

Study on Residual Life of Concrete Structural Beams and Plate after Fire

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Abstract: Fire has great influence on the durability of buildings, so it is necessary to predict the remaining life of structures after fire. Taking the concrete structure fire of a large shopping mall in a city as an example, the prediction model of the residual life of the concrete structural members was established based on the concrete carbonization mechanism, and the residual life of the beam and plate members was predicted, which could provide a basis for the later reinforcement design or evaluation.

Keywords: Fire, Concrete carbonization, Durability, Reinforcement design, Remaining life.

1. Introduction

Concrete carbonization is a natural physico-chemical process, which is caused by the infiltration of carbon dioxide in the surrounding environment into the concrete through the pores in the matrix[1]. It can change the high alkaline environment of the concrete itself, resulting in the destruction of the passivation film of the internal steel bar, and thus the corrosion of the steel bar. Ambient temperature has a significant influence on concrete carbonation. The higher the temperature, the faster the carbonation speed and the deeper the carbonation depth[2]. In case of fire, the carbonization of concrete structure is accelerated, which greatly affects the durability of the structure.

2. Calculation of Carbonation Depth of Concrete

Concrete carbonization is closely related to the surrounding fire temperature. In view of the different specific fire location, fire time and fire area of each concrete member in the fire site, the damage degree of the member after fire is obviously different. This paper uses the temperature field distribution theory to calculate the temperature of the concrete member at high temperature. For simplicity, the location with the highest temperature of the fire site was selected for calculation.

2.1. Temperature expression of concrete member

By observing the actual situation of fire development, it can be concluded that fire starts from growth-flourishing period to decay period. The temperature of concrete members has experienced a changing process from low to high, and then from high to low. Compared with the research results of some scholars, the sine curve can be closer to the actual situation of fire than the standard fire curve[3]. Surface temperature $\theta(t)$ expression of concrete member:

$$\theta(t) = \theta_{\max} \sin\left(\frac{\pi}{Tk}t\right) \quad (1)$$

In the expression:

θ_{\max} (°C)—represents the maximum fire temperature;

t (min)—represents the time from the start of the fire to a certain point in the fire process;

k (min)—represents the duration from the start to the end of the fire;

T —Represents the coefficient of fire duration, The general value is 0.6~1.0;

The determination of the maximum temperature θ_{\max} at the fire site is related to the type, characteristics, quantity, distribution, unit calorific value, combustion conditions and ventilation conditions of the burning fuel. It can be determined according to the characteristics of the residue in the fire, the burning condition of the structure appearance and the damage of the appendages. For example: Windows and doors glass and glass ornaments greater than 700°C softening or sticking, aluminum doors and Windows and accessories, decorative materials, kitchenware more than 650°C drops formed, construction plastic polyethylene, silicon, polyurethane more than 50°C softening.

2.2. The plate of concrete member

2.2.1. Internal temperature equation of the plate

The steel bar occupies a relatively small area in the concrete slab, so it is assumed that its temperature is the same as that of the surrounding concrete, and the influence of its own heat dissipation is ignored. Therefore, the internal temperature equation of the slab member can be simplified as the mean concrete heat conduction problem. The thermal diffusivity of ordinary concrete is not significantly affected by temperature and is generally considered to be a constant, that is $a = \lambda / (c \cdot \rho)$, λ is thermal conductivity, c is specific heat capacity and ρ bulk density. For the one dimensional heat conduction concrete slab members, the equation can be solved by using the assumption of a semi-infinite body.

According to literature[4], the heat conduction differential equation of a one-dimensional concrete slab semi-infinite object is as follows:

$$\frac{\partial \theta}{\partial t} = a \cdot \frac{\partial^2 \theta}{\partial x^2} \quad (2)$$

In the expression:

a —represents the thermal diffusivity, For ordinary

concrete, $a = 0.8mm^2 / s$;

x —represents the vertical distance between any point inside the concrete slab and the heated surface.

