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Research of Fire Resistance of Fire Protected Reinforced Concrete Structures

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Abstract. A finite element model for thermal engineering calculation of fire-resistant multi-hollow reinforced concrete floor in the ANSYS software package has been developed. The model allows to evaluate the fire resistance of fire-resistant and unprotected reinforced concrete structures both under load and without it. With the help of the developed model, the heat engineering calculation of the fire-resistant reinforced concrete multi-hollow slab was carried out. The results of numerical simulation are compared with the results of experimental study of fire resistance. An approach is proposed that allows taking into account all types of heat transfer by specifying cavities as a solid body with an equivalent coefficient of thermal conductivity. The adequacy of the developed model was checked, as a result of which it was established that the calculated values of temperatures correlate satisfactorily with the experimental data. The largest deviation in the measurement of temperatures is observed at 100 minutes of calculation and is about 3 °C, which is 9 %.

1 Introduction

In case of fire the violation of the overall stability of the building is due to the destruction of individual elements in the frame of the building. The risk of collapse of load-bearing structures in addition to material damage, also endangers the lives of site workers during evacuation and rescuers during firefighting. In the vast majority of cases, the destruction of structures leads to the complete destruction of property, engineering and technological equipment. Therefore, maintaining the load-bearing capacity of building structures in the event of a fire for a specified time is an urgent problem.

These factors create a need to protect people from the impact of the identified threats. One of the most dangerous factors is fires in buildings and structures. Ensuring the safety of people and property must be performed taking into account all stages of the life cycle of facilities, such as scientific support and monitoring, design, construction, operation, as well as to exclude fires [1]. Prevent the occurrence of fire allows technical means and organizational measures, in which the probability of occurrence and development of fire does not exceed the standard allowable value. The condition for reducing the irreversible consequences of fires at various facilities is the preservation of the bearing capacity of buildings, structures of technological structures and communications.

These stability requirements are provided by a set of measures provided for both production technology and the use of effective fire-retardant coatings for fire protection of building structures.

Therefore, in the context of globalization and increasing threats to humans, the first place is played by maintaining the resilience of buildings and structures in the event of fires and other natural disasters, as well as maintaining their functional purpose after such impacts.

2 Analysis of Literature Data and Problem Statement

Creating the basis for effective assessment of fire resistance of fire-retardant reinforced concrete building structures with scientifically sound parameters of fire-retardant coatings is an urgent problem. Solving this problem will increase the accuracy of the calculation of non-stationary heating of fire-retardant reinforced concrete structures with sufficient accuracy for engineering calculations, both using experimental research data and the results of numerical simulations in modern software [2].

In [3] the experimental results of bending tests at ambient temperature and fire resistance tests of two control beams and eight reinforced concrete beams reinforced with fibrous materials are presented. However, it should be noted that the researchers ignored the issues of modeling the thermal state of fire-retardant reinforced concrete structures.

In [4] presents a detailed analysis of the mechanisms responsible for the loss of bearing capacity of extruded multi-hollow slabs under the influence of fire temperature. A comparison of the results of numerical simulations with the results of fire resistance tests is presented. This means that there is no reliable data on the use of fire-retardant reinforced concrete floors with scientifically sound parameters of fire-retardant coatings.

In [5] the description of theoretical bases and basic hypotheses on modeling of different types of finite elements of any structure under the influence of fire temperature with the help of SAFIR software package is given. To overcome this problem the paper also explains how to use the software to its full potential. Despite the practical significance of such results, the issues of calculations of fire-retardant reinforced concrete structures have not been sufficiently considered. Obviously, this is due to the difficulty of building a fire-retardant structure in this software package and the correct setting of parameters of fire-retardant materials.

In [6] the results of numerical study of the characteristics of reinforced concrete composite flooring, which was subjected to fire by conducting three-dimensional thermomechanical analysis of composite floors using ANSYS. Comparing the results of real fire with the results of numerical simulations the accuracy of using numerical models to predict the impact of fire temperature on the behavior of structures. However it is not defined how this technique can be applied to other reinforced concrete structures, arbitrary fire temperatures. From a practical point of view this can cause difficulties in taking into account the thermophysical characteristics of fire-retardant coatings to increase the limits of fire resistance of reinforced concrete structures.

