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Analysis of the Temperature Field and Temperature Response of Reinforced Concrete Beam in Fire

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Abstract. The internal temperature of reinforced concrete members in fire directly influences the stress distribution and attenuation amplitude of performance. With ABAQUS finite element software, it analyzed the change rule about the temperature field of reinforced concrete beams with the development of time, and then to study further the temperature response such as stress, strain, displacement and so on. The analysis results indicated that the temperature increasing rate in the heated side of reinforced concrete beam is faster than the reverse side and internal components, the temperature increasing rate of steel is relatively faster than the concrete in the same position, and that the temperature stress of the former one is larger compared to the latter one. At the beginning stage of the fire, it has the characteristics such as quickly heating, strongly change in temperature response. When the temperature of environment tends to be stable, the development of the temperature stress, strain and displacement of members began to flatten at the same time. Because of the existence of large temperature difference and constraints, temperature stress and displacement will be higher, while the constraint affection become smaller under the action of temperature.

Introduction

Featuring a good integrity and shock resistance, reinforced concrete is one of the most important construction materials at present. Compared with wood structure, steel structure etc., reinforced concrete structure has a better fire resistance. However, the performances of concrete and rebar materials may be subject to a serious degradation in case of a fire, i.e. considerable redistribution of internal force will occur at the internal components and structures, which may result in a significant structural deformation and a significant degradation in performance of relevant structure, or even a threat to safety of the structure, i.e. the risk of total collapse and damage to structure [1]. Temperature field will change as temperature rises, which will bring about a change in temperature response. Because of temperature stress and expansive deformation at a relatively high temperature, stress of internal components will change significantly as time goes on, which will result in an obviously different failure mechanism in comparison with room temperature. Therefore, for analysis about fire resistance of building structure, it is critical to study the change rule for temperature field and temperature response in reinforced concrete structure in fire.

Currently, study of temperature field of reinforced concrete components in fire is mostly subject to finite element numerical simulation method, assisted by experiments. References [2-5] have already verified that the 3D component temperature field simulated by finite element method conforms well to the test results, indicating the feasibility of finite element method to simulate the temperature field of reinforced concrete structure. The studies of temperature stress have mainly focused on the medium- and long-term response of mass concrete during construction and curing [6-7], and there are few studies on transient temperature response of reinforced concrete structure in fire. In Reference[8], temperature stress of steel-tube reinforced concrete column has been calculated with finite element numerical simulation software, with calculated results in compliance with the engineering practices, but no analysis about deformation and displacement caused by temperature stress has been conducted.

In this paper, based on the given indoor heating curve in fire, ABAQUS software is used to establish a 3D finite element calculation model for temperature field of reinforced concrete beam [9,10], to calculate the temperature distributions of reinforced concrete beam at different times in fire, to further analyze the change rule of thermal stress, strain and displacement of reinforced concrete beam and lay a certain foundation to further study the mechanical properties and fire endurance of reinforced concrete structure at a relatively high temperature.

Basic Principle of Thermal Analysis

Heat can be transferred through thermal conduction, thermal convection and thermal radiation. In fire, heat is transferred to components through thermal convection and thermal radiation, and then the heat flow on surface is transferred towards the internal components through thermal conduction of components.

Thermal Conduction.

Thermal conduction is also called thermal conductivity, and can be defined as exchange of internal energy between two objects in total contact or between different portions of one object due to temperature gradient. Based on the Fourier's Law of Thermal Conduction, equation of 3D transient thermal conduction of reinforced concrete components is provided as follows:

$$\rho c \frac{\partial T}{\partial t} = \lambda \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] \quad (1)$$

Where: λ - coefficient of thermal conduction of material, W/(m·K)

ρ - mass density of material, kg/m^3

c - mass heat capacity of material, J/(kg·K)

T - temperature, K

t - time, s

Thermal Convection.

Thermal convection refers to exchange of heat between surface of solid and flow in contact with such surface due to existence of temperature difference. Based on the Newton's Law of Cooling, equation of heat flow transferred from air to components through thermal convection is provided as follows:

$$q = h \cdot (T_w - T_\infty) \quad (2)$$

Where: q - heat exchanged between surface of solid in unit area and flow within unit time, called heat flux, W/m^2.

h - coefficient of thermal convection on surface, taken as 25 W/(m^2·K)

T_w - temperature on surface of component, K

T_∞ - temperature of flow, K

Thermal Radiation.