Assume that the initial temperature of the component is the indoor temperature of $\theta_0 = 20^\circ C$, boundary conditions for temperature variation at a heated surface ($x = 0.0$):

When $t = 0$, $\theta(0, x) = \theta_0 = 20^\circ C$;

When $x = 0$, $\theta(t, 0) = \theta_{\max} \sin \frac{\pi}{\alpha\omega} t + \theta_0$;

When $x \rightarrow \infty$, $\theta(t, x) = \theta(t, \infty)$ is a finite value.

According to (2), the internal temperature field can be expressed as follows:

$$\theta(t, x) = \theta_{\max} e^{-\sqrt{\frac{\pi}{2a\alpha\omega}}x} \sin\left(\frac{\pi}{\alpha\omega}t - \sqrt{\frac{\pi}{2a\alpha\omega}}x\right) + \theta_0 \quad (3)$$

According to the above formula, when the maximum temperature reached at any point in the plate of a concrete member, that is, when $\sin\left(\frac{\pi}{\alpha\omega}t - \sqrt{\frac{\pi}{2a\alpha\omega}}x\right)$ is equal to 1, the expression is transformed into:

$$\theta(t, x)_{\max} = \theta(x)_{\max} = \theta_{\max} e^{-\sqrt{\frac{\pi}{2a\alpha\omega}}x} + \theta_0 \quad (4)$$

Considering the actual situation, Formula (4) was appropriately modified and later used as the formula to solve the temperature inside the concrete slab, as follows:

$$\theta(x)_{\max} = k' \theta_{\max} e^{-\sqrt{\frac{\pi}{2a\alpha\omega}}x} + \theta_0 \quad (5)$$

In the expression:

k' —represents the temperature correction coefficient of the plate. It can be seen from the literature[3] that its expression is $k' = 1/(1.22 - 0.0013\omega')$, among them, ω' — said the fire duration (Min).

2.2.2. The carbonization depth of concrete slab is determined

For safety reasons, the concrete slab members are assumed to be fully carbonized at temperatures above $400^\circ C$. Then $\theta(x)_{\max} = 400^\circ C$, substitute into equation (5) to get:

$$x = \sqrt{\frac{2a\alpha\omega}{\pi}} \ln\left(\frac{k' \theta_{\max}}{400 - \theta_0}\right) \quad (6)$$

The carbonization depth of concrete slab members can be determined by the above formula.

2.3. Concrete beam member

2.3.1. Internal temperature equation of the beam

In the fire, in addition to the bottom surface of the beam, the two sides are also heated, the heating condition is different

from that of the plate, is a three-sided heating member. So the temperature field distribution in the beam is very complicated. The heat conduction problem of beam can be simplified to two-dimensional heat conduction problem, whose heat conduction differential equation is as follows[4]:

$$\frac{\partial \theta}{\partial t} = a \cdot \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) \quad (7)$$

In the expression:

a — represents thermal diffusivity. In general, ordinary concrete $a = 0.8mm^2 / s$;

x, y —represents the two-dimensional coordinates of a point in the beam.

Considering that the beam is heated on multiple sides and the temperature Angle is in the range of corner points, the analysis shows that the isotherm in the beam can be well fitted by using the elliptic family trajectory with the center position unchanged and the ratio of long and short axes constant, as shown in FIG. 1.

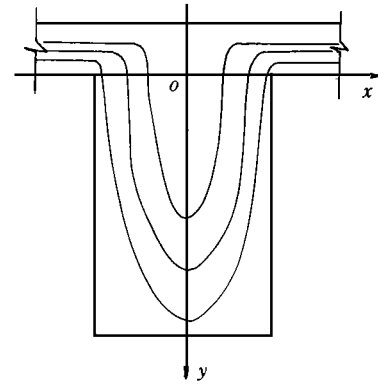


Figure 1. Curve fitting of rectangular beam member isotherms

The temperature on the isotherm can be determined by the temperature of each corresponding point on the X-axis, while the temperature of each point in the beam whose coordinate y is not equal to zero can be converted into the temperature of a corresponding point on the X-axis by the corresponding geometric relation. For the beam with a rectangular section, the relation is:

$$x' = b/2 - \sqrt{4x^2 + k^2 y^2} / 2 \quad (8)$$

In the expression:

b (mm)— stands for beam width;

k — stands for beam width to height ratio;

x' (mm)— represents the conversion distance from the heating surface to the corresponding point on the X-axis;

x, y —represent coordinate values at a point in the beam.