In [7] a parametric study of the behavior of steel, concrete and composite beams exposed to fire. An idea of the structural behavior of elements subjected to thermal and mechanical loads is given, the behavior of structures under the influence of fire is illustrated. It is shown how the selected design parameters affect the obtained results. Nonlinear heating and deflections due to thermal effects are especially considered. However, the researchers ignored the behavior of fire-retardant reinforced concrete structures and the influence of the parameters of fire-retardant coatings on the fire resistance of structures.

In [8] presents a review of the literature on the progressive destruction of structures due to fire and the impact of high temperatures on structures and elements. However, despite the progress in the calculation of structures for fire resistance the issues of thermal calculation of fire-resistant reinforced concrete structures remain unresolved.

In [9] the analysis of fire resistance of prefabricated reinforced concrete beams-columns, which are connected at the ends with reinforced concrete slabs and combined into a prefabricated reinforced concrete frame structure. The accuracy of the created model was checked only by means of computational experiment without check with experimental data. However, the proposed model does not take into account the use in such frame structures of fire-retardant reinforced concrete structures with scientifically sound parameters of fire-retardant coatings. This imposes certain restrictions on the analysis of fire resistance of fire-retardant reinforced concrete structures using the developed model.

A description of such restrictions can be found in [10], devoted to the consideration of progressive solutions for the use of effective means of fire protection of steel and reinforced

concrete structures of industrial buildings and structures. The approach used in this work is based on experimental studies of fire resistance of reinforced concrete slabs and slabs with a system of external reinforcement with different types of fire-retardant materials. The application of this approach allows to take into account for the thermal calculation of the dependence of changes in the coefficients of thermal conductivity and heat capacity of fire-retardant coatings. However, despite the advantages of this approach, the question of the influence of the coefficient of thermal conductivity and the specific volume of heat capacity of fire-retardant coatings on the fire resistance of structures remains open.

Systematization of the results of the analysis allows us to state that the existing approaches to solving the problem of estimating the limits of fire resistance of fire-retardant reinforced concrete building structures are based on experimental and computational procedures. Obviously, such approaches have both advantages and disadvantages in their implementation. It follows that the use of these procedures alone will not allow to obtain optimal solutions to ensure fire resistance of fire-resistant building structures. They do not allow to take into account the importance of thermophysical characteristics of fire-retardant coatings, heat transfer processes in fire-retardant structures under the influence of arbitrary temperature regimes of fire.

Thus, this part of the problem can be solved by developing adequate models for assessing the fire resistance of fire-retardant reinforced concrete building structures with scientifically sound parameters of fire-retardant coatings and materials of reinforced concrete structures. Solving this problem will increase the accuracy of evaluation of fire-retardant reinforced concrete structures both with the use of experimental studies and the results of numerical simulations in modern software packages.

3 The Purpose and Objectives of the Study

The aim of the work is to assess the fire resistance of fire-retardant reinforced concrete structures using the developed model, implemented in the software package ANSYS, for thermal calculation of fire-retardant reinforced concrete multi-hollow floor slabs under elevated fire temperatures.

To achieve this goal needed to solve the following tasks:

- to develop a 3D model of fire-retardant multi-hollow reinforced concrete floor in the ANSYS software package;
- to calculate the non-stationary heating of the fire-resistant multi-hollow reinforced concrete floor in the ANSYS software package;
- check the adequacy of the developed 3D model of fire-retardant multi-hollow reinforced concrete floor.

4 Development of a 3D Model of the Thermal State of Fire-Retardant Multi-Hollow Reinforced Concrete Floor

To build a model in the software package ANSYS used the results of tests for fire resistance of two multi-hollow reinforced concrete slabs FH 48-12-8 with dimensions of 4780×1190 mm and a thickness of 220 mm (Fig. 1).

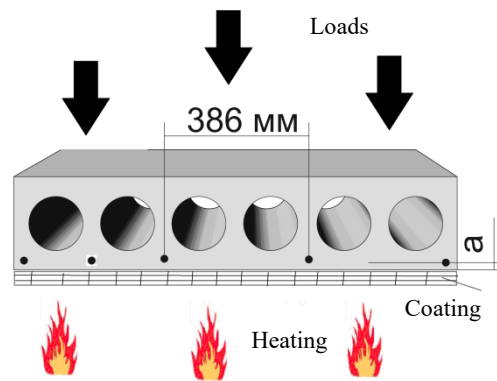


Fig.1. Scheme of temperature and static loads on the plate for modeling

The limit of fire resistance of a plate according to the manufacturer makes REI 45.

