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Analysis and fire resistance design of concrete filled steel tube reinforced concrete columns

*Lei Xu[1] and Yu-Bin Liu[2]

[1), 2)] *School of Civil & Architectural Engineering, DaLian Nationalities University, DaLian 116600, China*
[1)] *xulei@dlnu.edu.cn*

ABSTRACT

The use of concrete filled steel tube reinforced concrete (CFSTRC) columns has been the interests of many structural engineers. This paper reports a finite element analysis of the compressive behaviour of CFSTRC columns subjected to fire. The influences of important parameters that determine the fire resistance of the composite columns were investigated. On the basis of parametric analysis outcomes, simplified formulae were proposed, And good agreement were obtained either between the results predicted by fomulae and numerical simulation results or between the results predicted by fomulae and measured results.

1. INTRODUCTION

Concrete filled steel tube reinforced concrete (The "Concrete filled steel tube reinforced concrete" will be abbreviated as CFSTRC for the citation purpose.) columns are a kind of composite structures, they taking concrete filled steel tube (CFST) as the core region, and placing reinforcing cage and casting concrete encircle the central region. Their cross sections are typically shown in Fig. 1. Considering the circular steel tube can provide more effective confines to inner concrete and make the structure acquire more favorable mechanic performance, the paper mainly dealt with the columns with cross sections shown as Fig. 1(a) and 1(b). The structure developed on the basis of reinforced concrete (RC) and CFST structures. It remains advantages of two structures and overcomes their disadvantages. Its main superiorities are as following: (1) compared with RC columns, a substantial increase in load bearing capacity and stiffness of the columns and much better endurance characteristics can be obtained; (2) compared with CFST columns, CFSTRC is expected to have more favorable fire resistance, and the outward buckling and corrosion of the steel tube can also be avoided; (3) CFSTRC columns can be easily connected to RC beams, and higher construction speed the beam-column joint can be designed according to the knowledge of conventional reinforced concrete joint.

[1)] Professor
[2)] Professor

The structure is innovated and developed firstly by Chinese scholars (Lin 2008). Owing to the excellent mechanical performance of CFSTRC columns, this kind of new column structures has be used more and more extensively in high-rise buildings, super high-rise buidings, and large span buildings. For the moment, more than 30 high-rising buildings have adopted CFSTRC columns (Lin 2008).

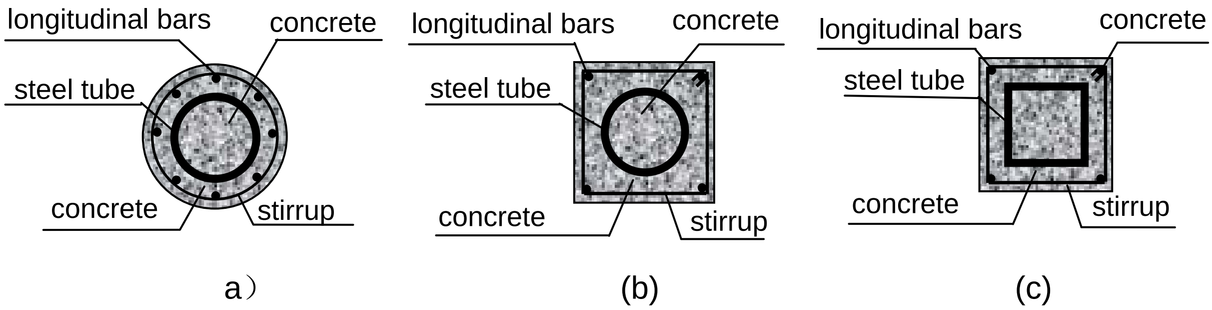


Fig. 1 Typical cross-section of CFSTRC columns

The CFSTRC column has also attracted more and more research interest since 1995 (Lin 2008). Through 10 years of the theoretical studies and the constantly extensive use of CFSTRC columns, “Technical specification for steel tube-reinforced concrete column structure（CECS188:2005）”promulgated and enforced in 2005.

But above reseaches are all concerned with the mechanic behaviours of the columns under the condition of room-temperater, researches on the mechanical properties exposed (or after exposure) to a fire of the structures are still in starting phase. It is also lack of fire design and calculation method in the relevant specifications and codes, including CECS188:2005. For the moment, only Zhou (2006) and Wu (2007) have experimentally and theoretically investigated on the axial compressive performance of the columns after exposure to fire and the bonding slip behavior of the columns before and after exposure to a fire respectively, Liu (2007) has numerically simulated the temperature distribution and fire resistance of axial compressive CFSTRC columns.

