Defect and Diffusion Forum
ISSN: 1662-9507, Vol. 437, pp 61-68
doi:10.4028/p-7LP4ry

Submitted: 2024-03-25
Accepted: 2024-05-15
Online: 2024-10-07

Assessment of the Influence of Features of Crack Formation in Reinforced Concrete Products on their Fire Resistance

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Keywords: fire resistance limit, critical temperature, cracking in concrete, crack opening in concrete, bending reinforced concrete element

Abstract. The paper considers possible scenarios of cracking during heating and their impact on fire resistance using the example of a bending reinforced concrete structure (beam). It is shown that if the calculated critical temperature of reinforcement is less than the critical temperature of concrete (this indicates a significant load on the structure), then cracks in the tensile zone of concrete are formed after reaching the second stage of the stress-strain state. The concrete of the protective layer does not have time to degrade, the depth of the crack remains constant, and the fire resistance limit is calculated taking into account that the thickness of the protective layer of concrete is reduced by the depth of the crack opening. If the calculated critical temperature of the reinforcement is greater than the critical temperature of the concrete (this indicates a slight load on the structure), then cracks are formed as a result of the degradation of the surface layer of concrete. Their depth should constantly increase with the progression of the concrete layer heating to the critical temperature. In this case, the calculation of the fire resistance limit can be performed without taking into account the formation of cracks. Based on the considered assumptions, a methodology for assessing the impact of cracks on the fire resistance limit of bending reinforced concrete structures is proposed, which consists in analyzing the possibility of open cracks (which is facilitated by heating) and estimating their depth. At the next stage, the heating time of the concrete layer to the crack opening depth $\tau_{\Delta 1}$ and the temperature in the crack after this time are estimated. Next, the time until the critical temperature of the reinforcement $\tau_{\Delta 2}$ is estimated when the concrete layer is heated from the bottom of the crack to the reinforcement. The fire resistance limit is defined as the sum of $\tau_{\Delta 1}$ and $\tau_{\Delta 2}$. The results of the calculations according to the proposed methodology showed that the presence of open cracks in bending reinforced concrete structures can almost halve the fire resistance limit.

1 Introduction

In industrial buildings with a reinforced concrete frame, the fire resistance limits of the main structural elements must be checked to confirm their fire resistance level. At the same time, the structural elements of buildings belonging to potentially hazardous objects or objects of high risk must be checked with due regard for possible combinations of special loads or other negative factors [1, 2]. Special loads, the consequences of which can have an additional impact on fire resistance, include explosions that cause deformation of structures, and various excessive mechanical impacts. The impact of corrosion cannot be discounted either.

All these factors affect the stability of building structures. They need to be foreseen during the design of the buildings objects of high risk, as well as taken into account during the inspection of buildings after accidents to predict the possibility of further operation.

Experimental methods for determining the fire resistance of reinforced concrete structures are not always suitable, firstly, due to the scale factor; secondly, during the inspection of existing structures; thirdly, due to the inability to reproduce negative effects and their combination.

Therefore, computational methods for determining fire resistance are of great importance, in which one can try to take into account, if not all, then at least the most important factors affecting the result [3, 4, 5, 6, 7].

One of these important factors is the presence of cracks. The danger of significant long-term and short-term deformations of reinforced concrete structures is that they cause the formation and opening of cracks in the concrete. Cracks can also form as a result of concrete corrosion. The processes of crack formation and development are aggravated by the effects of high temperature during a fire [8, 9].

The methods used to calculate fire resistance do not take into account the possible impact of cracks on the result. However, if this influence exists, it cannot be ignored. Thus, an urgent problem is the development of a method for calculating the fire resistance limit of reinforced concrete structures that would take into account the presence of cracks in them, which would allow for a more accurate assessment of the stability of structures in the event of a fire and, accordingly, increase the reliability of the buildings objects of high risk.

2 Analysis of Publications

The assessment of the fire resistance of building structures is based on the well-known limit state calculation methodology, which determines the time during which the bearing capacity of a structure under high temperature decreases to the value of the working load. [1, 6, 7]. It is believed that for bending reinforced concrete elements, strength is mainly provided by the condition of the steel reinforcement. In the static part of the calculation, the critical temperature of the steel reinforcement is determined, and in the thermal part, the time during which this critical temperature is reached when the protective layer of concrete is heated according to the standard mode. In this case, the protective layer of concrete is considered to be solid without damage.

The purpose of such a calculation is to come as close as possible to the experimental determination of the fire resistance limit of a reinforced concrete bending element, if possible. Comparison of the results of experimental and theoretical determination of the fire resistance limit in different works [7, 10, 11] shows that a complete coincidence is unattainable. One of the reasons for this is the inability to foresee all the peculiarities of the state of the tested samples in the calculations. This primarily refers to the presence of various imperfections in real reinforced concrete specimens that cannot be accurately accounted for. One of these imperfections, which, however, can be predicted to some extent, is the presence of cracks.