Loading is carried out by calibrated loads in the form of concrete blocks. The actual load on the samples is set based on the creation in the plates of stresses corresponding to the stresses from the specific distribution load of 570 kg/m^2 .

The temperature in the furnace was reproduced according to the standard temperature of the fire.

The tests according to the order lasted 242 minutes. A special test furnace and metrological verifiers of measuring equipment were used for the tests.

Using the results of fire resistance tests, we performed numerical simulation of the heating of a fire-resistant multi-hollow floor slab in the ANSYS software package.

The solution to the problem of nonstationary thermal conductivity was to determine the temperature of the concrete of the fire-retardant reinforced concrete floor at any point of the cross section at a given time.

To solve this problem, the cross section of the fire-retardant multi-hollow reinforced concrete floor, shown in Fig. 2.

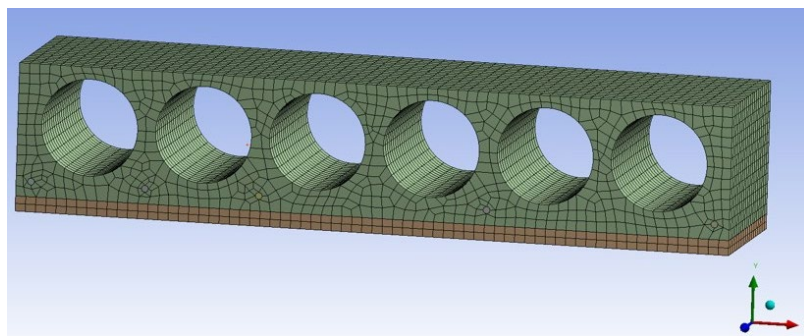


Fig. 2. Finite-element model of fire-retardant multi-hollow reinforced concrete floor in 3D setting

Reinforced concrete is a complex material consisting of concrete and steel reinforcement, which work together, but have different mechanical and rheological properties and change differently under conditions of high temperature heating. The paper uses a "discrete" approach, which consists in modeling the reinforcement with individual rods. Concrete and reinforcement are modeled with three-dimensional elements. This approach does not require the end mesh to be attached to the reinforcement pitch, which allows it to be used for tasks with real structural dimensions. It is also possible to take into account the nature of the joint work of concrete and reinforcement when heated - the emergence of forces due to the difference in temperature deformations and other effects. This approach is appropriate when reproducing fire resistance tests.

The effect of a fire flame on a reinforced concrete structure is a non-stationary process, so non-stationary thermal analysis is used to obtain the distribution of temperature fields in a fire-retardant reinforced concrete structure. The design of the fire-retardant reinforced concrete floor slab was

performed in the Design Modeller module of the ANSYS program with the subsequent thermal calculation in the TRANSIENT THERMAL module.

The computer model of fire-retardant reinforced concrete floor slab, developed in the ANSYS software package, contains the following types of finite elements: SOLID186, CONTA174, TARGE170 [11, 12].

5 Parameters for Thermal Calculation of Fire-Retardant Multi-Hollow Reinforced Concrete Floor

It should be noted that the thermal conductivity coefficient λ_a and the specific heat capacity of steel c_a were set according to [13].

To determine the thermophysical characteristics of the investigated plaster coating used the results of fire resistance tests described above.

According to the manufacturers of flame retardants, the thermal conductivity of the coating in the dry state is 0.11 W/m·K at 20°C.

However, it is clear that for most fire-retardant materials the thermophysical characteristics depend on the temperature due to physico-chemical processes occurring in them during heating [14, 15].

The results of calculations to determine the thermophysical characteristics of the plaster composition, which depend on temperature, are shown in Fig. 3.