From the literature review, it can be concluded that either the theoretical analysis methods on the mechanical characteristics or a simplified model that can predict the fire resistance of the CFSTRC columns exposed to fire need to be developed. So, in the paper, a finite element model is proposed firstly. The theoretical method is validated by tests, and the calculated results agree well with those of tests. Secondly, the parametric analysis on fire resistance of CFSTRC columns subjected to fire are carried out by using the finite element model. Finally, for practical application considerations, a simplified fire resistance formula of CFSTRC columns is developed. The achievements in the paper can be referred for the fire design codes making and the fire design of practical engineering.

2. FINITE ELEMENT MODELING

A finite element analysis (FEA) model by using ABAQUS software (SIMULIA 2007) was proposed in this paper to analyze the fire behaviours of the CFSTRC columns.

2.1Material properties

(1) Steel

For steel tubes and reinforcing steel, an elastic-plastic stress-strain relation model proposed by Lie (1993) was used. The details for the stress-strain relationships are described as following:

$$\sigma_s = \begin{cases} \dfrac{f(T,0.001)}{0.001}\varepsilon_s & \varepsilon_s \le \varepsilon_p \\ \dfrac{f(T,0.001)}{0.001}\varepsilon_p + f[T,(\varepsilon_s - \varepsilon_P + 0.001)] - f(T,0.001) & \varepsilon_s > \varepsilon_p \end{cases} \quad (1)$$

in which, $\varepsilon_p = 4\times10^{-6}\cdot f_y$;

$$f(T,0.001) = (50 - 0.04T)\times\{1-\exp[(-30+0.03T)\sqrt{0.001}]\}\times 6.9$$

The initial modulus of elasticity for steel was determined by the slopes of the stress-strain curves at high temperatures. The Poisson's ratio was taken as 0.3 in the model.

(2) Concrete

The damage plasticity model for concrete defined in ABAQUS was used in the analysis (SIMULIA 2007). The description of plastic behaviours and the yielding surface of concrete were predefined according to the equivalent uniaxial stress–strain relationships in the program. Typical stress-strain relationships of core concrete in steel tubes at different temperatures was proposed by Song (2010), which has been successfully used to analyze the fire-resistance behaviour of CFST members. For concrete out of steel tubes, the stress-strain relationships developed by Lie (1993) were used which had been proved to be well used in RC structure analysis. These stress-strain relations are:

For core concrete in steel tubes,

$$y = 2\cdot x - x^2 \qquad (x \le 1) \quad (2,a)$$

$$y = \begin{cases} 1 + q\cdot(x^{0.1\xi} - 1) & \xi \ge 1.12 \\ \dfrac{x}{\beta\cdot(x-1)^2 + x} & \xi < 1.12 \end{cases} \qquad (x > 1) \quad (2,b)$$

in which, $x = \varepsilon/\varepsilon_0$, $y = \sigma/\sigma_0$, $\sigma_0 = f_c^{\prime}/\left[1+1.986(T-20)^{3.21}\times10^{-9}\right]$,

$$\varepsilon_0 = \left(1300 + 12.5 f_c^{\prime} + 800\cdot\xi^{0.2}\right)\times10^{-6}\times\left(1.03 + 3.6\times10^{-4}\cdot T + 4.22\times10^{-6}\cdot T^2\right),$$

$$\eta = 1.6 + 1.5/x,\ \beta = \frac{f_c^{\prime 0.1}}{1.2\sqrt{1+\xi}}$$

ξ is the confinement factor of CFST core of CFSTRC columns, which consist of steel tube and the core concrete in steel tube. It is defined as follows:

$$\xi = \frac{A_s \cdot f_y(T)}{A_c \cdot f_{ck}} \tag{3}$$

in which, A_s is the cross-sectional area of steel tube, A_c is the cross-sectional area of concrete, f_{ck} is the characteristic compression strength of concrete which equals to 67% of the compression strength of cubic blocks (f_{cu}), $f_y(T)$ is the yield strength of steel tube at temperature T, which is defined as:

$$f_y(T) = \begin{cases} f_y & (T < 200°C) \\ \dfrac{0.91 f_y}{1 + 6.0 \times 10^{-17} \cdot (T-10)^6} & (T \geq 200°C) \end{cases} \tag{4}$$

For concrete out of steel tubes,

$$\sigma_c = \begin{cases} f_c'(T)\left[1 - \left(\dfrac{\varepsilon_{max} - \varepsilon_c}{\varepsilon_{max}}\right)^2\right] & \varepsilon_c \leq \varepsilon_{max} \\ f_c'(T)\left[1 - \left(\dfrac{\varepsilon_c - \varepsilon_{max}}{3\varepsilon_{max}}\right)^2\right] & \varepsilon_c > \varepsilon_{max} \end{cases} \tag{5}$$

in which, $\varepsilon_{max} = 0.0025 + \left(6T + 0.04T^2\right) \times 10^{-6}$

$$f_c'(T) = \begin{cases} f_c' & 0°C < T < 450°C \\ f_c'\left[2.011 - 2.353\left(\dfrac{T-20}{1000}\right)\right] & 450°C \leq T \leq 874°C \\ 0 & T > 874°C \end{cases}$$

f_c' is the cylinder compression strength of concrete.

