

Research on the Residual Bearing Capacity of Square Hollow Concrete-filled Steel Tube After Fire

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Abstract. In order to study the change of the residual bearing capacity of square hollow concrete-filled steel tube after fire, the finite element analysis software ABAQUS was used to establish the finite element model of square hollow concrete-filled steel tube under the ISO-834 standard fire heating condition, and the temperature distribution and deformation of the model were simulated and analyzed. Based on that, the influence of parameters such as the strength grade of concrete, the strength grade of steel, the calculated length of member and the hollow ratio of section on the residual bearing capacity of member after fire is simulated and analyzed. The results show that the temperature distribution of the component is mainly affected by the section size, concrete strength grade and steel yield strength, but is less affected by the calculated length. The temperature of the inner concrete and the inner steel tube decreases with the increase of the thickness of the member. The strength of steel and the size of section have more influence on the stress characteristics of the member after fire, but the strength grade of concrete and the length of the member have less influence. Among them, the increase of steel strength, concrete strength will enhance the fire-resistant limits of components. When the hollow ratio of the section increases, the fire resistance limit of the component increases first and then decreases. The increase of the calculated length will reduce the fire resistance limit of the member. The residual bearing capacity of the component decreases with the increase of fire time.

Keywords: Square hollow concrete-filled steel tube; fire test; residual bearing capacity; finite element analysis.

1. Introduction

In super high-rise buildings, concrete-filled steel tube column has better compressive and shear strength and more obvious advantages in static performance. In terms of fire resistance, Han Linhai's [1] experimental research shows that the steel tube can still tighten the concrete after the temperature rises, and the hoop effect between the steel tube and concrete can improve the fire resistance, so as to improve the structural reliability. As an important mechanical component in architecture, the mechanical properties and damage degree of columns under high temperature have always been the focus of research in civil engineering. At present, many scholars at home and abroad have done a series of research on the fire resistance of concrete-filled steel tube composite structures.

Sakino et al [2] first proposed the concept of steel tubular constrained concrete columns and conducted a series of studies on the hysteretic properties of steel tubular constrained concrete columns, successfully proved that the shear bearing capacity of steel tubular constrained concrete columns was significantly higher than that of ordinary reinforced concrete columns, and found that the component failure mode changed from shear failure to bending failure. In addition, Tomii et al [3] conducted an experimental study on the axial compressive capacity of cylindrical tubular concrete column, which considered the influence of steel tube thickness, concrete strength and friction between steel tube and concrete on the member bearing capacity. With the same parameters, the initial stiffness of concrete-filled steel tube was higher than that of concrete-filled steel tube. However, the bearing capacity of steel-tube confined concrete columns is higher. Based on the test results, Tomii et al. proposed the bearing formula of steel-tube confined plain concrete short axial compression columns. Sakino and Sun et al [4-5] made a comparative study of square steel tube confined concrete column and round

steel tube confined concrete column through experiments and studied the influence of steel tube width-thickness ratio and concrete strength on the bearing capacity of steel tube confined concrete column. They found that the bearing capacity of member increased significantly when the strength level of concrete increased. The increase of the ratio of width and thickness of steel tube has an adverse effect on the bearing capacity of the member. T.T. Lie et al [6] conducted a large number of experimental research and theoretical analysis on the fire resistance of reinforced concrete columns with internal reinforcement under fire and found that reinforced steel tubes with internal reinforcement could significantly improve the fire resistance limit and fire reliability. T.T. Lie also put forward the relation between thermal conductivity of steel and temperature.

$$k_s = \begin{cases} -0.022T + 48 & (0^\circ\text{C} < T \leq 900^\circ\text{C}) \\ 28.2 & (T > 900^\circ\text{C}) \end{cases} \quad (1)$$

The formula for calculating the reduction coefficient of concrete compressive strength at high temperature is:

$$k_{cT} = \begin{cases} 1.0 & 0^\circ\text{C} < T \leq 450^\circ\text{C} \\ 2.011 - 2.353\left(\frac{T-20}{1000}\right) & 450^\circ\text{C} \leq T < 874^\circ\text{C} \\ 0 & T \geq 874^\circ\text{C} \end{cases} \quad (2)$$