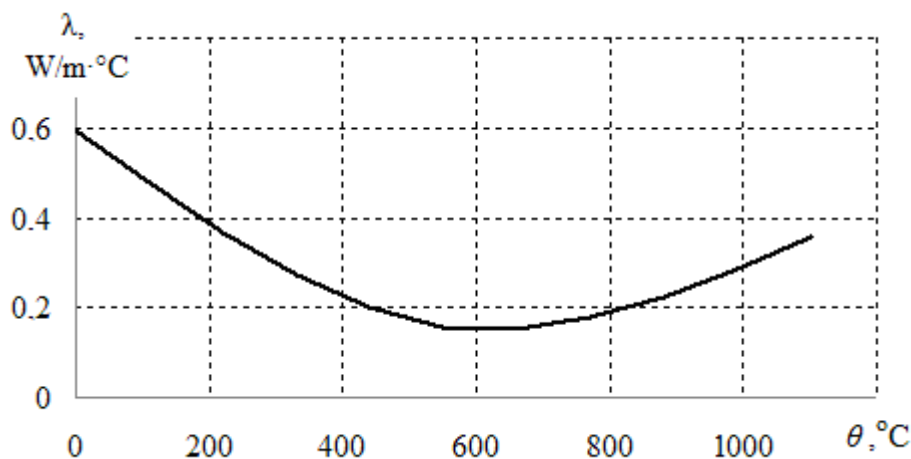


Fig. 3. Dependence of the effective coefficient of thermal conductivity of plaster coating on the temperature found by solving the inverse problems of thermal conductivity according to fire resistance tests

From fig. 3 it follows that the coefficient of thermal conductivity of the material with increasing temperature (up to 600 °C) decreases, and then its value increases. The decrease in the thermal conductivity can be explained by the fact that in this temperature range a material is formed in the material that has a lower thermal conductivity than in the material that has not been subjected to heat. The further increase in the thermal conductivity is due to the increase in the radiation component of this coefficient, which is associated with an increase in the intensity of heat transfer through the structure of such material.

It should be noted that the average values of temperatures from the unheated surface of the fire-retardant multi-hollow reinforced concrete floor were used to find the thermophysical characteristics of the coating.

The specific volumetric heat capacity of the coating was found by solving the inverse problems of thermal conductivity and was $C_v=10^6$ J/m³·°C. The density of the coating is $\rho_p=500$ kg/m³ (manufacturer's data) and as a result the specific volumetric heat capacity of the coating was 2000 J/(kg·°C).

The coefficient of thermal conductivity of the floor concrete and the specific volumetric heat capacity were also found by solving the inverse problems of thermal conductivity based on the results of fire tests [16].

Other parameters for modeling the thermal state of fire-retardant reinforced concrete floors:

Φ – is the angular coefficient, $\Phi = 1.0$;

ε_m – is the coefficient of thermal radiation of the heating surface of the coating, $\varepsilon_m = 0.7$;

ε_f – is the coefficient of thermal radiation of the flame, $\varepsilon_f = 1.0$;

ρ_a – density of steel, $\rho_a = 7850 \text{ kg/m}^3$;

σ – Stefan Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8} \text{ W/(m}^2 \cdot \text{°C}^4)$;

θ_0 – initial temperature, $\theta_0 = 20 \text{ °C}$;

density of concrete 2300 kg/m^3 .

6 Thermal Calculation and Verification of the Adequacy of the Developed Finite Element Model

As a result of numerical simulations the solution of direct problems of thermal conductivity resulted in temperature distributions in fire-retardant multi-hollow reinforced concrete floors. Figure 6 shows the temperature distribution of the fire-retardant floor at 60 and 120 minutes of fire exposure according to the standard temperature of the fire.