The tensile property of all concrete was defined as a stress and fracture energy relationship provided in the concrete damaged plasticity model. The fracture energy of concrete at elevated temperature was calculated by the following equation (Lu 2011):

$$G_f[T] = G_f \cdot \left(0.2882 + 8 \times 10^{-4} T - 1 \times 10^{-6} T^2\right) \tag{6}$$

in which, G_f is the fracture energy of concrete at ambient temperature, which is defined as:

$$G_f = \alpha \cdot \left(\frac{f_c'}{10}\right)^{0.7} \cdot 2.5 \times 10^{-3} \quad (N/mm) \tag{7}$$

The influences of thermal expansion of concrete and steel are considered according to that recommended by Lie (1993).

2.2 Procedure of analysis

A sequentially-coupled thermal-stress analysis procedure has been adopted to analyze the mechanical behaviour of CFSTRC columns exposed to fire. This procedure is to simulate the heat transfer process firstly, after that, the acquired nodal temperatures within menmbers will be imported into the structural analysis model to calculate the structural response of members at different temperature. In order to ensure the correctly transfer of nodal temperatures from the heat transfer model to the mechanical model, the mesh and node numbering of these two models must be identical.

The heat transfer analysis model of CFSTRC columns has been prosposed by the author of this paper and the details of the model has been described in Xu (2012). On the basis of it, the structural analysis will be modelled.

In the structural analysis model of CFSTRC columns, the 8-node linear reduced-integration 3D solid element (C3D8R) was used for concrete and steel tube, and the 2-node linear 3-D truss element (T3D2) was used to model the steel reinforcing bars. Two rigid end plates were added to column's model in order to apply load and they also adopted the 8-node linear reduced-integration 3D solid element with (C3D8R) for structural analysis.

The interactions of steel tube and concrete either in or out of steel tube were simulated by contact interaction in ABAQUS (SIMULIA 2007). The surfaces of the concrete and steel in the contact were defined as a contact pair, one as master surface and another as slave surface. The master and slave surfaces may contact or separate from each other. The mechanical properties of the contact pair are defined in normal and tangential direction respectively. The ``hard contact'' model was selected for the normal direction and the "Coulomb friction" model was selected for the tangential direction. A friction coefficient of 0.25 was found suitable for predicting the fire response of CFSTRC columns at elevated temperatures. The normal ``Hard contact'' relation was selected to simulate the interface behaviour between the end plate and concrete. The end plate connected with the steel tube by `TIE' constraint.

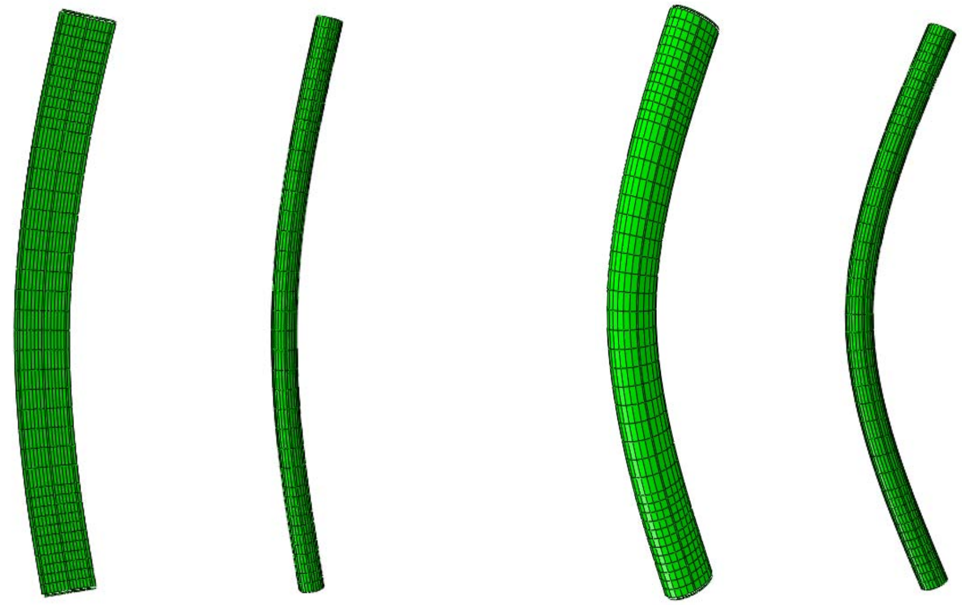
The boundary conditions will be applied on the end plates to simulate the actual boundary conditions. For pinned boundary condition, the translation UX and UY will be constraint along the loading line on the top end-plate, and the translation UX, UY and UZ on the bottom end-plate will also be constrained.

