. After considering the effect of initial imperfections and global instability, the formula is extended to study long CFST columns under room temperature. The N-M interaction curves of long CFST columns are obtained next and compared with those from existing design formulas, independent numerical calculations and available experimental results. Finally, a unified calculation formula that is applicable to both long and short CFST columns under normal and elevated temperatures is developed on the basis of the average temperature approach.

2. Unified N-M interaction equation of short CFST columns under combined axial and bending loads

2.1. Limit analysis method for calculating fire resistance of CFST

At the limit state, the steel tube is fully yielded and the concrete in compression reaches its strength limit. As adopted in Eurocode 4 [4], it is assumed that the steel and concrete interactions and the tensile strength of the concrete are negligible. Therefore, they will not be considered in the calculations throughout this paper.

Assuming that a CFST is subjected to ISO-834 standard fire. The temperature field of the CFST is non-uniform and time dependent, which can be calculated from a heat transfer analysis by using COMSOL Multiphysics. More details of the heat transfer model for CFST columns in fire are described in Wang et al. [16] and Yu et al. [17], which were validated by experimental results. The temperature dependent material properties can be taken from Eurocode 4 [4] or Lie [18], the latter has been adopted by Chinese Design Codes [19] (GB 50936-2014). For the cross section shown in Fig.1, at a given time instance, the ultimate axial force, N_T, and the ultimate moment, M_T, can be calculated, respectively, as.

$$N_T = \iint\limits_{A_{c,c}} f_{ck,x,y,T} dA + \iint\limits_{A_{s,c}} f_{s,x,y,T} dA - \iint\limits_{A_{s,t}} f_{s,x,y,T} dA \tag{1}$$

$$M_T = \iint\limits_{A_{c,c}} y \cdot f_{ck,x,y,T} dA + 2 \iint\limits_{A_{s,c}} y \cdot f_{s,x,y,T} dA \tag{2}$$

where the moment, M_T, is taken about the x-axis; A_s, $A_{s,\,c}$ and $A_{s,\,t}$ denote the total area, the area in compression and the area in tension of the steel, respectively; A_c, $A_{c,\,c}$, $A_{c,\,t}$ and A_k are the respective total area, area in compression, area in tension and hollow area of the concrete; $f_{s,\,x,\,y,\,T}$ and $f_{ck,\,x,\,y,\,T}$ are, respectively, the strength of steel and concrete at location (x, y) where temperature is T.

Eqs. (1) and (2) can be used to describe three ultimate loading cases, including: (a) $M_T = 0$ and $N_T < 0$, i.e., the column is subjected to uniaxial tension; (b)a $M_T = 0$ and $N_T > 0$, i.e., the column is subjected to uniaxial compression; and (c) $M_T \neq 0$ and $N_T = 0$, i.e., the column is subjected to pure bending. Thus, the load bearing capacities calculated from these three cases are, respectively, tensile bearing capacity, compressive bearing capacity and bending bearing capacity.

2.2. Calculation of N-M interaction curves

Consider first a series of circular CFST columns with different section profiles. The diameter of the steel tube, D, is from 200 to 1200 mm; the thickness of the steel tube, t, is from 3 mm to 18 mm. The hollow ratio of the section ψ, which is defined as the ratio of the central hollow area and the total area enclosed by the outside boundary of the section, i.e., $\psi = A_k/(A_c + A_k)$, is from 0.0 to 0.65, the grade of steel ranges from Q235 to Q460 and the concrete are the commonly-used C30 to C80, where the numbers after C denote cube compressive strength of the concrete, f_{cu}, in MPa. For octagonal and square CFST columns, the non-circular sections are transformed to their equivalent circular sections having the same cross-sectional areas as their respective non-circular originals. The transformation is based on an equivalence approach that has been successfully used previously in similar applications by the authors [20]. Table 1 presents six chosen values for each of the five design parameters within the ranges described above. Since considering a full combination of all possible designs in Table 1 requires extensive computational effort, the uniform design experimentation method is used to select representative designs from Table 1 for calculations. Thus, the number of designs to be calculated is reduced from the combinations shown in Table 1 to those shown in Table 2. In Tables 1, f_y is yield strength of steel and f_c' denotes characteristic value of cylinder compressive strength of concrete, which can be converted from f_{cu}, i.e., $f_c' = 0.8\, f_{\mathrm{cu}}$ [21].

It is assumed that the columns are subjected a combined axial compression and bending under elevated temperature. Applying Eqs. (1) and (2) repeatedly for all the possible combinations listed in Table 2 for every 10 min intervals up to 4 h, the ultimate bending moment, tension and compression of all the cases are obtained, from which the N-M curves of the columns are plotted. To save space and without loss of generality, Figs 2–4 show the curves of selected columns specified in Table 2 for solid (No. 1) and hollow (No. 6) columns having circular, square and octagonal sections. Equivalent diameter $\overline{D}$ and thickness $\overline{t}$ are used when the sections are not circular.

In the above figures, the outmost curves (black) are the N-M curves of the respective columns under room temperature. The curves are plotted then at 10 min intervals, from the right to left, until 240 min fire exposure time is reached. It is evident from the figures that all the curves

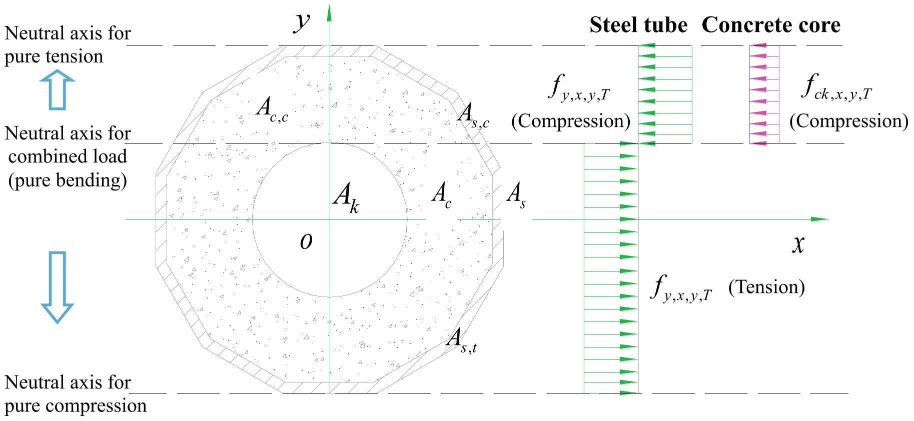

Fig. 1. CFST section under fire subject to compression and bending.