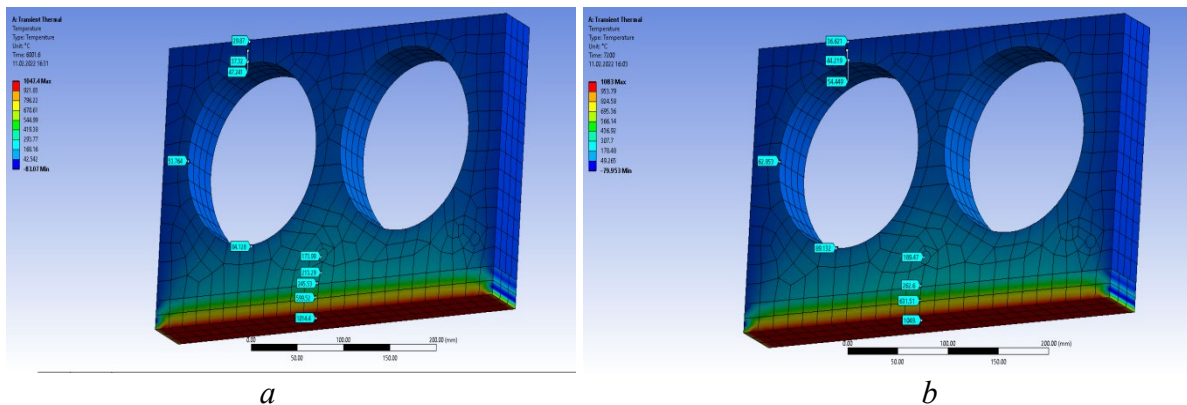


Fig. 4. Temperature distribution in the fragment of fire-retardant reinforced concrete slab for 60 and 120 minutes of its test

Particular emphasis in the study of temperature fields shown in Fig. 4, it is necessary to pay for heating of cavities of multihollow reinforced concrete overlapping. The correctness of setting the thermophysical and mechanical characteristics of this layer has the greatest impact on the accuracy of modeling. It should be noted that there are several approaches to finding the equivalent thermal conductivity of the layer with cavities. The first approach is based on setting in air cavities with its characteristics. In the second approach, it is possible to realize the lack of convective and radioactive heat transfer, but this leads to large errors. And the third approach allows to take into account all types of heat transfer by specifying the cavities as a solid body with an equivalent coefficient of thermal conductivity, which in each case is calculated separately [14–16].

Figure 5 shows the temperature distribution in the fire-retardant multi-hollow reinforced concrete floor slab at 180 and 240 minutes of its testing.

As can be seen from Fig. 5, the calculated temperatures are satisfactorily correlated with the experimental data. This is confirmed by the data of Figs. 6, which shows a satisfactory convergence of experimental and calculated temperatures.

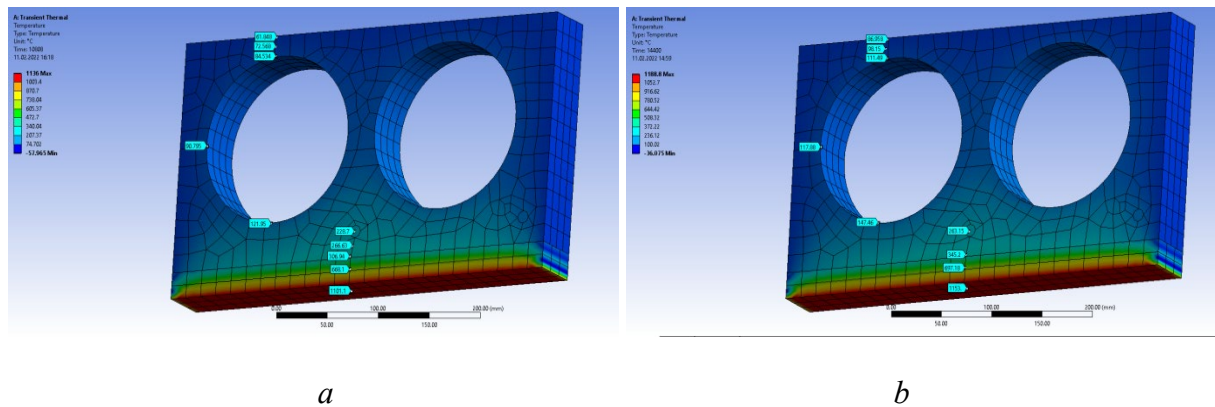


Fig. 5. Temperature distribution in the fragment of fire-retardant reinforced concrete slab for 180 and 240 minutes of its test

