The procedure of fire-resistance calculation for compressed reinforced concrete elements

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Abstract. Fire-resistance calculations adopted in the regulatory system (both in the Russian and in European) are based on calculations of isofields of section heatup of structural elements. Heatup isofields for reinforced concrete elements specified in the regulatory system have been obtained by the concrete section calculation not considering inclusions of reinforcement bars. But it is known that accuracy of the fire-resistance calculation of reinforced concrete elements depends on performance accuracy of a thermotechnical calculation. Having performed this calculation the temperature field distribution by element section and strength characteristics depending on it are determined. Temperature distribution by element section depends on such parameters as heat-absorption capacity and thermal conductivity of section parts, section humidity. Within the work the approach to solving the problem of consideration of the actual temperature field when calculating fire-resistance of reinforced concrete and steel-reinforced concrete elements has been reviewed. Calculations of fire-resistance at temperature fields not considering inclusions of reinforcement bars (concrete section) as well as at temperature fields considering reinforcement bar inclusions have been performed. Additional coefficients introduced in the fire-resistance calculation when using Russian and European methods have been calculated for the reviewed section with 600×600 overall dimensions. According to calculation results the change of section bearing capacity upon the calculation considering thermotechnical characteristics of the reinforcement bars has been observed.

1. Introduction

As a rule two methods [5-9; 11-16] are used when calculating fire-resistance of reinforced concrete elements: the accurate and m-method of ultimate isotherm. The general reinforced concrete deformation mechanics is brought to standard calculation methods [3; 4; 10].

The accurate calculation method is based on application of actual diagrams of concrete and reinforcement bars upon fire effect in time. This method is difficult for the majority of engineers as computers are required for such calculations in which the calculation can be implemented with a number of differently deformed zones.

The limit temperature isotherm method is the main engineering method of the fire-resistance calculation both in Russia and in Europe. This method is the most common and based on the assumption that concrete heated above the limit temperature loses strength fully — and it is neglected upon the calculation. Concrete heated below the limit temperature remains firm without changes. Temperature isofields are given for the method in annexes [5-9; 11-16]. The main problem of the limit temperature method is that temperature isofields are distributed by concrete section not considering heat-absorption capacity and heat transmission of temperature inclusions of reinforcement bars.
The purpose of this work is as follows: establishment of the reinforcement factor impact on heatup of reinforced concrete sections. Research tasks: determination of the temperature field calculation method, development of the section list for the research, calculation of temperature fields of elements, development of coefficients for the ultimate temperature isotherm method.

2. Methods

The ABAQUS software package has been used for the calculation. Package operation description is given in details in [22; 23].

Ambient temperature when calculation is found according to [1; 2]:

\[ t = 345 \log(8t + 1) + t_e \]  

(1)

where \( t \) — heatup time, min;
\( t_e \) — initial temperature (adopted as equal to 20 °C).

The total thermal flux to the structure surface is determined as follows:

\[ Q = Q_c + Q_r \]  

(2)

where \( Q_c \) — heat convective flux, W/m²;
\( Q_r \) — radiative heat flux, W/m².

\[ Q_c = a_c(t - t_{surf}) \]  

(3)

where \( a_c \) — heat-exchange coefficient, W/m² °C;
\( t_{surf} \) — surface temperature, °C.

The heat-exchange coefficient \( a_c \) is allowed to take equal to 29 [8].

\[ Q_r = 5.67\varepsilon_{red}(0.01t + 2.31)^4 - (t_{surf} + 2.73)^4 \]  

(4)

where 5.67 — the proportionality factor in the Stefan-Boltzmann's law:
\( \varepsilon_{red} \) — reduced emissivity factor in the system of heat transfer from the medium to the structure surface (for the “heating medium — concrete surface” system: \( \varepsilon_{red} = 0.56 \)).