In the domestic research situation, Liu et al [7] put forward a new component - steel tube restrained profile steel concrete column. The new component places the profile steel inside the concrete, and the member is not equipped with reinforcement. Liu initiated an experimental study on the mechanical performance of the axially compressed steel tubular confined reinforced concrete column under fire conditions, measured the temperature of the key measuring points, the axial deforce-time relationship curve and the fire resistance limit of the component, and conducted a comparative test on the axially compressed steel tubular confined concrete column and the concrete filled steel tubular column, and obtained the failure mode of both under fire conditions. A simplified calculation formula for the temperature of steel tube, steel bar and concrete in steel tube confined reinforced concrete under fire and a simplified calculation formula for the bearing capacity of members are presented.

$$N_u = A_a f_a + A_c f \quad (3)$$

Among them: for steel section area, area for concrete, for steel yield strength, as constraint of concrete compressive strength.

$$f_{cc} = f_c \left(-1.254 + 2.254 \sqrt{1 + 7.94 \frac{f_r'}{f_c}} - 2 \frac{f_r'}{f_c} \right) \quad (4)$$

Among them: design values for axial compressive strength of concrete, for outsourcing the effective restraint stress of steel tube on core concrete.

$$f_r' = \frac{2t_s f_y}{D - 2t_s} \quad (5)$$

Among them: for steel yield strength; D is the outer diameter of the steel tube, and t_s is the wall thickness of the steel tube.

And now the structural fire resistance test, most countries in the world are using the theoretical test curve provided by the International Standards Organization ISO-834, the expression is:

Temperature rise segment:

$$T = T_0 + 345 \log_{10}(8t + 1) \quad (6)$$

Temperature drop segment:

$$k_s = \begin{cases} T_h - 10.417(t - t_h) & t_h \leq 30 \text{ min} \\ T_h - 4.617 \frac{3 - t_h}{60} (t - t_h) & 30 \text{ min} < t_h \leq 120 \text{ min} \\ T_h - 4.617(t - t_h) & t_h > 120 \text{ min} \end{cases} \quad (7)$$

Zhang [8] carried out an axial pressure performance test of reinforced concrete short columns with initial load after the whole process of high temperature action, analyzed the bearing capacity and deformation condition, and the results show that the initial load has an impact on the high temperature axial bearing capacity, stiffness and ductility of reinforced concrete short columns, among which the bearing capacity and stiffness increase, ductility decreases significantly.

To sum up, the existing scholars have carried out a lot of experimental research on the fire resistance limits of concrete-filled steel tube under and after fire and put forward a series of reliable design methods. For square hollow concrete-filled steel tube member, the internal steel tube can provide effective constraints, thus reducing the deformation of the member under fire and improving the stability of the structure. At present, the research on the fire resistance of square hollow concrete-filled steel tube is not enough at home and abroad, and its fire resistance mechanism is not clear. At the same time, the influence of parameters such as hollow ratio, concrete strength and steel yield strength on the fire resistance of square hollow concrete-filled tubular column has not been quantified. Based on this, the author used ABAQUS software to study the fire resistance limit of hollow concrete-filled steel tube column under fire, and quantified the influence of length, hollow ratio, concrete strength, steel yield strength and other parameters on the fire resistance limit of square hollow concrete-filled steel tube.

2. Establishment of finite element model

Finite element software ABAQUS is used to numerically simulate the fire resistance limits of square hollow concrete-filled steel tube after fire. Three-dimensional temperature and mechanical field models were established respectively to study their mechanical properties under axial and eccentric loads, and the following analyses were carried out: Firstly, the finite element model of the temperature field of concrete-filled tubular square hollow column is established, and then the temperature variation rule of the member is analyzed in the heating stage. The temperature rise curve adopts ISO834 fire standard temperature rise curve, and the initial temperature is 20°C. The 8-node three-dimensional solid unit DC3D8 model was adopted for concrete, and the 4-node shell element DS4 model was adopted for both internal and external steel tubes. Tie form was used for restraint between concrete and steel tubes, and the thermal parameters of concrete and steel were referred to the suggestions of T.T. Lie [9]. It should be noted that this model assumes 5% water content in concrete to simulate the effect of water content in concrete on the heat transfer of components. The density of concrete is 2200kg/m³ and that of steel is 7850kg/m³.

