Journal of Building Engineering 3 (2015) 144–154

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Interaction approach for concrete filled steel tube columns under fire conditions

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ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form
14 July 2015
Accepted 15 July 2015
Available online 19 July 2015

Keywords:
CFST column
Fire resistance
Rankine approach
Shear bond
Finite element

ABSTRACT

The Rankine approach has been extended to predict the fire resistance of concrete filled steel tube (CFST) columns. The conventional Rankine approach only considers a linear interaction between elastic buckling and plastic squashing, and ignores the coupling interaction of these two failure modes. This assumption leads to a lower bound prediction compared with actual failure loads. A modified Rankine approach is proposed to predict the fire resistance of CFST columns considering the shear bond effect. The predictions are compared with 118 CFST column tests from four laboratories. It shows that for most of the cases, the proposed approach predicts the failure load more accurately compared with the calculation method recommended in EN 1994-1-2 (EC4 (H)). A 3D finite element model is developed to calibrate the accuracy of the proposed method under different design conditions. Parametric studies were performed to quantify the engineering fire resistance design factors of CFST columns.

1. Introduction

Concrete filled steel tube (CFST) columns have been widely used in modern constructions. Compared with reinforced concrete columns, CFST columns have higher strength, larger stiffness and ductility. Recently, several of engineering design codes are established based on numerical and experimental investigations. Han et al. [1,2] developed a method to calculate the fire resistance of protected/unprotected CFST columns subjected to standard fire, which has been incorporated into the Chinese Code [3]. In Europe, the design methods for fire resistance of CFST columns are included in EN 1994-1-2 [4]. Wang [5–7], Aribert et al. [8], Ribeiro et al. [9] and Espinos et al. [10,11] have investigated the simple calculation model recommended in EC4. They show that the specific method is generally accurate; however, it is complicated and predicts unsafe results for slender columns. In North America, Kodur et al. [12–14] proposed a simple approach consisting of a single design equation which includes the major parameters affecting the fire resistance of CFST columns. This approach has been incorporated into the National Building Code of Canada [15] and America [16,17]. In Singapore, Tan et al. [18–23] proposed a theoretical formulation to predict the fire resistance of steel/RC/CFST columns under uniaxial and biaxial bending subjected to standard fire. The approach comprises of concrete and steel strength reduction factors as a function of fire exposure time. The eccentricity of the applied load was determined by balanced failure point of the column section. The failure load can be determined based on extension of the ACI method for ultimate strength prediction at ambient temperature. All of these researchers performed comprehensive investigations. However, most of the approaches are based on finite element method (FEM) and empirical formulas due to the complex of non-uniform temperature distribution in cross-section and concrete spalling. The physical meaning and failure mechanism of CFST columns under fire conditions still needs further study.

On the other hand, the behavior of CFST columns exposed to fire was widely studied experimentally and numerically. Kodur et al. [24] and Wang et al. [25] developed numerical models to simulate the fire behavior of CFST columns filled with high strength concrete and both of their work obtained satisfactory results. Ding and Wang [26] developed a three-dimensional numerical model for CFST columns subjected to fire and investigated the important features of thermal resistance at the steel-concrete interface. Hong and Varma [27] and Espinos et al. [28] developed a three-dimensional numerical model and performed comprehensive parametric studies. Song et al. [29] and Yao et al. [30,31] investigated the fire resistance of columns subjected to natural fire. Several experimental fire tests were carried out by different researchers and available in the literature [1,32–35].

In the current work, a modified Rankine approach is proposed to predict the fire resistance of CFST columns combining with the

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http://dx.doi.org/10.1016/j.jobe.2015.07.006
2352-7102/

shear bond effect. The coupling interaction effect between plastic squashing and elastic buckling and the physical meanings are discussed. Conventional Rankine approach considers non-uniform temperature distribution in concrete cross-section, employs reduction factors for strength and stiffness of concrete and steel as a function of time. It gives a fundamental understanding to the behavior of columns under fire conditions combining the concept of plastic squashing and elastic buckling. In this paper, the physical meaning of the modified Rankine approach is studied, the effect of shear bond is adopted to predict the fire resistance of 118 CFST columns from four laboratories [32,33] with different column slenderness ratios, concrete covers, cross-sectional areas and fire exposure times. The predictions of modified Rankine approach are compared with both FEM analysis results and experimental data. The results show that the developed approach can predict the failure load of CFST columns more accurately compared with conventional Rankine approach and the simple calculation model recommended in Annex H of EN 1994-1-2 (EC4 (H)).

2. Theoretical model

2.1. Conventional Rankine approach

A Rankine formula based interaction approach has been applied to predict the fire resistance of steel columns and frames by Tang et al. [18]. Their approach divides a column into two hypothetical sub-columns, assuming the two sub-columns act independently of each other and ignore the coupling interaction. The conventional Rankine approach can be expressed as follows [36]

$$\frac{1}{P_R} = \frac{1}{P_P} + \frac{1}{P_e} \tag{1}$$

where P_P, P_e, P_R represent the plastic collapse load, elastic critical load and Rankine load, respectively.