The typical finite element meshing and predicted failure modes of CFSTRC columns with circular and square cross section by using above model were shown in Fig. 2(a) and (b), respectively. The failure modes of steel tube in the columns were also been shown in the Figure.

It can be seen from Fig. 2 that the columns reach their ultimate strength due to overall buckling. Because the existance of the concrete both inside and outside of steel tube, there are neither inward nor outward local buckling occurred in steel tube.

2.3 Verifications of the FEA model

A set of tests on CFSTRC columns with both circular and square sections were carried out by the present author in the former research stage. The detailed information for these tests was given in Table 1 in this paper. The predicted fire resistance of these specimens were also given in Table 1 for comparison. It can be found the comparison that, a good agreement is obtained between the predicted and test results.



member CFST core member CFST core

(a) square cross-section (b) circular cross-section

Fig. 2 Typical finite element meshing and failure modes of CFSTRC columns

Table 1 Testing member information and fire resistance

Specimen size $L\times B(D)\times D_s$ (mm)	t_s (mm)	f_y (MPa)	f_{yb} (MPa)	f_{cu}(MPa) Concrete outside steel tube	f_{cu}(MPa) Concrete inside steel tube	n	Measured fire endurance (min)	Predicted fire endurance (min)
3810×300×203	6	287	377	34.1	125	0.6	125	126
3810×300×159	8	287	377	34.1	135	0.6	135	134
3810×300×203	6	287	377	29.3	29	0.7	29	28
3810×300×159	8	287	377	29.3	30	0.7	30	35

3. PARAMETRIC ANALYSIS

Above proposed finite element model is used to analyse the effect of parameters on the fire resistance (t_R) of CFSTRC columns. All parameters that will influence the fire resistance of CFSTRC columns include: axial load level (n), dimension of cross-section (C), steel tube ratio (α_s), sectional core area ratio (α_{sc}), slenderness ratio (λ), eccentricity ratio (e/r_o), yield strength of steel tube (f_y), yield strength of reinforcing bars

(f_{yb}), concrete strength (f_{cu}), ratio of longitudinal reinforcement (ρ_s). In the following, the influencing law of these parameters on fire resistance will be discussed through a typical example. The basic calculating conditions of the example are as follows: the columns subjected to ISO-834 (1999) standard fire, initial deflection is L/1000, C=2000mm, α_s=0.06, α_{sc}=0.2, ρ_s=1.2%, f_y=345Mpa, f_{yb}=335Mpa, the cubic strength of concrete out of steel tube is 60Mpa, the cubic strength of concrete in steel tube is 40Mpa, λ=40.

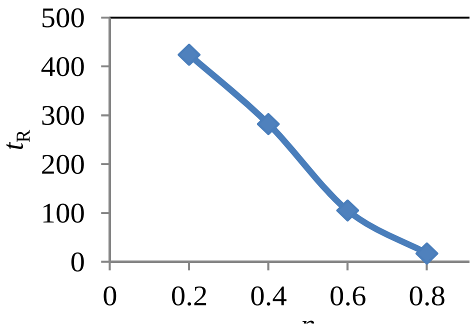
The effect of axial load level (n) on fire resistance is shown in Fig. 3. Axial load level has a significant influence on the fire resistance of CFSTRC columns. Fire resistance decreases dramatically as the axial load level increases. When axial load level reach to 0.8, the columns will failure after exposing fire about 15 minutes.

The effect of outer perimeter (C) of CFSTRC columns on fire resistance is shown in Fig. 4. It seems that the increase in the outer perimeter leads to a obviously increase in the fire resistance. And the fire endurance time of CFSTRC columns with square cross-section is longer than CFSTRC columns with circular cross-section when their outer perimeters are equal.

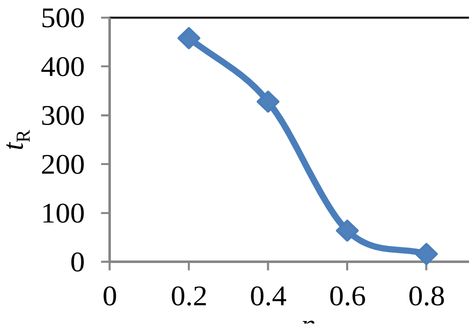
The parameter of sectional core area ratio (α_{sc}) of CFSTRC columns reflects the thickness of outer concrete insulating layer, and the effect of the parameter on fire resistance is showned in Fig. 5. It can be found that the fire resistance of the CFSTRC columns increase as the sectional core area ratio increases when the value of α_{sc} is less than 0.35. Once α_{sc} is greater than 0.35, the fire resistance will decrease with the increase of α_{sc}.

Fig. 6 shows the influence of slenderness ratio (λ) on the fire resistance of CFSTRC columns. Fire resistance decreases obviously as the slenderness ration increases when λ is less than 40, but the decreasing trend tends to be gently when λ exceeds 40.