Accidental cracking in reinforced concrete structures can occur as a result of either mechanical or thermal impact (when the concrete temperature exceeds the critical temperature) or a combination of these factors.

Under mechanical stress, cracks begin to form in the tensile zone of concrete after reaching the second stage of the stress-strain state [12, 13, 14]. With a further increase in load, cracks open. It is noted in [9, 12] that in heavy concrete, cracks with a width of 1 mm extend to a depth of 10–20 mm. However, these studies only considered the formation of cracks when samples were overloaded under normal conditions.

When exposed to heat, cracks form when the critical temperature of concrete t_{bcr} is reached. For concrete with silicate aggregate, this is approximately 575 °C (which corresponds to the polymorphic structural transition of β-quartz to α-quartz) [15]. It is shown in [16] that this transformation causes degradation of the surface layer of concrete, which is manifested in the appearance of a network of cracks on its surface. It is also indicated that an additional reason for this is the increase in internal stresses both between the concrete components and between the cement stone grains. However, the paper does not consider the simultaneous effect of mechanical loading on the tested specimens. Therefore, there is reason to assume that only the formation of cracks was observed without their opening.

Thus, the unresolved part of the problem is to determine the peculiarities of crack formation in a bending reinforced concrete structure under the simultaneous action of high temperature and load in terms of determining the degree of influence of these cracks on the calculation of the fire resistance limit of the structure.

3 Analysis of the Features of Crack Formation in a Bending Reinforced Concrete Element During Heating

The aim of the study is to improve the methodology for calculating the fire resistance limit of a bending reinforced concrete structure, taking into account the possibility of cracking in it.

To achieve the research goal, the following tasks need to be solved:

1. To analyze the peculiarities of crack formation in a bending reinforced concrete element depending on the ratio between the critical temperatures of concrete and steel reinforcement.
2. To propose an improved method for taking into account the heating time of the protective layer of concrete depending on the mechanism of crack formation.

Let's consider this task on the example of a bending reinforced concrete structure with silicate-filled concrete. To do this, it makes sense to find out the causes of crack formation and correlate them with the calculated critical temperature of the steel reinforcement, since the strength of the structure depends on it.

If we assume that the thickness of the protective concrete layer decreases at the site of the crack, then the time for heating the steel reinforcement to the critical temperature, when a plastic hinge is formed and the bending reinforced concrete structure is destroyed, will also decrease. Two scenarios are possible here:

1) if the calculated critical temperature of the reinforcement is less than 575 ºC (which indicates a significant load on the structure), then cracks (if they have not occurred earlier) can form in the tensile zone of concrete only after reaching stage II of the stress-strain state. In this case, it can be assumed that during the time required to heat the steel reinforcement to the critical temperature, the concrete of the protective layer does not have time to degrade and the crack depth remains constant. Then it is necessary to calculate the crack opening and, assuming that the crack opening depth depends on the crack width as $h_{crc} \approx (10...20) \cdot a_{crc}$, calculate the fire resistance limit taking into account that the thickness of the protective layer of concrete is reduced by the crack opening depth;

2) if the calculated critical temperature of the reinforcement is greater than 575 ºC (this indicates a low load on the structure), cracks may form as a result of degradation of the surface layer of concrete. Their depth should increase steadily as the concrete layer warms up to the critical temperature. It can even be expected that the rate of crack development will exceed the rate of advancement of the concrete heating limit to the critical temperature, since the thermal resistance in the vicinity of the crack walls is less than that of the surface of the reinforced concrete structure. In this way, pre-existing cracks that have formed earlier can develop. Nevertheless, crack opening (if it occurs) is unlikely to affect the rate of heating of the protective layer of concrete as a factor, since it will be secondary in this case. That is, when cracks form and open as the concrete warms up, cracking occurs gradually (in layers) simultaneously with the heating of the concrete to the critical temperature, and in this case, cracking does not affect the heating rate. Thus, in the considered case, the thickness of the protective layer of concrete will continuously decrease by the depth of crack development along with the warming up layer, and cracking should not be taken into account when calculating the fire resistance limit.

Also, summarizing both scenarios, it can be concluded that if there were no cracks in the protective layer of concrete of a bending reinforced concrete element before the fire exposure, then it makes no sense to take into account the reduction in the thickness of the protective layer of concrete when calculating the fire resistance limit, since this layer can already be considered sufficiently heated at the time of crack formation.

4 Improving the Methodology for Calculating the Fire Resistance Limit of a Bending Reinforced Concrete Structure

It is proposed to calculate the fire resistance limit of a bending reinforced concrete structure, taking into account the possibility of crack formation and opening, in the following sequence:

1. Determination of the critical temperature of reinforcement at the corresponding load.

2. Determination of the width of the cracks that opened during heating and assessment of their depth. If the opened cracks were formed before heating, proceed to step 5.