Tang et al. [18] modified the Rankine formula to take the temperature effects into account. The formula can be expressed as follows

$$\frac{1}{P_R(T)} = \frac{1}{P_P(T)} + \frac{1}{P_e(T)} \tag{2}$$

In reality, the two sub-columns are deformed together and mutually restricted. The coupling interaction is termed “shear bond” [18], which increases the ultimate capacity of the column. Tan and co-workers [19,20] extended the approach to RC and CFST columns under standard fire conditions, their work shows that the Rankine formula gives lower bound of the failure loads. Yao et al. [21] suggested that the conventional Rankine approach only considers a linear interaction between two different failure modes of the column, namely, plastic squashing and linear elastic buckling, it ignores the coupling interaction between the two modes. By incorporating the coupling interaction effect into the Rankine formula, the modified approach can predict the failure load of RC columns under fire conditions more accurately.

In the current work, the authors proposed a modified Rankine approach to predict the fire resistance of CFST columns by combining the shear bond effect. In order to extend the Rankine approach to predict fire resistance of CFST columns, the authors adopt Eqs. (3a)–(3c). For columns subjected to axial load, P_p can be expressed as follows

$$P_p^{core}(t) = 0.85\beta_c(t)f_c^{`}(20\ ℃)A_c + \beta_{yr}(t)f_{yr}(20\ ℃)A_{sr} \tag{3a}$$

$$P_p^{tube}(t) = k_y^{tube}(t)f_y(20\ ℃)A_s \tag{3b}$$

$$P_p = P_p^{core}(t) + P_p^{tube}(t) = 0.85\beta_c(t)f_c^{`}(20\ ℃)A_c + \beta_{yr}(t)f_{yr}(20\ ℃)A_{sr} + k_y^{tube}(t)f_y(20\ ℃)A_s \tag{3c}$$

where $f_c^{`}(20\ °C)f_c^{`}(20\ °C)$, $f_{yr}(20\ °C)f_{yr}(20\ °C)$, $f_y(20\ °C)f_y(20\ °C)$ are the cylindrical compressive strength of concrete, yield stress of steel reinforcement and yield stress of steel tube at ambient temperature, respectively; A_c, A_{sr}, A_s stand for the area of concrete section, steel reinforcement and steel tube; $\beta_c(t)$, $\beta_{yr}(t)$, $k_y^{tube}(t)$ represent the strength reduction of concrete, steel reinforcement and steel tube at elevated temperature.

Considering the non-uniform temperature distribution across the section, the material strength reduction factors of concrete and steel under fire conditions $\beta_{c(t)}$ and $\beta_{yr}(t)$ can be determined by Eqs. (4) and (5) as the function of fire exposure time t [37]:

$$\beta_c(t) = \frac{\sum_{i=1}^{m} A_{ci}f_{ci}^{`}(t)}{A_c f_c^{`}(20\ ℃)} = \frac{\gamma(t)}{\sqrt{1 + (0.3A_c^{-0.5}t)^{A_c^{-0.25}}}} \tag{4}$$

$$\beta_{yr}(t) = \gamma(t) \times \left(1 - \frac{0.9t}{0.046d^{`} + 0.11}\right) \geq 0 \tag{5}$$

where $\sum_{i=1}^{m} A_{ci}f_{ci}^{`}(t)$ is the summation of $A_c f_c^{`}(20\ °C)$ when dividing the cross-section into m finite elements; $d^{`}$ is the concrete cover (The concrete cover is the least distance between the surface of embedded reinforcement and the outer surface of the concrete for reinforced concrete filled in the CFST columns (RCFST)). The reduction factor $\gamma(t)$ is to account for possible spalling of concrete at elevated temperature. It should be noted that CFST columns are usually not susceptible to concrete spalling because of steel tube. $\gamma(t) = 1$ for CFST columns is assumed under fire conditions. The fire exposure time t is related to aggregate types and standard fire curves, here assuming $t_e = \alpha_{agg}\alpha_{ISO}t$, $\alpha_{agg} = 1.0$ for siliceous aggregate and $\alpha_{agg} = 0.9$ for carbonate aggregate; $\alpha_{ISO} = 1.0$ for the ISO-834 fire and $\alpha_{ISO} = 0.85$ for the ASTM-E119 fire [37]. Thermal analysis of CFST columns was performed, it is noted that temperature in the steel tube is nearly uniform and does not depend on the steel wall thickness and column cross sectional size. The relationship between strength reduction factor $k_y^{tube}(t)$ –and fire exposure time t is shown in Fig. 1.

With the formulas recommended by Tang and Tan [19], the elastic critical load P_e can be determined by Eq. (6):

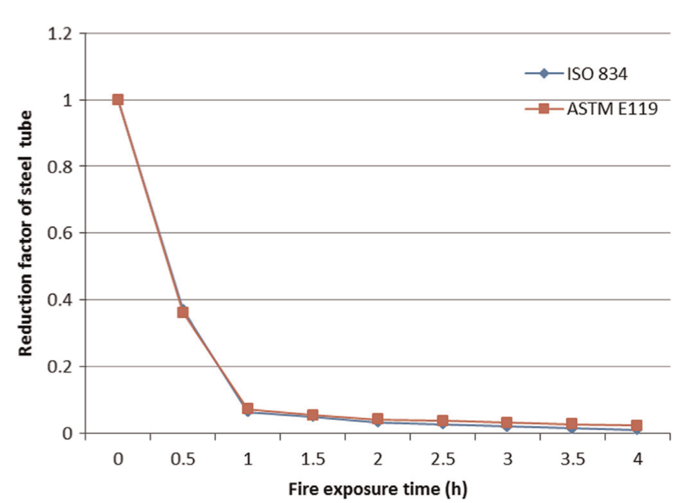

Fig. 1. Relationship between strength reduction factor and fire exposure time.