The heat-conductivity factor for carbonate (lime filler) concrete, W/m °C [5-7]:

\[ \lambda = 1.14 - 0.00055t \]  

(5)

The heat capacity ratio for concrete, kJ/kg °C [5-7]:

\[ C = 0.71 + 0.00083 \]  

(6)

The heat-conductivity factor for steel, W/m °C [5-7]:

\[ \lambda = 58 - 0.048t \]  

(7)

The heat capacity ratio for steel, kJ/kg °C [5-7]:

\[ C = 0.44 + 0.00063t \]  

(8)

Impact of humidity is taken into consideration based on [11] using the method of increase of concrete heat-absorption capacity.

3. Results and Discussion

The work establishes dependences of bearing capacity of concrete and reinforcement bars depending on:

— reinforcement percent of reinforced concrete sections;
— concrete cover of reinforced concrete sections;
— reinforcement percent of the middle and peripheral parts of steel-reinforced concrete sections.

600×600 mm section with different reinforcement (table 1) was taken as an example of the calculation.
Table 1. Reinforcement of 600×600 section.

| It. No. | Section sketch | Reinforcement | Reinforcement percent | The ratio of rigid reinforcement to flexible reinforcement |
|---------|----------------|---------------|-----------------------|----------------------------------------------------------|
|         |                | Flexible, cm² | Rigid, cm² | Total, cm² |                                           |
| 1       |                | –             | –           | –          | –                                          |
| 2       |                | 150.79        | –          | 150.79     | 4.7                                        |
| 3       |                | 150.79        | –          | 150.79     | 4.7                                        |
| 4       |                | 150.79        | –          | 150.79     | 4.7                                        |
| 5       |                | 251.79        | –          | 251.79     | 7.8                                        |
| 6       |                | 325.2         | –          | 325.2      | 10                                         |
| 7       |                | 100.53        | 370.49     | 471.02     | 14.5                                       |
| 8       |                | 251.32        | 218.69     | 470.01     | 14.5                                       |
| 9       |                | 100.53        | 218.69     | 319.22     | 9.9                                        |

For derivation of dependences on reinforcement percent of reinforced concrete sections with flexible reinforcement bars the following sections are used:
1, 2, 5, 6

The following sections are used for derivation of dependences on the protection cover:
2, 3, 4

The following sections are used for derivation of dependences on the ratio of rigid reinforcement to flexible reinforcement for steel-reinforced concrete sections:
7, 8 and 6, 9.

As the example of differences in temperature fields figure 1 provides characteristic fields for sections 1, 6, 8 at 240 minutes of heatup.
The following conclusions can be drawn according to figure 1:

1. The temperature field upon reinforcement inclusions has temperature redistribution;
2. Temperature in points with reinforcement bar location below when calculating the section with heat-conducting inclusions of reinforcement bars than when calculating the concrete section. Temperature in the section centre is higher when calculating the section with heat-conducting inclusions of reinforcement bars than when calculating the concrete section. These circumstances are due to the fact that reinforcement bars have bigger heat-absorptive capacity and bigger heat-transmission capacity than concrete: heat is transferred in the section centre from the peripheral part.

Main adopted parameters in the fire-resistance calculations of reinforced concrete and steel-reinforced concrete sections are:

1. Reinforcement bar resistance. Resistance correction is performed by the value of temperature heatup and the reinforcement bar class depending on temperature.
2. Concrete resistance. This parameter in the "limit temperature isotherm" method is adopted equal to 0 for concrete heated up to limit critical temperature. For concrete heated up less than the critical temperature — equal to the characteristic resistance of concrete.
3. Geometrical parameters of the zone with limit critical temperature. This zone is characterized by concrete heatup depth to critical temperature.

4. Correction coefficients

Reinforcement bar resistance. The clarified reinforcement bar resistance can be corrected by introduction of an additional coefficient for the clarified temperature field. This coefficient can be found by dividing bearing capacity for the reinforcement bars determined by actual ($N_{r\,(act)}$) heatup to bearing capacity for concrete section heatup ($N_{r\,(conc)}$).

