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ASSESSMENT OF FIRE RESISTANCE OF FIREPROOF REINFORCED CONCRETE STRUCTURES

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A finite-element model for the heat engineering calculation of fireproof reinforced concrete slab has been built, which is designed to assess the fire resistance of unprotected reinforced concrete structures. A feature of the model is the correct choice of types of heat transfer in the cavities of reinforced concrete ceilings. An algorithm that includes experimental and calculation procedures in determining the fire resistance of unprotected reinforced concrete structures has been applied. The initial, boundary conditions for the construction of the model were formulated; the thermophysical properties of materials were substantiated. Thermal calculation of fireproof multi-hollow reinforced concrete ceiling under conditions of fire was carried out. The adequacy of the developed finite-element model was checked. A satisfactory convergence of experimental and calculated temperatures with an accuracy of 10 % was established, which would suffice for the engineering calculations.

The model built makes it possible to assess the fire resistance of unprotected reinforced concrete structures. Thus, there is reason to argue that the model constructed can partially or completely replace the experimental assessment of fire resistance, provided that the construction and setting of the model parameters are correct

Keywords: fire resistance of structure, heat engineering calculation, reinforced concrete structures, fire retardant coating, fire resistance assessment

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1. Introduction

The limits of fire resistance of fire-protected and unprotected building structures can be determined both by calculation methods and based on experimental tests for fire resistance [1]. At the same time, despite the presence of requirements for temperature influences, they are often neglected in practice, which leads to significant economic losses [2]. Note that the development of methods for calculating the fire resistance of structures, especially in terms of solving a heat engineering problem, became possible owing to the use of modern software [3].

The application of estimation methods for assessing the fire resistance of unprotected and fire-protected reinforced concrete building structures, compared with experimental ones, has several advantages [4, 5]. The advantages are the possibility of making calculations without large material costs [6, 7]. However, software that is expensive must be certified. In addition, highly qualified specialists who will be able to correctly and reasonably set the parameters when modeling unprotected building structures.

Inaccuracies in setting the initial, boundary conditions and in the use of mathematical and physical models of the processes occurring during the thermal effects of a fire can lead to an erroneous assessment of the fire resistance of fire-protected building structures. This could lead to miscalculations in the design of buildings and facilities from such structures.

The requirements for the stability of buildings and structures are provided by a set of measures that involve both production technology and the use of building structures with scientifically based parameters of flame-retardant coatings, which are represented by a wide range. Analysis of the characteristics and parameters of coatings requires detailed study.

That is why the construction of the basis for effective assessment of fire resistance of fire-protected reinforced concrete building structures with scientifically justified parameters of fire-retardant coatings is a relevant task. Tackling this issue will increase the level of fire resistance of buildings and structures under high-temperature exposure.

2. Literature review and problem statement

The calculation of building structures for fire resistance includes heat engineering and static parts. The thermal part consists in calculating the temperature fields in the cross-section of the structure, which change over time when exposed to fire. The static part of the calculation for fire resistance is to determine the loss by structures of their bearing capacity due to changes in the mechanical properties of materials [8]. The existing world experience of testing for fire resistance of reinforced concrete structures shows that under different conditions, structures with higher mechanical characteristics usually have a higher rate of fire resistance [7, 8].

The results of estimation calculations are reported in [9], making it possible to predict the use of bending reinforced concrete elements based on concrete with dispersed fibers under conditions of increased fire danger, depending on the percentage of reinforcement and loading. However, the issues of behavior of bending reinforced concrete elements under fire conditions with the use of fire retardant coatings with scientifically based parameters to increase the limits of fire resistance of structures remained unresolved.

Reinforced concrete structural elements were modeled in [10]; thermal analysis was performed using the ABAQUS software package. A comparison of research results was carried out taking into account the influence of boundary conditions, temperature, convection, and radiation. It was established that setting convective and radiation boundary conditions made it possible to obtain more accurate results. The use of thermal characteristics according to Eurocode 2 (taking into account moisture emission) made it possible to reduce the discrepancies between calculated and experimental temperatures. Despite the practical significance of such results, the issues of modeling the thermal state of unprotected reinforced concrete structures have not been sufficiently considered.

The task of assessing the fire resistance of steel frame structures with swelling coatings is considered in [11]; a procedure for calculating the heating time to the critical temperature of steel columns and beams protected by a swelling coating is proposed. The paper shows the importance of taking into account the influence of the time of loss of strength when heating a steel structure on the calculation of the fire resistance limit of the «flame retardant coating-steel structure» system. However, the influence of the time of loss of strength should be taken into account only when predicting the fire resistance of steel frame structures with reactive flame-retardant coatings.