3. Determination of the heating time of the protective layer of concrete to the depth of crack opening.

4. Determination of the temperature in the crack during the heating of the protective layer of concrete to its depth.

5. Determination of the time of heating to the critical temperature of the reinforcement of the residual layer of concrete (from the bottom of the crack to the reinforcement).

6. Determination of the fire resistance limit as the sum of the times in paragraphs 3 and 5.

Let us apply the proposed method for calculating the fire resistance limit on the example of a reinforced concrete beam with a cross section of 0.7×0.3 m with a protective layer thickness of a_s=0.035 m made of B25 concrete (R_b=14.5 MPa) with silicate filler, with reinforcement in the tensile zone of 8Ø18 A400C and in the compressed zone of 4Ø18 A400C (R_s=340 MPa) was selected.

According to the preliminary analysis, the case is considered when the load under which the bending moment is generated is selected so that the calculated critical temperature of the reinforcement does not exceed 575 ºC. The assumption is also taken into account that cracks in the protective layer of concrete open only when its surface warms up to a certain depth to the critical temperature of concrete.

Under these conditions, the limit of a reinforced concrete beam is calculated, taking into account the possibility of crack formation and opening using the proposed method.

1. The critical temperature of reinforcement t_{Scr} is determined in the table based on the ratio:

$$\gamma_{st} = \frac{M_p}{R_s \cdot A_s \cdot h_0 (1 - 0,5\xi)}, \quad (1)$$

where γ_{st} is the coefficient of reduction of steel resistance; M_p is the bending moment of the beam in the middle of the span; A_s is the cross-sectional area of the reinforcement in the tensile zone, A_s=20.36 cm^2; ξ is the coefficient of the relative height of the compressed zone of concrete.

The fire resistance limit of a reinforced concrete beam without taking into account cracks is determined from ratio [12]:

$$erf \frac{k\sqrt{a_b} + x}{2\sqrt{a_b \cdot \theta}} = \frac{t_1 - t_2}{t_3 - t_4}, \quad (2)$$

where k is the density coefficient of concrete; a_b is the thermal conductivity coefficient of concrete; $x \equiv a_s$ is the thickness of the protective layer; $\theta \equiv \tau_s$ is the fire resistance limit; $t_1 \equiv t_l$ and $t_3 \equiv t_l$ are the temperature of a standard fire, t_l = 1250 ºC; $t_2 \equiv t_{Scr}$ is the critical temperature of reinforcement; $t_4 \equiv t_0$ is the initial temperature on the heated surface, t_0 = 20 ºC.

2. The crack opening width a_{crc} is calculated according to [12]:

$$a_{crc} = \varphi_1\varphi_2\varphi_3\psi\frac{\sigma_s}{E_s}\sqrt[3]{d}\ , \tag{3}$$

where φ_1=1, φ_2=1, φ_3=1 are coefficients depending on the duration of the load action, type of reinforcement, type of load; E_s is the elastic modulus, E_s=210000 MPa; σ_s is the stress in the longitudinal tensile reinforcement:

$$\sigma_s = \frac{M_p}{z_s\left(A_s + A_s^{/}\right)}, \tag{4}$$

where z_s is the distance from the center of gravity of the stretched reinforcement to the point of application of the equivalent force in the compressed zone of the element, z_s = 0.5 m; A'_s is the cross-sectional area of the reinforcement in the compressed zone, A'_s =10.18 cm^2; ψ is a coefficient that takes into account the uneven distribution of relative deformations of the tensile reinforcement between cracks in the concrete:

$$\psi = 20\left(3,5 - 100\frac{\left(A_s + A_s^{/}\right)}{h_0 \cdot b}\right), \tag{5}$$

where b is the width of the beam; h_0 is the useful thickness of concrete.

3. The time of heating of the concrete layer to the depth of crack opening $\tau_{\Delta 1}$ is determined based on the relationship (2), where $x \equiv \delta$ is the limit of concrete heating to the temperature t_{bcr}; $\theta \equiv \tau_{\Delta 1}$; $t_1 \equiv t_l$ and $t_3 \equiv t_l$; $t_2 \equiv t_{bcr}$ is the critical temperature of concrete, t_{bcr} = 575 °C; $t_4 \equiv t_0$.