The effect of other parameters including steel tube ratio (α_s), eccentricity ratio (e/r_o), yield strength of steel tube (f_y), yield strength of reinforcing bars (f_{yb}), the strength of concrete in steel tube and the strength of concrete out of steel tube (f_{cu}), ratio of longitudinal reinforcement (ρ_s) on fire resistance of CFSTRC are shown Fig. 7-13 respectively. In general, the effect of these parameters on fire resestance is slight.

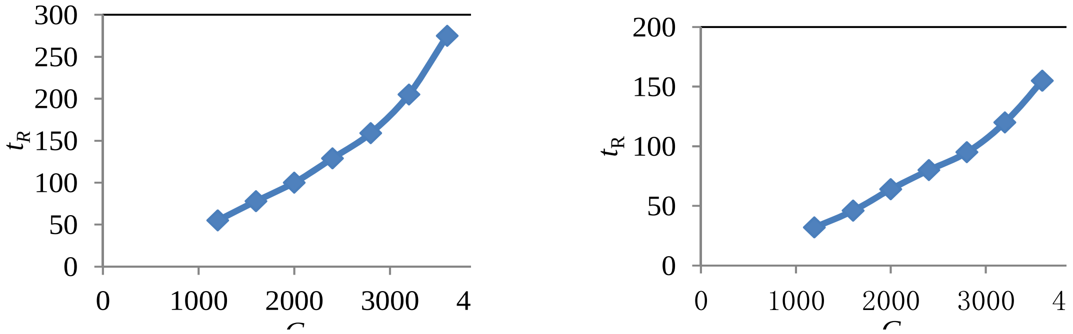


（a）square cross-section



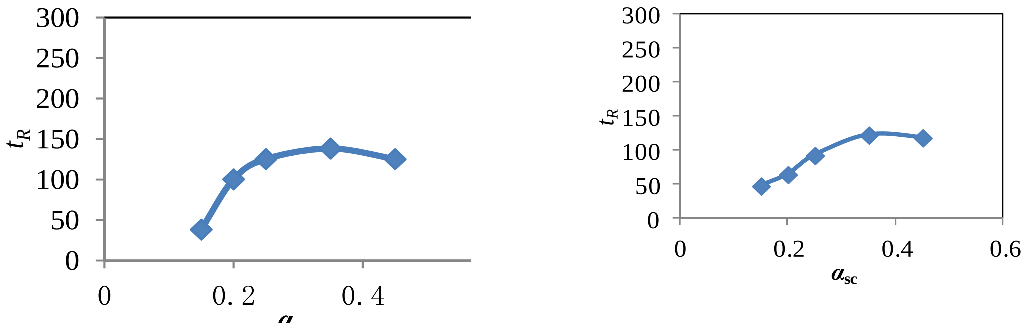
（b）circular cross-section

Fig. 3 The effect of axial load level on fire resistance



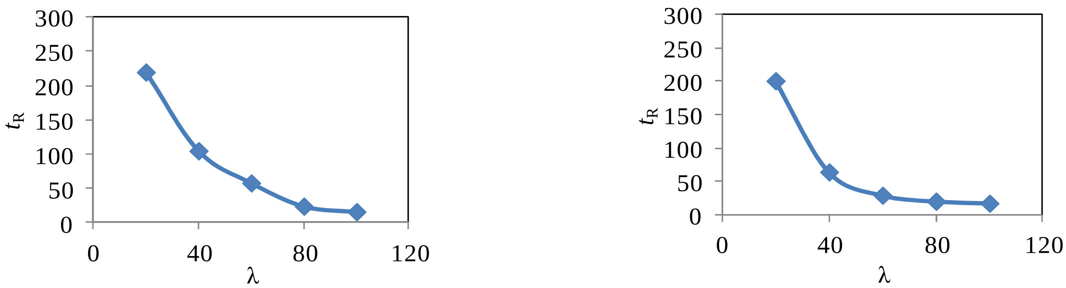
（a） square cross-section （b） circular cross-section

Fig. 4 The effect of outer perimeter on fire resistance



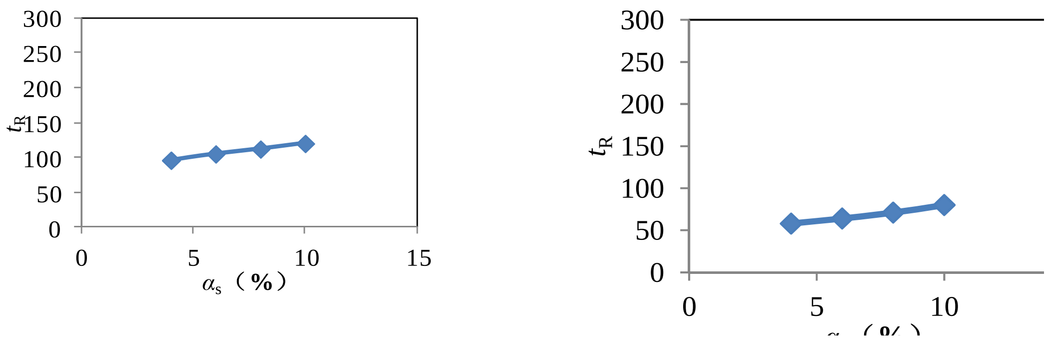
（a） square cross-section （b） circular cross-section