Concrete resistance and heatup depth of the zone with limit critical temperature. Correction of one of these parameters is possible (simultaneous correction will be resulted in doubling of coefficients). Correction of the zone with limit critical temperature is the most feasible. This coefficient can be found by dividing the heatup depth determined by actual ($a_{t\,(act)}$) heatup to heatup depth for concrete section heatup ($a_{t\,(conc)}$).

5. Coefficients for the reviewed section

Reinforced concrete elements. Dependences for concrete and reinforcement bars on reinforcement percent

Characteristic dependences given in figures 2, 3 have been obtained for reinforced concrete elements with 600×600 section. In whole for the reviewed example the following can be distinguished: increase of bearing capacity of reinforced sections calculated considering the actual temperature field.
Reinforced concrete elements. Coefficients of temperature field change depending on the protective cover.

Bearing capacity for concrete only is reviewed for reinforced concrete elements. Bearing capacity for reinforcement bars is not reviewed as it is taken into consideration in dependences on the reinforcement percent.

| Table 2. 600×600 section heatup depth to critical temperature. |
|---------------------------------------------------------------|
| Time, min | Section | Heat up of section No.2 to 500 °C, cm | Heat up of section No.3 to 500 °C, cm | Heat up of section No.4 to 500 °C, cm |
|-----------|---------|---------------------------------------|---------------------------------------|---------------------------------------|
| 60        | 2       | 2.50                                  | 2.50                                  | 2.50                                  |
| 120       | 2       | 4.30                                  | 4.30                                  | 4.30                                  |
| 180       | 2       | 6.50                                  | 6.30                                  | 6.40                                  |
| 240       | 2       | 8.20                                  | 7.90                                  | 8.00                                  |

In whole the following conclusion can be drawn: as bearing capacity change does not take place before 120 minutes of heatup and bearing capacity increases after 120 minutes so introduction of coefficients of change of bearing capacity for concrete depending on the protective cover is not feasible.

Steel-reinforced concrete sections. Temperature field change coefficients depending on the ratio of percentage of rigid reinforcement to flexible reinforcement.

Characteristic dependences given in figures 4-6 have been obtained for steel-reinforced concrete elements with 600×600 section. Obtained dependences possess the character difficult to describe but in whole for the reviewed example the following can be distinguished: increase of bearing capacity of reinforced sections calculated considering the actual temperature field.
Reinforcement percent 14.5

**Figure 4.** The ratio of concrete heatup depth determined by actual section $a_{(act)}$ to heatup depth for concrete section $a_{(conc)}$ depending on the ratio of percentage of rigid reinforcement to flexible reinforcement.

Reinforcement percent 10

**Figure 5.** The ratio of bearing capacity for flexible reinforcement bars determined by actual $N_{r_{(act)}}$ heatup to bearing capacity for concrete section heatup $N_{r_{(conc)}}$ depending on the ration of percentage of rigid reinforcement to flexible reinforcement.
Figure 6. The ratio of bearing capacity for rigid reinforcement bars determined by actual $N_{r,\text{act}}$ heatup to bearing capacity for concrete section heatup $N_{r,\text{conc}}$ depending on the ration of percentage of rigid reinforcement to flexible reinforcement.

6. Conclusions

The following conclusions can be drawn according to research results:

— calculations per the developed new fire-resistance calculation method for compressed reinforced concrete elements upon receipt of temperature fields considering the reinforcement factor produce satisfactory reproducibility;

— additional coefficients introduced in fire-resistance calculations have been calculated depending on the reinforcement percent of reinforced concrete sections, the concrete cover of reinforced concrete sections, the reinforcement percent of the middle and peripheral parts of steel-reinforced concrete sections;

— fire-resistance determined considering the actual temperature field enables to take more reasonable and in some cases more cost-effective solutions for structural reinforcement.

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