Considering that the beam is heated on multiple sides, the heat conduction is not only related to the beam size b and h , but also to the ratio k of the two. The solution of one-

dimensional heat conduction problem is modified to solve the temperature of the corresponding points on the X-axis, namely:

$$\theta(x) = k' \cdot \theta_{\max} e^{-\sqrt{\frac{\pi}{2a\alpha\omega}}x} + \theta_0 \quad (9)$$

In the expression:

k' —represents the temperature correction coefficient of the beam, and its expression is:

$$k' = 1.353 - 0.5443k - 0.01k + 0.056x \quad (10)$$

For the temperature of points on the non-x-axis inside the beam, only x in formulas (9) and (10) can be converted into distance x' .

2.3.2. The carbonization depth of concrete beam

The carbonization depth of the beam can be calculated by substituting the result of x into x' from Equation (10) into Equation (6).

3. Prediction of Residual Carbonation Life of Concrete Structure After Fire

3.1. Residual life of concrete carbonation

Literature[5] proposed the random model of concrete carbonation depth as follows:

$$D = k\sqrt{t} \quad (11)$$

In the expression:

b (mm)—represents the measured carbonation depth of concrete ;

t —represents the time needed to measure the carbonation depth D of concrete;

k — represents the the carbonation coefficient, According to the following formula:

$$k = 2.56\mu_{K_{mc}} \cdot k_j \cdot k_{CO_2} \cdot k_p \cdot k_s \cdot \sqrt[3]{T_0 RH(1-RH)} \cdot \left(\frac{57.94}{f_{cuk}} - 0.76 \right) \quad (12)$$

In the expression:

$\mu_{K_{mc}}$ — represents the average value of uncertainty coefficient of carbonization calculation model, it's usually $\mu_{K_{mc}} = 0.996$;

k_j — represents the position influence coefficient, which is 1.4 for the Angle region and 1.0 for the non-angle region of the component;

k_{CO_2} —represents the influence coefficient of CO_2 concentration, $k_{CO_2} = \sqrt{C_0/0.03}$, C_0 is CO_2 concentration;

k_p —represents the influence coefficient of maintenance pouring, it's usually $k_p = 1.2$;

k_s —represents the influence coefficient of working stress, the value is 1.0 under compression and 1.1 under tension;

T_0 (°C)—stands for ambient temperature;

RH —indicates the relative humidity of the environment;

f_{cuk} (MPa) —represent the standard value of concrete strength.

Substitute the expression (6) into equation (11) to find the corresponding time t_0 [6], as follows:

$$t_0 = \frac{2a\alpha\omega}{k^2\pi} \ln^2 \left(\frac{k'\theta_{\max}}{400 - \theta_0} \right) \quad (13)$$

In the expression:

t_0 — represents fire equivalent carbonation time.

It is assumed that the structure fails when the depth of carbonation hits the steel bar. Therefore, the remaining carbonation life of concrete structure after fire can be expressed as:

$$T = \frac{s^2}{k^2} - \frac{2a\alpha\omega}{k^2\pi} \ln^2 \left(\frac{k'\theta_{\max}}{400 - \theta_0} \right) \quad (14)$$

In the expression:

T — represents the remaining carbonation life of concrete structure after fire;

s — represents the thickness of protective layer of concrete structure;

$\frac{s^2}{k^2}$ —represents the durability life of concrete structure against carbonization.

3.2. Examples of engineering

A fire broke out in a large shopping mall in a city. The concrete frame structure needs to be tested to determine the remaining life of a concrete beam and slab. The design strength class of the concrete beam is C30, and the design strength class of the slab is C25. The thickness of the protective layer of the beam is 30mm, and the thickness of the protective layer of the slab is 25mm. According to the on-site residue fire investigation and analysis, the ambient temperature of the beam and plate members of the structure was in the high temperature of 700°C when the fire broke out, and the duration was 1 hour and 20 minutes. Predict the remaining carbonation life of the concrete slab.