Thermal radiation refers to a heat exchange process in which an object emits electromagnetic energy which is absorbed by other objects and converted into heat energy. Based on the Stefan-Boltzmann's Law, equation of heat transferred from air to components through thermal radiation is provided as follows:

$$E = \varepsilon \cdot \sigma \cdot \left[T_\infty^{\,4} - T_w^{\,4} \right] \quad (3)$$

Where: E - total radiant energy emitted by an object at some temperature and in unit surface area and unit time, W/m^2.

ε - comprehensive coefficient of radiation, taken as 0.5

σ - Stefan-Boltzmann constant, taken as 5.67×10^{-8}W/(m^2·K^4)

T_∞ - temperature of flow, K

T_w - temperature on surface of component, K

Fire Model.

As for the calculation model used in this paper, fire heating curve ISO-834 prepared by the International Standardization Organization (ISO) is used:

$$T = T_0 + 345 lg(8t - 1) \tag{4}$$

Where: T - temperature at time t, °C

T_0 - initial temperature, taken as 20°C

t - heating time, min

Material Parameters

Thermal Performance of Material.

Thermal parameters of materials (including coefficient of thermal conduction, mass heat capacity, linear expansion coefficient of temperature and mass density) are one of the essential prerequisites to solve the temperature field.

Thermal Parameters of Concrete.

Coefficient of thermal conduction and mass heat capacity of concrete are both subject to the equation below given in the Eurocode [11]:

$$\lambda_c = 2 - 0.24\frac{T}{120} + 0.012\left[\frac{T}{120}\right]^2 \qquad 20°C \le T \le 1200°C \tag{5}$$

$$c_c = 900 + 80\frac{T}{120} - 4\left[\frac{T}{120}\right]^2 \qquad 20°C \le T \le 1200°C \tag{6}$$

Linear expansion coefficient of temperature of concrete is subject to the equation below given in Lie[12]:

$$\alpha_c = (0.008T + 6) \times 10^{-6} \tag{7}$$

Within the range of temperature change in fire, mass density of concrete changes only a little, and is therefore deemed as a constant, taken as ρ_c=2400kg/m^{3}in this paper.

Thermal Parameters of Rebar.

Coefficient of thermal conduction of rebar is subject to the equation below given in the Eurocode [11]:

$$\lambda_s = \begin{cases} 54 - 3.33 \times 10^{-2}T & 20°C \le T \le 800°C \\ 27.3 & T > 800°C \end{cases} \tag{8}$$

Mass heat capacity of rebar is subject to the equation below given in the ECCS (European Conwebtion for Constructural Steelwork) [13]:

$$c_s = 38 \times 10^{-5}T^2 + 20 \times 10^{-2}T + 470 \qquad 20°C \le T \le 1200°C \tag{9}$$

Linear expansion coefficient of temperature of rebar is subject to the equation below given in Lie[12]:

$$\alpha_s = \begin{cases} (0.004T + 12) \times 10^{-6} & T < 1000°C \\ 16 \times 10^{-6} & T \ge 1000°C \end{cases} \tag{10}$$

Within the range of temperature change in fire, mass density of rebar changes only a little, and is therefore deemed as a constant, taken as ρ_s=7800kg/m^3 in this paper.

Thermal Constitutive Relations of Materials.

Constitutive relations of materials are one of the essential prerequisites to determine the thermal stress of component. The values of elasticity modulus and Poisson's ratio of rebar and concrete are listed in the Table 1 below provided that rebar and concrete are both elastic materials and elasticity modulus will not change with temperature.

Table 1 Constitutive Relations of Materials

Materials	Elasticity Modulus/Pa	Poisson's Ratio
C30 concrete	30×10^9	0.2
HRB335 rebar	200×10^9	0.3

Example Analysis

Modeling.

As for calculations in this paper, sectional dimension of reinforced concrete beam in fire is b×h×l=200mm×400mm×6000mm, thickness of concrete cover is taken as 25mm, and model of rebar is Φ20. Refer to Fig. 1 for sectional view. In order to shorten the operation time, beam in 1/10 of its length (600mm) and 1/2 of its width (100mm) is taken for analysis, with nodes as major study areas. In this case, left and top of the beam are unheated sides. Refer to Fig. 2 for the finite element model established.