The results of the assessment of the fire resistance of precast concrete beams-columns, which are connected at the ends with reinforced concrete slabs and combined into a precast concrete frame structure, are presented in [12]. To verify the accuracy of the constructed model, only a computational experiment was used in assessing the fire resistance of the structures under consideration but without a fire protection system. This imposes restrictions on the use of the model in frame structures of fire-protected reinforced concrete structures with scientifically based parameters of flame-retardant coatings.

The results of building a model of a freely resting steel beam in the ANSYS software package are reported in [13, 14]. Using the model, the calculation of the beam exposed to the standard temperature regime of the fire was carried out. However, despite the advantages of this approach, the question remains open regarding the calculations of fire-protected reinforced concrete structures, due to the importance of correctly setting the parameters of flame-retardant coatings (coefficient of thermal conductivity and heat capacity).

The results of numerical modeling of the test for fire resistance of load-bearing walls, performed by using different configurations of fire furnaces, are given in [15]. The difference between the maximum and minimum temperatures only on the surface of reinforced concrete was determined. The methods proposed in that study do not make it possible to assess the fire resistance of fire-protected load-bearing reinforced concrete walls.

In [16], a methodology for assessing the fire resistance of reinforced concrete ceilings has been devised. The procedure for applying approaches to the calculation of fire resistance limits based on the method of final differences was advanced. The requirements for materials, boundary conditions, design schemes, grid models, as well as the criterion base for the onset of boundary states were proposed for consideration in the methodology. However, this procedure cannot be used for reinforced concrete ceilings protected by flame-retardant coatings. Perhaps this may be due to the lack of reliable data on the properties of fire-retardant coatings.

A description of the theoretical foundations and basic hypotheses for modeling different types of finite elements of any structure when exposed to fire temperature using the SAFIR software package is provided in [17]. The paper explains how to use the software in its entirety. Despite the practical significance of such results, the issues regarding the calculations of fire-protected reinforced concrete structures have not been sufficiently considered. Obviously, this is due to the difficulties of building a fireproof structure in this software package and the correct setting of the parameters of flame-retardant materials.

The results of a parametric study of the behavior of concrete beams under the influence of fire are reported in [18]. An idea is given of the behavior of concrete beams exposed to thermal and mechanical loads. Deflections of structures due to thermal exposure are considered. The results of a numerical study into the characteristics of a steel-concrete composite ceiling that was subjected to fire by conducting three-dimensional thermomechanical analysis using the ANSYS software are presented in [19]. Comparing the results of a real fire with the results of numerical modeling, the accuracy of using numerical models to predict the effect of fire temperature on the behavior of structures has been established. However, it is not determined how this procedure can be used for fire-protected reinforced concrete structures.

From a practical point of view, this can cause difficulties associated with taking into account the thermophysical characteristics of flame-retardant coatings to increase the fire resistance limits of reinforced concrete structures.

In [20], studies on the progressive destruction of reinforced concrete structures under the influence of high fire temperature are presented. Nevertheless, the researchers ignored the question of the influence of heating the structure before the onset of the limiting state of fire resistance by heat engineering calculation.

The results of tests for fire resistance of two control beams and eight reinforced concrete beams reinforced with fibrous materials are presented in [21]. However, it should be noted that the researchers ignored the issues of modeling the thermal state of fire-protected reinforced concrete structures.

In [22], a developed computer model based on the finite-element method for advanced analysis capable of assessing the behavior of reinforced concrete structures exposed to fire is offered. The calculations were carried out in the NASEN software package, which is used to analyze structures under fire conditions. The model makes it possible to take into account the effects of geometric nonlinearity, nonlinearity of the material, and nonlinear thermal gradients, as well as changes in material properties with increasing temperature. However, with the help of the model built, it is impossible to simulate the thermal calculation of fire-protected reinforced concrete structures. Perhaps this is due to the lack of reliable data on the thermophysical characteristics of fire-retardant coatings.

The most significant success in the practice of assessing the fire resistance of reinforced concrete structures was achieved by a scientific school headed by the famous scientist Fomin. Studies into the calculation of fire resistance of reinforced concrete structures using refined and simplified methods using the LIRA software package using examples of the calculation of reinforced concrete ceiling slabs are reported in [23]. The authors have devised a method based on the construction of computer models in the LIRA software. The method is based on the use of nonlinear approaches based on the basic principles and assumptions from the theory of thermal conductivity, certain principles and assumptions of structural mechanics, taking into account a change in the mechanical properties of materials on temperatures. However, the paper does not address the use of the method to evaluate fire-protected reinforced concrete structures.