3.2.1. Concrete slab member

According to the surrounding environment of the plate member, the following data can be obtained:

$\mu_{K_{mc}} = 0.996$, $k_j = 1$, $k_{CO_2} = 2.45$, $k_s = 1.1$, $T_0 = 18^\circ C$, $RH = 0.75$, $f_{cuk} = 18MPa$, Substituting into the expression (12), we get:

$$k = 2.56 \times 0.996 \times 1.0 \times 2.45 \times 1.2 \times 1.0 \times \sqrt[3]{18 \times 0.75 \times (1 - 0.75)} \times \left(\frac{57.94}{18} - 0.76 \right) = 7.83$$

$$k' = 1 / (1.22 - 0.0013\omega) = 1 / (1.22 - 0.0013 \times 80) = 0.90$$

The above data are substituted into Equation (14) to

determine the remaining carbonization life of concrete structural slab members after fire:

$$T = \frac{s^2}{k^2} - \frac{2a\alpha\omega}{k^2\pi} \ln^2 \left(\frac{k'\theta_{\max}}{400 - \theta_0} \right)$$

$$= \frac{25^2}{7.83^2} - \frac{2 \times 0.6 \times 0.8 \times 4800}{7.83^2 \times 3.14} \ln^2 \left(\frac{0.90 \times 4800}{400 - 18} \right) = 10.20 - 5.89 = 4.31$$

years

3.2.2. Concrete beam member

The beam section size is $b \times h = 350\text{mm} \times 500\text{mm}$, the surrounding environment data is as follows: $\mu_{K_{mc}} = 0.996$, $k_j = 1.4$, $k_{CO_2} = 2.45$, $k_s = 1.1$, $T_0 = 18^\circ\text{C}$, $RH = 0.75$, $f_{cuk} = 20\text{MPa}$, beam in the high temperature coordinates of $x = -75\text{mm}$, $y = 350\text{mm}$, as shown in figure 2.

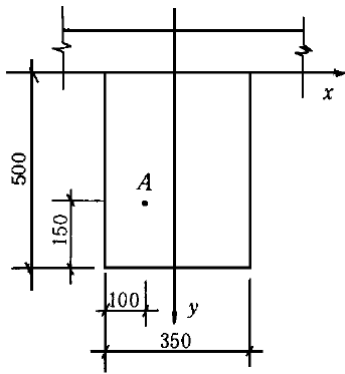


Figure 2. Maximum temperature coordinates of rectangular beam members

By substituting relevant data into expressions (8), (10) and (12), we can get:

$$x' = 350/2 - \sqrt{4 \times 75^2 + 0.7^2 \times 350^2} / 2 = 31.4\text{mm}$$

$$k' = 1.353 - 0.5443 \times 0.7 - 0.001 \times 80 + 0.0056 \times 31.4 = 1.068$$

$$k = 2.56 \times 0.996 \times 1.4 \times 2.45 \times 1.2 \times 1.1 \times \sqrt[3]{18} \times 0.75 \times (1 - 0.75) \times \left(\frac{57.94}{20} - 0.76 \right) = 9.53$$

The above data are substituted into Equation (14) to determine the remaining carbonization life of beam members

of concrete structure after fire:

$$T = \frac{s^2}{k^2} - \frac{2a\alpha\omega}{k^2\pi} \ln^2 \left(\frac{k'\theta_{\max}}{400 - \theta_0} \right)$$

$$= \frac{30^2}{9.53^2} - \frac{2 \times 0.6 \times 0.8 \times 4800}{9.53^2 \times 3.14} \ln^2 \left(\frac{1.068 \times 4800}{400 - 18} \right) = 9.92 - 7.29 = 2.63 \text{ years}$$

It can be seen from the above that in case of fire, the carbonization of concrete structure is extremely accelerated, which greatly damages the structural durability of concrete structural members.

4. Conclusions

Fire can accelerate the carbonization of concrete structure and seriously affect the durability of the structure. Therefore, for the structural members necessary to be strengthened after fire, it is particularly important to determine the subsequent service life of the reinforcement design by what reinforcement method according to the burning situation of the reinforcement area, and to predict the remaining life of the concrete structural members.

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