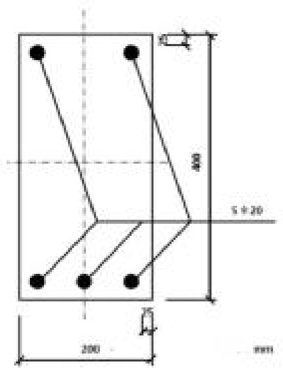


Fig. 1 Schematic Diagram of Reinforced Concrete Beam

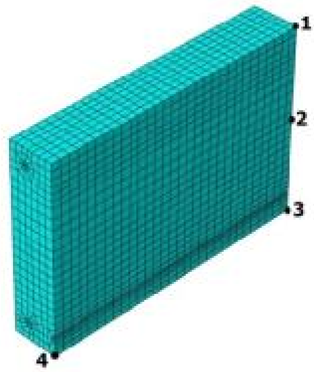
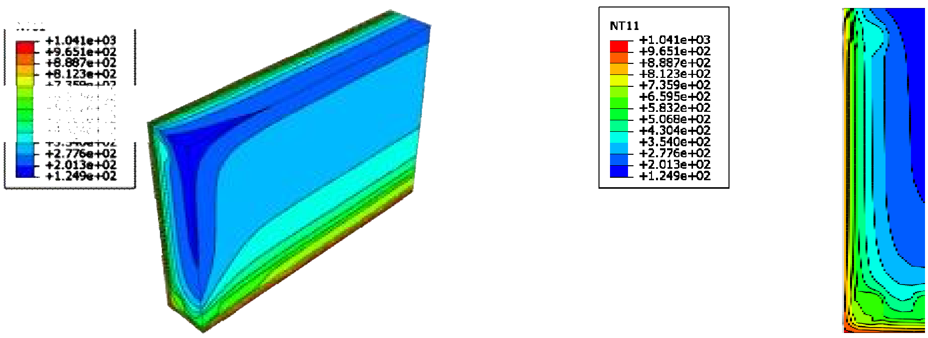


Fig. 2 Finite Element Model of Reinforced Concrete Beam

Analysis about Temperature Field.

ABAQUS/Standard module, heat transfer analysis steps (Heat transfer) and 3D 8-node linear thermal analysis unit DC3D8 are used for analysis about temperature field. Analysis about temperature field may exclude consideration of influence by stress field because only the distribution of temperature field is taken into account and the internal forces and deformations of a variety of structures will generally not influence the heat transfer processes of those structures. Neither the constitutive relations of materials nor the boundary conditions are defined. Expansive deformation of the model may not be considered provided that there is no bond slip between concrete and rebar. Refer to Fig. 3 for temperature distribution of reinforced concrete beam in 2h under the heating conditions of ISO834.



(a) Side View (b) Front View

Fig. 3 Nephogram of Temperature Field of Component in Fire for 2h

According to Fig. 3(a), temperatures at left and top of the reinforced concrete beam are lower than them at other portions. This is because the left end face and top face of the beam are respectively connected with column and floor slab and are of unheated sides, so heat can only transfer through thermal conduction of internal components. According to Fig. 3(b), there is an abnormal change in temperature field at rebar, i.e. obvious tendency to internal components. This is because the thermal conduction rate mainly relies on the coefficient of thermal conduction of material. The thermal conduction rate of steel is higher than that of concrete because the coefficient of thermal conduction of steel is higher than that of concrete.

For the purpose of analyzing the change rule of temperature with development of time at different positions of reinforced concrete beam, 4 critical positions are selected (refer to Fig. 2), and a temperature-time curve is drawn (refer to Fig. 4).

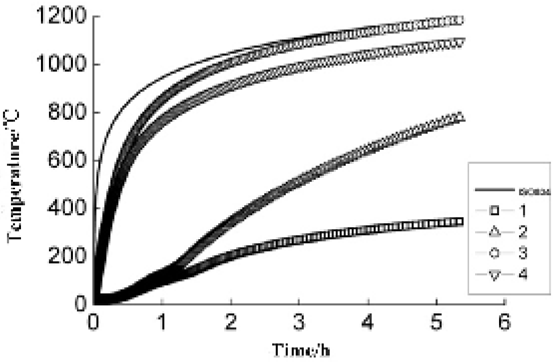


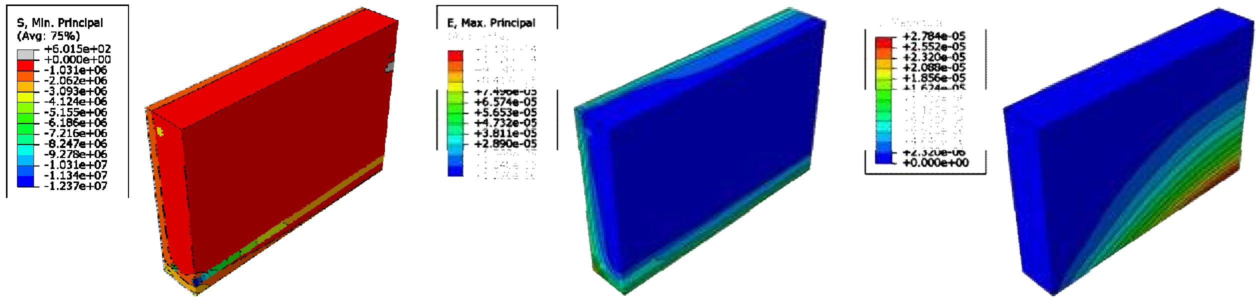
Fig. 4 Temperature-time Curve of Temperatures at Critical Positions