The finite element model of mechanical field of hollow concrete-filled steel tube short column under fire condition was established and the deformation of the member under corresponding temperature rise was simulated by the finite element model, and the data of deformation variation with time was obtained.

The mechanical field model is based on the temperature field model. In the mechanical field model, the tension-compressive stress-strain model of concrete and the tension-compressive stress-strain model of steel after fire proposed by Han et al [10] are adopted for both concrete and steel. The Poisson's ratio of steel varies little with temperature and is uniformly set at 0.30, while the Poisson's ratio of concrete is greatly affected by temperature, and the values suggested by Han Linhai et al are also adopted. In the mechanical field model, 8-node three-dimensional solid element C3D8R model is used for concrete, and 4-node shell element S4R model is used for both internal and external steel tubes. Interaction between concrete and inner and outer steel tubes was set up to simulate the binding effect among them, and the tangential friction coefficient was taken as 0.4. When setting constraints, a reference point is set in the center of the upper and lower surfaces of the component, and is bound

with the upper and lower surfaces in rigidbody mode. One end of the component restricts the rotation and displacement in the X, Y and Z directions, while the other end restricts the displacement in the X, Y directions and the rotation in the X and Z directions. The structure can move freely in the Z direction and rotate freely in the XZ plane. Considering the geometric nonlinearity of steel, the initial defect is taken as 1/1000 of the member length.

The elastic modulus of concrete decreases with the increase of temperature. The following fitting methods can be adopted:

$$E(T) = \begin{cases} (100 - 0.0744T) \times 10^{-2} \cdot E & (0 < T \leq 300^{\circ}C) \\ (127.54 - 0.1662T) \times 10^{-2} \cdot E & (300^{\circ}C < T \leq 700^{\circ}C) \\ 0.11E & (700^{\circ}C < T \leq 900^{\circ}C) \end{cases} \quad (8)$$

The relationship between thermal conductivity of steel (k_s , unit: W/ (m·°C)) and temperature suggested by T.T.Lie is as follows:

$$k_s = \begin{cases} -0.22T + 48 & 0^{\circ}C \leq T \leq 900^{\circ}C \\ 28.2 & T \geq 900^{\circ}C \end{cases} \quad (9)$$

The relationship between the product of specific heat (c_s , unit: J/ (kg·°C)) and bulk density (ρ_s , unit: kg/m³) of steel and temperature suggested by T.T.Lie is:

$$\rho_s c_s = \begin{cases} (0.004T + 3.3) \times 10^6 & 0^{\circ}C \leq T \leq 650^{\circ}C \\ (0.068T - 38.3) \times 10^6 & 650^{\circ}C \leq T \leq 725^{\circ}C \\ (-0.086T + 73.35) \times 10^6 & 725^{\circ}C \leq T \leq 800^{\circ}C \\ 4.55 \times 10^6 & T > 800^{\circ}C \end{cases} \quad (10)$$

The relation between the thermal conductivity of concrete (k_c , unit: W/ (m·°C)) and temperature suggested by T.T. Lie is as follows:

$$k_c = \begin{cases} 1.355 & 0^{\circ}C \leq T \leq 293^{\circ}C \\ -0.001241T + 1.7162 & T \geq 293^{\circ}C \end{cases} \quad (11)$$