Our review has revealed that experimental methods for assessing the fire resistance of fire-protected reinforced concrete structures are the most accurate and provide the most reliable information on the limits of fire resistance of building structures under the conditions of their testing under standardized fire temperatures. Nevertheless, along with the advantages, such methods have a series of disadvantages. Such disadvantages include the complexity of manufacturing, preparing, and conducting tests for fire resistance of large-sized building structures, high material costs during testing in certified laboratories. In addition, the disadvantages include the impossibility of transferring the test results of one structure to structures of all sizes and types, unsatisfactory adhesion of the fire-retardant coating to the protected surface during the impact of fire, the problem of maintaining the integrity of the fireproof coating, and as a result, non-fulfillment of its protective functions. All this imposes some restrictions on the use of only an experimental method for assessing the fire resistance of fire-protected reinforced concrete structures, taking into account the above disadvantages. The use of estimation methods for assessing the fire resistance of fire-protected reinforced concrete building structures, compared to experimental ones, has a number of advantages, including the possibility of making calculations without high material costs, although software that can be expensive must be certified, as well as highly qualified specialists who will be able to correctly and reasonably set the parameters of the thermal state model of fire-protected building structures. After all, inaccuracies in setting the initial, boundary conditions and inaccuracy in the use of mathematical and physical models of thermal processes in fire-protected structures under the thermal effects of fire can lead to an erroneous assessment of the fire resistance of fire-protected building structures, and therefore to miscalculations in the design of buildings and facilities from such structures.

The systematization of the conducted studies makes it possible to argue about the trend of using the calculation-experimental method for assessing the limits of fire resistance of fire-protected reinforced concrete building structures and the flame-retardant ability of coatings for such structures. This method makes it possible to take into account the value of the thermophysical characteristics of fire-retardant coatings and the processes of heat transfer in the structure under the influence of temperature conditions of fire. The method makes it possible to take into account all the above miscalculations; it is accurate enough for engineering calculations when assessing the limits of fire resistance of fire-protected structures with fire-retardant coatings, as a scientific basis for increasing the level of fire safety of objects by their fire protection with standardized parameters.

Thus, the unresolved part of the problem is the inability to assess the fire resistance of fire-protected reinforced concrete building structures using adequate computer models that would make it possible to model the non-stationary heating of fire-protected reinforced concrete structures. At the same time, such models should be able to determine the temperature in any cross-section of the structure (at any point and time) under the influence of standardized temperature conditions of fire and take into account the parameters of fire-retardant coatings. Tackling this issue will lead to the possibility of assessing the fire resistance of fire-protected reinforced concrete structures with accuracy (up to 5 %) that is enough for engineering calculations.

3. The study materials and methods

The aim of this work is to assess the fire resistance of fireproof reinforced concrete ceilings using the developed computer model, which is implemented in the software package LIRA-CAD (Ukraine), under the influence of elevated fire temperatures.

This makes it possible to assess the fire resistance of fire-protected reinforced concrete structures with scientifically based parameters of flame-retardant coatings.

To achieve the set aim, the following tasks have been solved:

– to build a finite-element model of a fireproof multi-hollow reinforced concrete ceiling;

– to simulate non-stationary heating of a fireproof multi-hollow reinforced concrete ceiling;

– to assess the accuracy of the developed finite-element model of a fireproof multi-hollow reinforced concrete ceiling.

4. Materials and methods to study the fire resistance of fire-protected reinforced concrete structures

4. 1. Tested materials

Two samples of multi-hollow reinforced concrete ceilings with dimensions of 4780×1190×220 mm were tested. The ceiling consists of a load-bearing steel frame of five lower longitudinal bearing prestressed reinforcement rods with a diameter and reinforcing wires with a diameter of 4 mm. Concrete class, C12/15. The thickness of the protective layer of rock concrete (Fig. 1) was 20 mm.

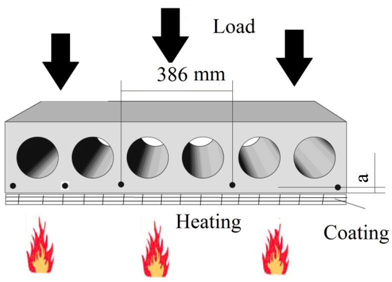

Fig. 1. Temperature and static load on a ceiling

The fire resistance limit of the ceiling is REI 45. A layer of flame-retardant was applied to the ceiling from below and on the sides, which formed a coating with an average thickness of 25.9 mm. During the tests, there was no loss of integrity, thermal insulation capacity and bearing capacity of the fireproof reinforced concrete ceiling.