According to Fig. 4: Temperature rises rapidly at positions 3 and 4, followed by position 2, and then point 1. Position 3 is selected on heated side, where the surface temperature is close to ambient temperature. After the temperature becomes stable for a relatively long time, temperature at position 3 has been basically equal to the ambient temperature. Position 4 is selected at the end of the beam, i.e. at the node between heated side and unheated side, so the temperature rises relatively rapidly in this position. However, the final temperature is lower than the ambient temperature. At position 1, temperature rise shows a relatively gentle trend, and the temperature at this position is still below 400℃ even when ambient temperature rises to 1200℃, this is because the top end of the beam is an unheated side, so temperature can only be transferred through thermal conduction of heat from two heated sides of the beam. Position 2 is selected at the center of the beam section. Heat at this position is transferred from two sides and three heated undersides, so temperature at this position is higher than that at position 1. It can be seen from the analysis above that: The temperature rise will become more and more gentle and temperature will become lower and lower as the distance away from the heated side increases.

Temperature Response Analysis.

Temperature differences will come out at different portions of the materials as temperature changes, resulting in uneven thermal expansion or shrinkage. However, free expansion and shrinkage due to temperature change at different portions are not allowed as any object still needs to be kept as a continuous whole. The stress arising from any external constraints and mutual constraints between different internal components which may restrict the complete free expansion is referred to as the temperature stress. The produced temperature stress will inevitably result in temperature deformation and displacement, which will bring about adverse impact on structural components.

ABAQUS can provide sequential coupling thermal stress analysis functions: The stress-strain field in this kind of analysis depends on temperature field, but temperature field is not influenced by stress-strain field. Temperature stress is suitable for being solved with ABAQUS/standard, general statistical analysis step (Static General) and 3D 8-node linear decrement integral unit C3D8R. First of all, heat transfer analysis is conducted, and then the obtained temperature field is used as known conditions for thermal stress analysis, so as to obtain the stress-strain field. Calculated results of temperature field for 10min are imported into the thermal stress analysis module. Those calculated results are shown in Fig. 5.

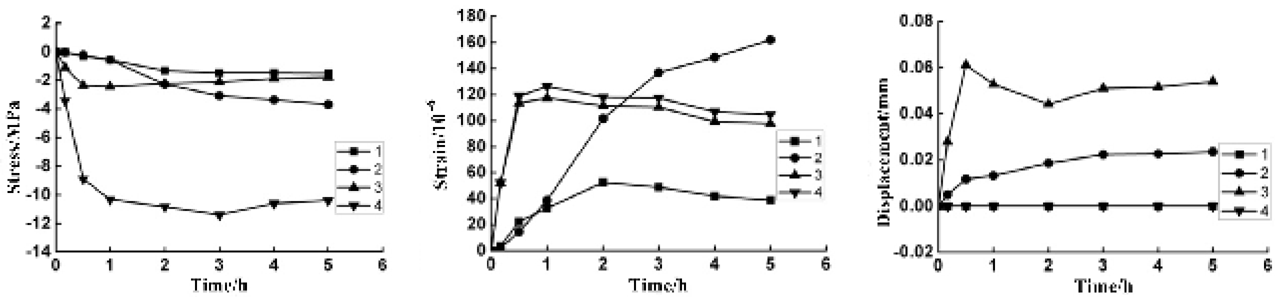


(a) Nephogram of Maximum Principal Stress　(b) Nephogram of Maximum Principal Strain　(c) Nephogram of Displacement