Fig. 5 The effect of sectional core area ratio on fire resistance



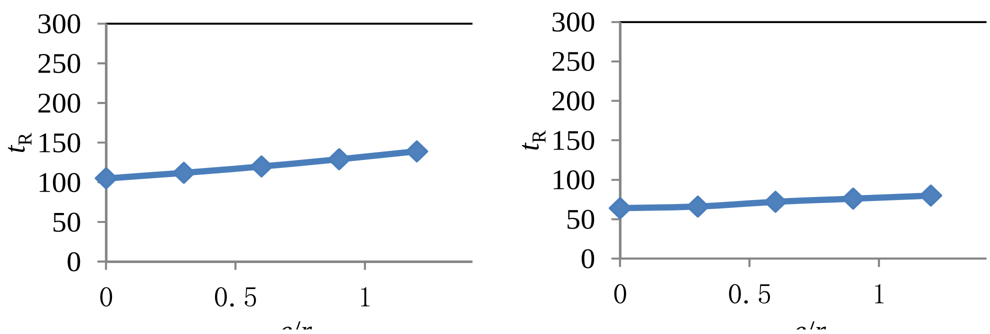
（a） square cross-section （b） circular cross-section

Fig. 6 The effect of slenderness ratio on fire resistance



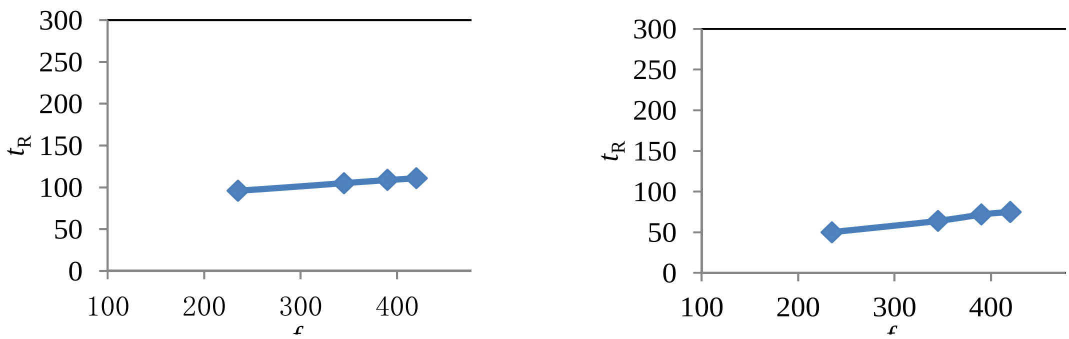
(a) square cross-section (b) circular cross-section

Fig. 7 The effect of steel tube ratio on fire resistance



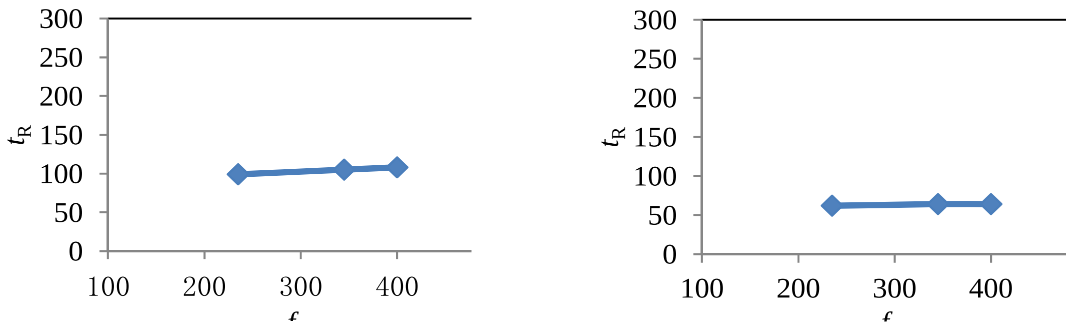
(a) square cross-section (b) circular cross-section