The relation between the product of specific heat (c_c , unit: J/ (kg·°C)) and bulk density (ρ_s , unit: kg/m³) of concrete and temperature suggested by T.T. Lie is:

$$\rho_s c_c = \begin{cases} 2.566 \times 10^6 & 0^{\circ}C \leq T \leq 400^{\circ}C \\ (0.1765T - 68.034) \times 10^6 & 400^{\circ}C \leq T \leq 410^{\circ}C \\ (-0.05043T + 25.00671) \times 10^6 & 410^{\circ}C \leq T \leq 445^{\circ}C \\ 2.566 \times 10^6 & 445^{\circ}C \leq T \leq 500^{\circ}C \\ (0.01603T - 5.44881) \times 10^6 & 500^{\circ}C \leq T \leq 635^{\circ}C \\ (0.16635T - 100.90225) \times 10^6 & 635^{\circ}C \leq T \leq 715^{\circ}C \\ (-0.22103T + 176.07343) \times 10^6 & 715^{\circ}C \leq T \leq 785^{\circ}C \\ 2.566 \times 10^6 & T > 785^{\circ}C \end{cases} \quad (12)$$

3. Simulation results and analysis

According to the simulation results, the following images can be drawn: FIG. 1 to FIG. 3 are time-displacement curve, displacement-load curve and time-load curve when the strength grade of concrete changes with other variables being the same; FIG. 4 to FIG. 6 show the time-displacement curve, displacement-load curve and time-load curve when the calculated length changes with other variables being the same FIG. 7 to FIG. 9 show the displacement-time curve, load-displacement curve and load-time curve when the strength grade of steel changes with other variables being the same. FIG. 10 to FIG. 12 show the displacement-time curve, load-displacement curve and load-time curve when the hollow-ratio of the section changes with other variables being the same.

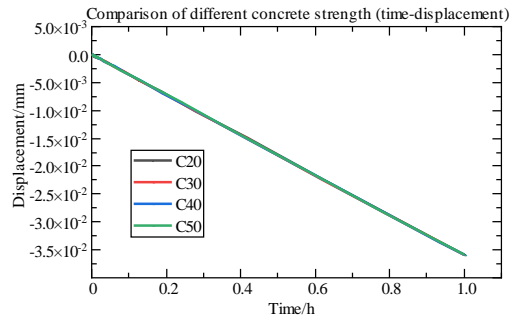


Fig 1. Comparison of different concrete strength.
(Time-displacement).

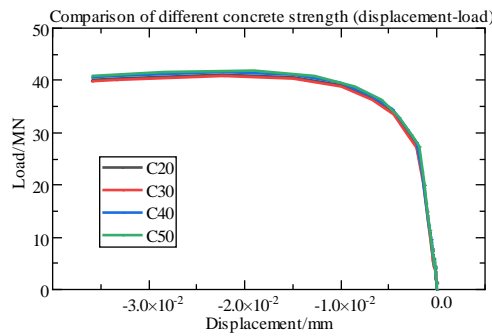


Fig 2. Comparison of different concrete strength.
(Displacement-load).

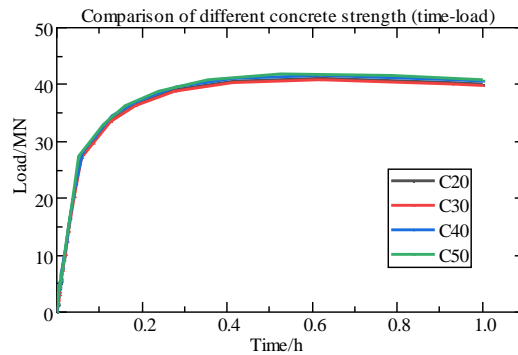


Fig 3. Comparison of different concrete strength.
(Time-load).

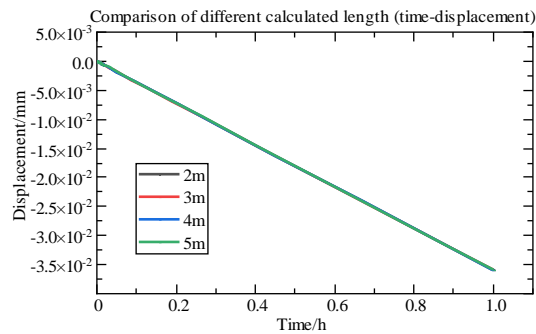


Fig 4. Comparison of different calculated length.
(Time-displacement).