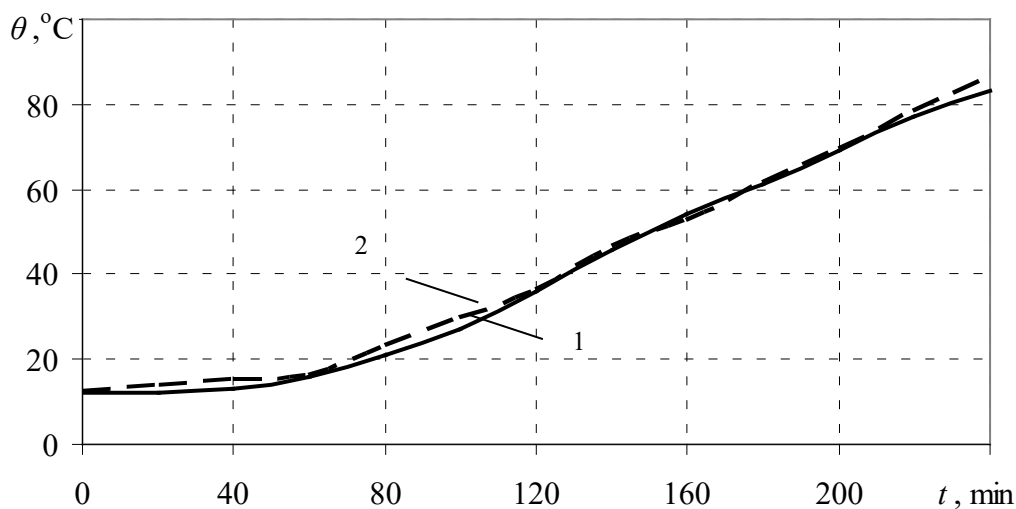


Fig. 6. Dependence of temperature on the time of fire exposure from the unheated surface of the reinforced concrete fireproof floor: 1 - experimental temperature from the unheated surface; 2 - design temperature obtained by simulation in the software package ANSYS

Based on the results shown in Fig. 6, it is possible to state correctness of construction of model in the ANSYS software environment, correctness of setting of parameters, initial and boundary conditions. To prove this statement it is sufficient to investigate the nature of the curves of temperature change from the unheated surface of the fire-retardant reinforced concrete floor from the time of fire exposure (Fig. 6).

As shown in Fig. 6 the largest deviation area in the measurement of temperatures is observed at 100 minutes of calculation and is about 3°C, which is 9%. This means that taking into account all the parameters when building a computer model of thermal processes in the system "reinforced concrete floor-fireproof coating" opens the possibility to assess the fire resistance of fireproof reinforced concrete structures with application of load under fire conditions at standard fire temperatures.

This does not differ from the experimental data (Fig. 6, curve 1), as the calculated curve (Fig. 6, curve 2) changes in temperature from the time of fire exposure from the unheated surface of the fire-retardant floor correlates well with the experimental. This indicates the adequacy of the developed model, which cannot be achieved using other approaches to setting heat transfer in the floor cavities. Approaches based on setting in air cavities with its characteristics and lack of convective and radioactive heat transfer lead to large errors in the calculation (up to 50%).

7 Conclusions

1. A 3D model of fire-retardant multi-hollow reinforced concrete floor in the ANSYS software package has been developed, which allows to simulate non-stationary heating of a fire-retardant structure, taking into account thermophysical and mechanical properties of materials of which the structure consists. A feature of the model is the ability to specify the characteristics of the layer with cavities, which is an important factor in regulating the accuracy of modeling, which can increase the convergence of the results of computational and experimental approaches to assessing fire resistance. Found an approach that allows to take into account all types of heat transfer by specifying the cavities as a solid body with an equivalent coefficient of thermal conductivity, which in each case is calculated separately. Concrete and reinforcement are modeled with three-dimensional elements.

2. Using the developed model, the heat engineering calculation of the fire-retardant reinforced concrete multi-hollow slab was carried out, the essence of which was to solve the problem of non-stationary thermal conductivity. The calculation was based on determining the concrete temperature of the reinforced concrete floor at any point of the cross section at a given time (including at the place of installation of reinforcement, which is extremely important in static calculation). As a result, it was found that the calculated values of temperatures correlate satisfactorily with the experimental data. The largest deviation in the measurement of temperatures is observed at 100 minutes of calculation and is about 3 °C, which is 9 %.

3. The quality of the developed model of thermal processes in the system "reinforced concrete floor-fire-retardant coating" in the software package ANSYS is checked. It is established that taking into account all parameters opens the possibility to assess the fire resistance of fire-retardant reinforced concrete structures with the application of load under fire exposure at standard fire temperatures. The quality of efficiency of the developed model for estimation of fire resistance of fire-protected reinforced concrete structures and adequacy to real processes is checked. They occur when heating fire-retardant reinforced concrete structures in conditions of high-temperature fire.

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