Fig. 8 The effect of eccentricity ratio on fire resistance



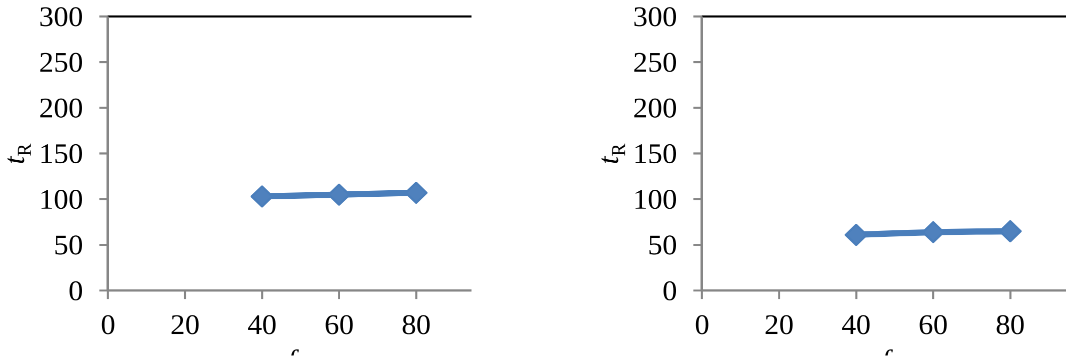
(a) square cross-section (b) circular cross-section

Fig. 9 The effect of yield strength of steel tube on fire resistance



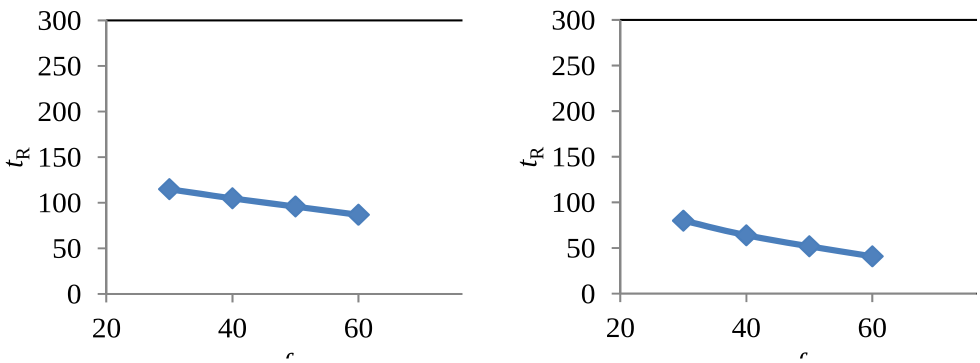
（a） square cross-section （b） circular cross-section

Fig. 10 The effect of yield strength of reinforcing bars on fire resistance



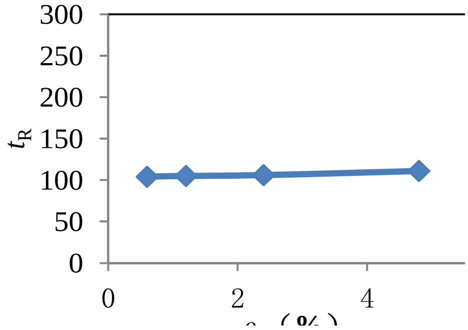
（a） square cross-section （b） circular cross-section

Fig. 11 The effect of the strength of concrete in steel tube on fire resistance

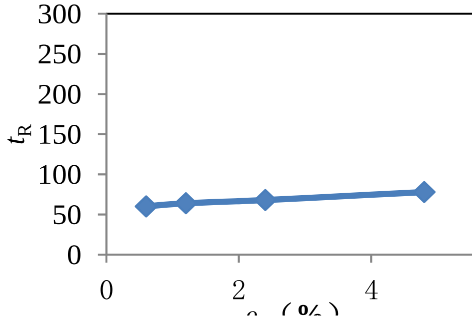


（a） square cross-section （b） circular cross-section

Fig. 12 The effect of the strength of concrete out of steel tube on fire resistance



(a) square cross-section



(b) circular cross-section

Fig. 13 The effect of longitudinal reinforcement ratio on fire resistance

4. PRACTICAL DESIGN FORMULA FOR FIRE RESISTANCE

Due to the protection of the concrete out of steel tube and the interaction of steel tube and core concrete, the CFSTRC columns has a favorable fire resistance. By using the analysis model proposed in the paper, the fire resistance of the columns can be calculated. But the calculation procedure tends to be complicated, so the method is not suitable for practice application. In order to provide reference for the fire design of practical engineering, the simplified calculating formulae are proposed.