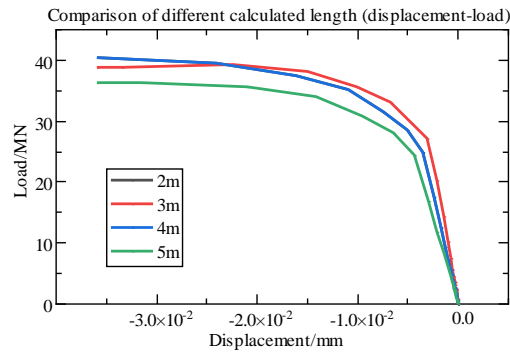


Fig 5. Comparison of different calculated length.
(Displacement-load).

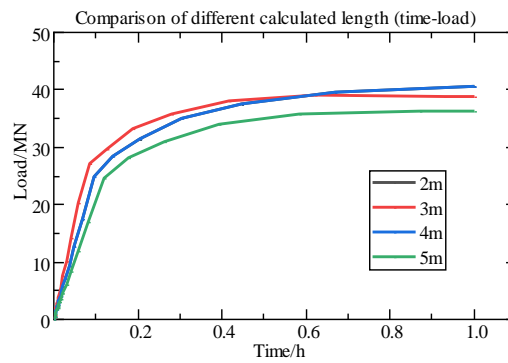


Fig 6. Comparison of different calculated length.
(Time-load).

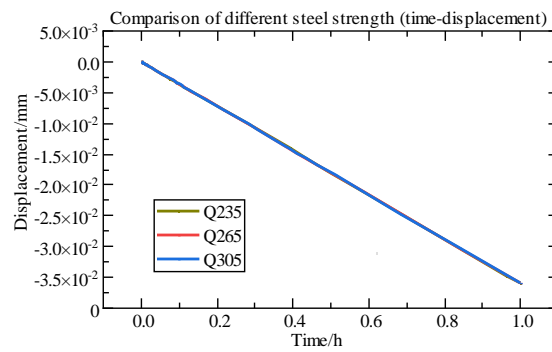


Fig 7. Comparison of different steel strength.
(Time-displacement).

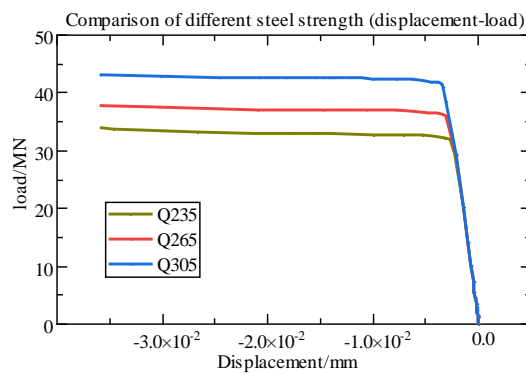


Fig 8. Comparison of different steel strength.
(Displacement-load).

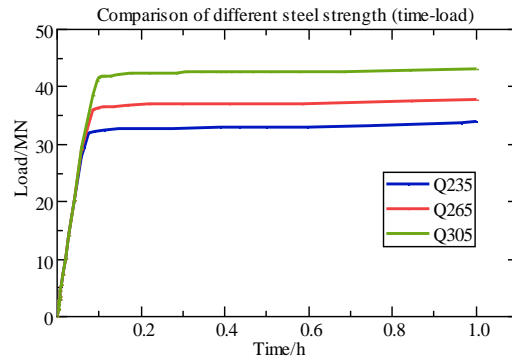


Fig 9. Comparison of different steel strength.
(Time-load)

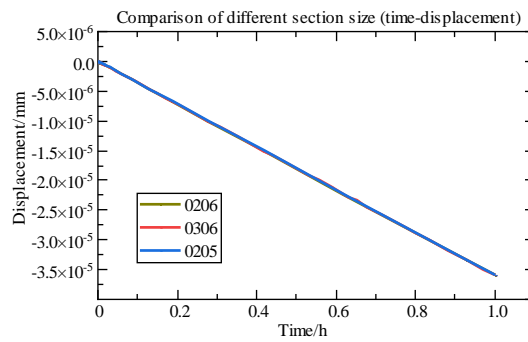


Fig 10. Comparison of different steel strength.
(Time-load).