Fig. 5 Temperature Response in Fire for 10min

Nephogram of the maximum principal stress of reinforced concrete beam under temperature action is shown in Fig. (5a): In this case, stress applied to components is dominated by compressive stress (in ABAQUS, tensile stress is positive and compressive stress is negative), which is in compliance with the actual thermal expansion. Compressive stress around the heated side is greater than that of internal components because of a higher degree of expansion at a greater temperature difference around the heated side. At the same position, the compressive stress of rebar is greater than that of concrete mainly because the elasticity modulus and linear expansion coefficient of temperature of rebar are greater than them of concrete. Moreover, at the same position, temperature of rebar is higher than that of concrete, so that rebar will be subject to a greater temperature deformation than concrete, which will result in a higher temperature stress. There are greater stresses at the ends of reinforced concrete beam because of a greater thermal secondary force under the restraining action of columns at those ends. Fig. 5(b) is the nephogram of the maximum principal strain of reinforced concrete beam under temperature action, indicating that all strain values are positive, which mean that the components are being compressed. Strains around the components are greater than them of internal components also because of a greater temperature strain caused by a higher temperature stress around the components. Fig. 5(c) is the nephogram of displacement of reinforced concrete beam under temperature action, indicating that displacement at the position close to left end and the position close to top end of the beam is little or even zero. This is because those two positions are constrained by columns and plates. The position far away from the boundary constraint is subject to a greater displacement.

It can be seen from the analysis above that temperature response varies at different positions of components. In order to further analyze the change rules of temperature stress, strain and displacement of reinforced concrete beam along with temperature change, temperature response during 5h of heating under heating conditions of ISO834 is analyzed at four selected positions (Fig. 2), as shown in Fig. 6.



(a) Stress-time Curve　(b) Strain-time Curve　(c) Displacement-time Curve

Fig. 6 Temperature Response-time Curve at Critical Positions

It can be seen from Fig. 6(a) that: The maximum principal stresses at each of those critical positions are all of compressive stresses throughout the fire. Positions 1 and 2 are selected on the unheated sides of components, so during the fire, heat transferring to those two positions is delayed, resulting in a corresponding delay in increase of temperature stress. In addition, as those positions are far away from the heated side, temperatures at them keep a gentle rise trend throughout the whole time, and temperature stresses keep an increasing trend. Compressive stresses at positions 3 and 4 have experienced a sudden increase along with the rise of temperature at the beginning, and then showed a relatively gentle trend. This is because positions 3 and 4 are selected on the surfaces of components where temperature has experienced a sudden rise in case of a fire, resulting in a thermal expansion in concrete material and a sudden increase in compressive stress. Temperature difference at boundaries of the components are gradually reducing as ambient temperature is becoming stable and heat is being transferred to the internal components, so that the temperature stress is becoming stable and reducing a bit later. In addition, a greater thermal secondary stress is caused by boundary constraint at position 4 in contact with column, so temperature stress at position 4 is much greater than that at the other three positions.

Strain is caused by deformation under stressed action on object, reflecting the degree of deformation of the object. It can be seen from Fig. 6(b) that: Strain change trends at positions 3 and 4 are similar to the stress change trends at the same positions, i.e. they have experienced a sudden increase at the beginning, and then become stable and gradually reduced a bit after 0.5h. Strain at position 2 increases as temperature rises, and reaches the maximum value after 3h, which indicates that the deformation of internal components is greater than that around the components after 3h. Deformation and strain at position 1 are relatively small because of the boundary constraints.

The existence of temperature stress can inevitably cause temperatures deformation, which can further result in displacement. It can be seen from Fig. 6(c) that: Displacements at positions 1 and 4 are always zero under the boundary constraints at these positions. At position 2 which is selected at the center of components and only subject to mutual constraints between internal components, displacement at it increases as temperature rises. Displacement at position 3 which is selected on the boundaries of components where there are no boundary constraints is greater than those at the other three positions. Displacements at each of the critical positions selected have all become stable when the fire lasts for a very long time.

According to Fig. 6, stress, strain and displacement are all subject to a significant change at the beginning of the fire, this is because temperature rises rapidly at the beginning of the fire model, in this case temperature on the surfaces of the components first reaches the fire temperature with temperature of internal components close to room temperature, which results in the maximum temperature difference throughout the fire, so a greater temperature response exists at this time.

Conclusions

(1) Temperature rises rapidly at the portions of reinforced concrete beam close to heated side and then gradually becomes stable to ambient temperature; temperature rises in a time delay at internal components and around unheated side, showing a gentle trend and always much lower than ambient temperature.

(2) Temperature rises in a rate at rebar higher than at concrete in the same position, resulting in a greater temperature stress at rebar than at concrete.

(3) Temperature rises rapidly at the beginning of the fire, and during this period, temperature response changes strongly due to a huge temperature difference between insides and outsides of components. Changes of temperature stress, strain and displacement in components are becoming gentle as ambient temperature is becoming stable.

(4) Great temperature stress is caused by huge temperature difference and constraints, and may further cause increase in temperature strain, i.e. the greater deformation. The smaller the constraint effect is, the greater the displacement under temperature action is.

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