4. The temperature in the crack $t_{\Delta 1}$ during the heating of the concrete layer to its depth $\tau_{\Delta 1}$ is determined by the formula:

$$t_{\Delta 1} = 345\lg\left(8\tau_{\Delta 1} + 1\right) + t_0\,. \tag{6}$$

5. The heating time $\tau_{\Delta 2}$ to the critical temperature of the reinforcement t_{Scr} of the concrete layer Δa (from the bottom of the crack to the reinforcement) is determined based on the relationship (2), where $x \equiv \Delta a = a_s - \delta$; $\theta \equiv \tau_{\Delta 2}$; $t_1 \equiv t_{\Delta 1}$; $t_2 \equiv t_{Scr}$; $t_3 \equiv t_l$; $t_4 \equiv t_{\Delta 1}$.

6. The fire resistance limit of a bending reinforced concrete structure, taking into account crack opening, $\tau_{s.cr}$, can be defined as follows:

$$\tau_{s.cr} = \tau_{\Delta 1} + \tau_{\Delta 2}. \tag{7}$$

For the selected beam, the width of cracks opening, the critical temperature of the reinforcement, and the fire resistance limit without taking into account cracks were calculated using the proposed method, depending on the value of the bending moment.

The calculations of the fire resistance limit, taking into account cracks, were performed according to the proposed method in the case when the calculated critical temperature of the reinforcement is less than 575 °C. They were performed under the assumption that cracks in the protective layer of concrete open only when its surface warms up to a certain depth to the critical temperature of concrete. The depth of the cracks was taken as a function of their width, assuming $h_{crc} \approx (10\ldots20)\cdot a_{crc}$.

The results of the calculations are shown in Table 1.

5 Discussion of Calculation Results

The results given in Table 1 show that the presence of open cracks in bending reinforced concrete structures can greatly affect their fire resistance.

When a beam is loaded uniformly, the highest stresses and, consequently, crack formation occur in the middle part of the beam. The width and depth of the cracks, as well as the critical temperature of the reinforcement, depend on the load, which is characterized by the bending moment. For this reason, as the bending moment increases, the critical temperature of the reinforcement decreases, cracks in the stretched zone of the concrete open wider and their depth increases, locally reducing the concrete layer near the reinforcement, which is warming up. All this accelerates the formation of a plastic joint in the reinforcement during heating and, accordingly, the destruction of the beam.

Table 1. Design characteristics of a reinforced concrete beam depending on the bending moment and crack depth

Design characteristics	Bending moment, M, [MN·m]		
	0.25	0.3	0.35
The steel reinforcement resistance reduction coefficient, γ_{st}	0.60	0.732	0.87
Critical temperature of working steel reinforcement, t_{Scr} [°C]	550	506	470
Fire resistance limit excluding cracks, τ [min]	126	108	96
Estimated crack opening width, a_{crc} [mm]	0.08	0.10	0.112
Fire resistance limit at crack depth 10 mm, τ [min]	86	74	66
Fire resistance limit at crack depth 15 mm, τ [min]	69	59	53
Fire resistance limit at crack depth 20 mm, τ [min]	54	47	41

The calculations showed that for the selected case, when the calculated critical temperature of the reinforcement is less than 575 °C, the decrease in the fire resistance limit of bending reinforced concrete structures depending on the depth of open cracks can be approximately estimated at 3.0 min·mm^{-1} compared to the fire resistance limit without taking into account cracks τ_s. That is, knowing the depth of open cracks in the protective layer of concrete of a bending reinforced concrete structure, it is possible to approximately estimate its fire resistance limit as:

$$\tau_{s.cr} = \tau_s - 3.0 \cdot h_{crc}. \quad (8)$$

These results confirm the danger of overloading of bending reinforced concrete structures, as it causes the appearance and opening of cracks in them, which leads to faster heating of the protective layer of concrete in the places of crack formation. The calculations based on the proposed methodology make it possible to justify, in each case, measures to increase the fire resistance of bending reinforced concrete structures by applying fireproof coatings to them. In addition, it can be recommended that in cases where reinforced concrete structures are used at high-risk facilities, to reduce cracking in the protective layer of concrete, its plasticity should be increased by impregnating it with special polymer compounds. Also for this purpose, important bending reinforced concrete structures with a protective layer of fiber reinforced concrete can be manufactured as described in [17].

6 Conclusions

1. The paper proposes an improved methodology for calculating the fire resistance limit of bending reinforced concrete structures in the presence of cracks, which includes a gradual determination:

- of critical temperature of reinforcement;
- of width of crack opening and estimation of the depth of opened cracks;
- of heating time of the protective layer of concrete to the depth of crack opening;
- of temperature in the crack during the heating of the protective layer of concrete to its depth;

– of heating time to the critical temperature of the reinforcement of the concrete layer from the bottom of the crack to the reinforcement;

– of final calculation of the fire resistance limit.

2. Evaluation calculations have shown that in the presence of cracks opening in the protective layer of concrete during heating, the fire resistance of bending reinforced concrete structures decreases compared to the fire resistance limit without taking into account cracks by about 3.0 min·mm^{-1}, depending on the depth of the cracks.

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