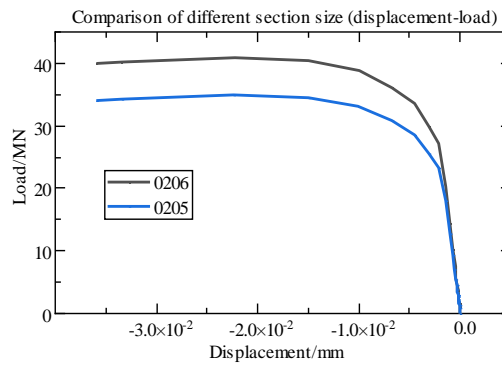


Fig 11. Comparison of different section size.
(Displacement-load).

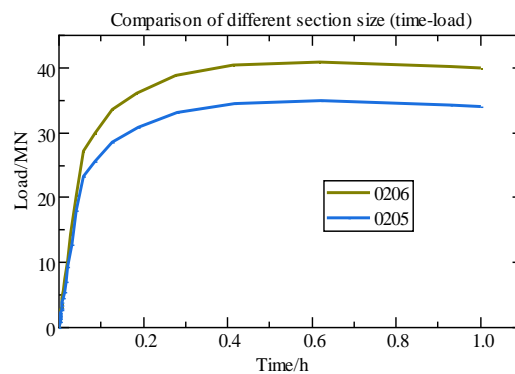


Fig 12. Comparison of different section size.
(Time-load).

The simulation results include temperature field and component deformation.

Temperature field: the temperature distribution is similar under different conditions of concrete strength grade, steel strength, calculated length and section hollow ratio.

The temperature distribution is similar in any cross section, the highest temperature is located in the outer steel tube, reaching more than 500 degrees Celsius, the lowest temperature is located in the inner steel tube, about 20 degrees Celsius, the middle concrete temperature is moderate, the main range is 200-400 degrees Celsius.

Deformation: When setting initial defects, the square hollow concrete-filled steel tubular column will have lateral deformation, and the external load is also eccentric.

The deformation characteristics of concrete strength grade, steel strength and section hollow ratio are similar under different conditions. The calculated length has a great influence on the deformation, and the deformation will increase with the increase of the member length. The member with 5m length has the largest deformation.

At the same time, according to the deformation results, it can be seen that the maximum deformation occurs at the middle point of the column, and the deformation decreases gradually from the middle to both ends. The deformation at both ends is only about 8.33% of the deformation in middle.

4. Conclusion

Through the numerical analysis of the fire resistance limit of the hollow concrete-filled steel tube column, the temperature distribution, mechanical properties and deformation distribution law were quantified. The following conclusions were obtained:

(1) The temperature distribution of the member is mainly affected by the section size, concrete strength grade and steel yield strength, while the calculated length has little effect on the temperature change of the member. The temperature of the inner concrete and the temperature of the inner steel tube decreases with the increase of the thickness of the member.

(2) The mechanical characteristics of the member after fire are greatly affected by the strength of steel and the size of the section, but are less affected by the strength grade of concrete and the length of the member. Among them, the increase of steel strength, concrete strength will enhance the fire-resistant limits of components. When the hollow ratio of the section increases, the fire resistance limit of the component increases first and then decreases. The increase of the calculated length will reduce the fire resistance limit of the member. The residual bearing capacity of the component decreases with the increase of fire time.

The research carried out in this paper only includes part of the possible cases of concrete-filled steel tube under fire. Other cases may also occur in actual occasions:

(1) Study on columns considered in conjunction with the building as a whole. This paper only focuses on the residual bearing capacity of the column itself under fire. In a building, the stress condition and temperature distribution of a column may be affected by other parts of the building, and the fire resistance limit may also change to a certain extent

(2) Study on columns of other cross-sectional form. In this paper, square hollow concrete-filled steel tube section is studied. Other hollow sections may also have better fire resistance performance, which needs further study

(3) Study on fire resistance of hollow concrete-filled steel tube under non-uniform fire condition. When the actual fire occurs, the structural column is mostly subjected to two or three sides of fire, which is different from the four sides of uniform fire studied in this paper, and needs further analysis as well.

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