4. 2. Fire resistance tests of reinforced concrete ceiling

A horizontal furnace was used to test the ceiling. Samples were installed on top of the furnace and rested on the furnace with edges through supports made of basalt slabs.

When modeling the load, concrete blocks were used, calculated to be 570 kg/m^2. That corresponded to the stresses in the ceilings of 5.7 kN/m^2.

Thermal impact on the ceiling lasted for 242 minutes according to the standard temperature regime of the fire.

The deflection value and the rate of increase in deformation of samples on minute 242 of tests were, respectively, 42 mm and 0.4 mm/min (sample No. 1), and 46 mm and 0.4 mm/min (sample No. 2).

To measure the average and maximum temperature from the non-heated surface of the fireproof ceiling, 5 thermocouples were installed, one thermocouple in the center of the sample and four in the geometric centers of the quarters of the sample. The temperatures obtained as a result of fire resistance tests were used to find the thermophysical characteristics of concrete and the passive flame-retardant coating that was investigated. To determine the characteristics, in this work we used a package of application software FRIEND-2, which implements algorithms for solving direct and inverse problems of thermal conductivity. The program makes it possible to determine the thermophysical characteristics of building materials and flame-retardant coatings of metal, reinforced concrete structures, as well as other parameters of heat exchange processes based on the results of non-stationary temperature measurements inside or on the surface of samples.

The calculations were performed using licensed software provided by TOV LIRA SAPR (Ukraine) (license No. 1/8583, dated 16.02.2022).

5. Simulation results of non-stationary heating of fire-protected reinforced concrete structures

5. 1. Construction of a finite-element model of a fireproof multi-hollow reinforced concrete ceiling

The solution to the problem of non-stationary thermal conductivity was reduced to determining the temperature of concrete of a fireproof reinforced concrete ceiling at any point of cross-section at a given time.

The calculation algorithm implied determining the temperature in each cross-sectional node of the developed estimation model. The coordinate grid was superimposed so that its nodes were located not only in the cross-sectional thickness but also along its perimeter. In addition, the nodes were to be placed in the center of the rods for structures with flexible reinforcement, and along the length of the shelves and walls in the middle of their thickness for structures with rigid reinforcement. The grid pitch is recommended to be set within 0.01–0.03 m but it must be larger than the maximum diameter of the working reinforcement (12 mm). One of the most important stages of finite-element analysis is the construction of a grid of finite elements. The accuracy of calculation using the finite-element method depends on the correct choice of types and sizes of finite elements. A rectangular grid with four nodes was chosen, which gives more accurate results than a grid with triangular elements, which is explained as follows. A fine mesh is needed where a large gradient of deformations or stresses is expected (hole, turning, cracking, etc.). At the same time, a large mesh can be used in areas with excellent deformations or stresses that vary little, as well as in areas that are not of particular interest for calculations. In this regard, before building a finite-element grid, it is necessary to select the estimated areas of concentration of stresses.

The accuracy of the calculation results decreases if the dimensions of neighboring elements near the stress concentrator differ significantly.

Finite elements in a fireproof reinforced concrete ceiling were assumed to be 2 thicknesses in size (that is, for a slab with a thickness of 200 m, the size of the finite element was taken equal to 400×400 mm). The size of the finite element of the ceiling slab was set to more than 1/6 of the span of the slab but not less than 1/15 of the span of the slab. 10 finite elements were specified for the span of the ceiling slab.

Thus, the grid of finite elements is based on elements close to squares, which is an ideal option for calculating the matrix; the length of the elements does not exceed 1/10 of the cross-sectional size, which corresponds to the recommendation for the formation of a grid of finite elements. Reducing the size will lead to an increase in a significant number of finite elements, and this will lead to an increase in the time of calculation and use of more powerful computing equipment while the analysis of results will not be affected.

The cross-section of the multi-hollow reinforced concrete ceiling was modeled using the 15th feature of the scheme in the LIRA-CAD software environment (Fig. 2).

The model consists of 3107 nodes and 3372 elements. The partitioning step along the cross-section was h=0.01 m, the time step Δt=60 s. The simulated elements of the finite-element model were assigned stiffness types, as shown in Table 1.

At the third stage, an external load was set. To do this, in load 1, all the nodes of the scheme were highlighted, and a load was set in them, which will correspond to the initial temperature of the structure of 20 °C. After setting the load on the nodes, they turn green.