From the analysis in section 3, the results can be conclude that axial load level (n), dimension of cross-section (C), sectional core area ratio (α_{sc}) and slenderness ratio (λ) are the mainly influence parameters on the fire resistance of CFSTRC columns. Based on these parameters, a great quantity of calculation and simulation were carried out. On the foundation of these analyses, the practical calculating formulae are put forward. In the range of normal parameter in the practical engineering, that is, α_s=0.04~0.20, f_y=235 ~420MPa, f_{cu}=30~100MPa, C=1200~6000mm, λ=10~200, the fire resistance t_R can be calculated by the following formulae:

For square cross-section:

$$t_R = 37.57 \cdot \alpha \cdot \beta \cdot \frac{e^{1.29C_0}}{\lambda_0^{1.745}} \qquad (8,a)$$

in which, $\alpha = \begin{cases} n_0^2 + 2.745n_0 - 4.538 & n_0 \le 1 \\ \dfrac{-0.763}{n_0^{6.202}} & n_0 \ge 1 \end{cases}$,

$\beta = \alpha_{sc0}^2 - 3.496\alpha_{sc0} + 1.618$,

$C_0 = C/2000, \lambda_0 = \lambda/40, n_0 = n/0.6, \alpha_{sc0} = \alpha_{sc}/0.2$。

For circular cross-section:

$$t_R = 100 \cdot \alpha \cdot \beta \cdot \frac{e^{1.259C_0}}{\lambda_0^{\ 1.591}} \qquad (8,b)$$

in which, $\alpha = \begin{cases} n_0^{\ 2} - 0.188n_0 - 0.923 & n_0 \le 1 \\ \dfrac{-0.116}{n_0^{\ 4.845}} & n_0 \ge 1 \end{cases}$

$\beta = \alpha_{sc0}^{\ 2} - 4.081\alpha_{sc0} + 1.593$,

$C_0 = C/2000, \lambda_0 = \lambda/40, n_0 = n/0.6, \alpha_{sc0} = \alpha_{sc}/0.2$。

The fire resistances of CFSTRC columns predicted using Eq. (8) are compared with numerical model predicted results in Fig. 14(a) and (b) for CFSTRC columns with circular and square sections respectively, there is a good agreement. Fig. 15 shows the predicted fire resistances by Eq. (8) agree well with the experimental results.

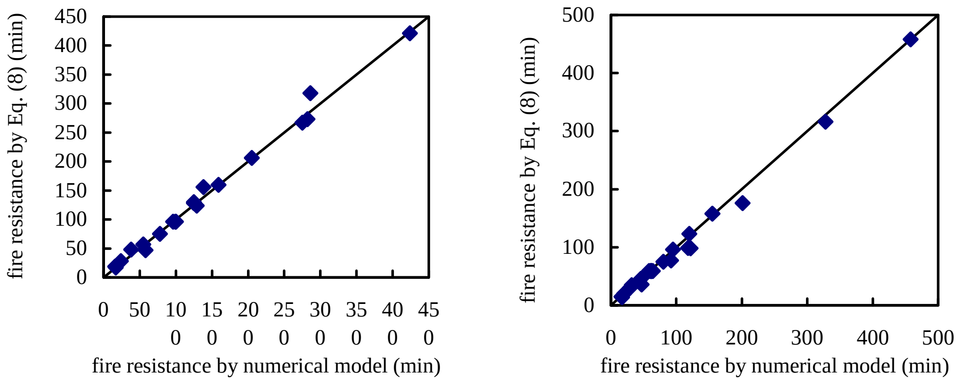


Fig. 14 Comparison of fire resistance between Eq. (8) and numerical analysis results

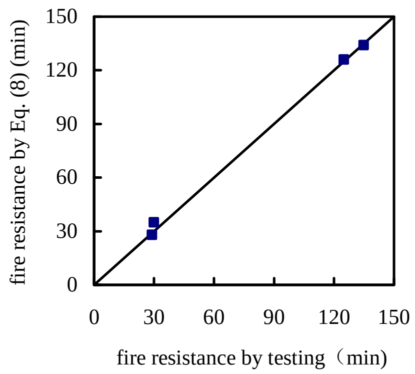


Fig. 15 Comparison of fire resistance between Eq. (8) and test results.

5. CONCLUSIONS

Based on the results of this study, several conclusions can be drawn within the limitations of the research work in this paper:

1. A finite element analysis (FEA) model was established to predict the fire resistance of CFSTRC columns under axial compression. The calculated results using this model shows good agreement with test results.

2. Axial load level (n), dimension of cross-section (C), sectional core area ratio (α_{sc}) and slenderness ratio (λ) are the mainly influence parameters on the fire resistance of CFSTRC columns: (1) The fire resistance decreases dramatically as the axial load level increases, (2) it will increase obviously with the increase of the outer perimeter, (3) when λ is less than 40, the fire resistance decreases obviously as the slenderness ration increases, but the decreasing trend tends to be gently when λ exceeds 40, (4) when the value of α_{sc} is less than 0.35, the fire resistance increases as the sectional core area ratio increases, whereas the fire resistance will decrease with the increase of α_{sc} when the value of α_{sc} is greater than 0.35.

3. A simplified model is developed to calculate the fire resistance of CFSTRC columns. The results predicted by simplified model are compared with the numerical simulation results and tested results respectively. It was found that the predicted results by simplified model are in good agreement with both testing results and numerical simulation results.

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