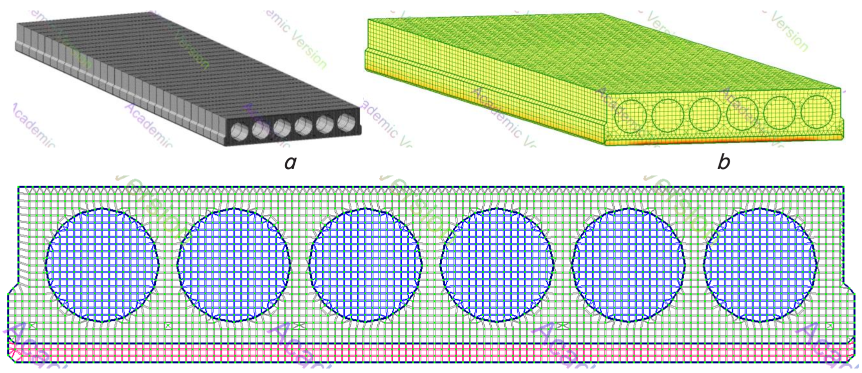

Fig. 2. 3D model of reinforced concrete ceiling (*a, b*) and 2D (*c*) model: *a* — reinforced concrete ceiling; *b* — fire-protected reinforced concrete ceiling; *c* — fire-protected reinforced concrete ceiling

Table 1

Stiffness characteristics for modeling

No.	Title	Comment	*H*, cm	*K*, J/(m·s·°C)	*C*, J/(kg·°C)	R_O, N/m^3
1	Thermal conductivity	Concrete	100	1.300	970	23,030
2	Thermal conductivity	Air	100	3.180	950	12.76
3	Thermal conductivity	Fire protection	100	0.071	2,000	4,903
4	Convection	Heating surface	100	a=25 J/(s·m^2·°C)	–	–

5. 2. Simulation of non-stationary heating of fireproof multi-hollow reinforced concrete ceiling

The thermal conductivity λ_a and the specific heat capacity of steel c_a were set according to [24].

To determine the thermophysical characteristics of the studied plaster coating, the results of tests for fire resistance were used.

According to the manufacturers of flame-retardant substance, the coefficient of thermal conductivity of the coating in the dry state is 0.11 W/m·°C at 20 °C, although the thermophysical characteristics should be set as temperature dependences.

The coefficient of thermal conductivity of the flame-retardant coating (Fig. 3) was set in the form of temperature dependences [25].

The specific volumetric heat capacity of the coating was found by solving the inverse problems of thermal conductivity and amounted to 2000 J/(kg·°C). In this case, the density of the coating is ρ_p=500 kg/m^3. The regularity of the behavior of the coefficient of thermal conductivity of the flame-retardant coating is described by the regression dependence of the type: $\lambda_p = 1 \cdot 10^{-07} \cdot \theta^2 - 0.0001 \cdot \theta + 0.0863$ with an approximation reliability of 0.9924 (Fig. 3).

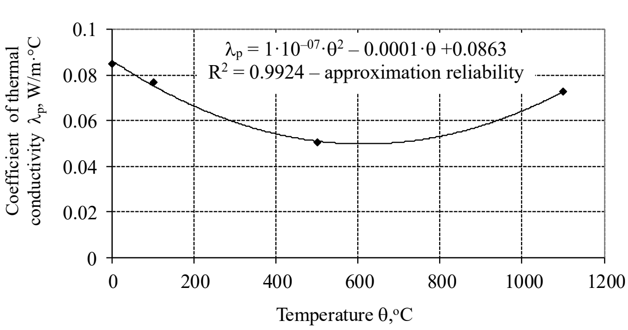

Fig. 3. Coefficient of thermal conductivity of fire-retardant coating: ◆ — estimated points

The coefficient of thermal conductivity and the specific volumetric heat capacity of concrete of fireproof reinforced concrete ceiling were found by solving inverse problems of thermal conductivity according to the results of fire tests [25].

The temperature in the first fiber of the concrete cross-section during the warm-up under a standard temperature regime of the fire changes in 240 minutes from the initial 20 °C to about 200 °C. Therefore, all the thermophysical and mechanical properties of concrete were set in this temperature range.

Parameters of the thermal process model (initial and boundary conditions) for modeling the non-stationary heating of fireproof reinforced concrete ceilings:

– F is the angular coefficient, F=1.0;

– ε_m – coefficient of thermal radiation of the heated surface of the coating, ε_m=0.7;

– ε_f – coefficient of thermal radiation of the flame, ε_f=1.0;

– ρ_s – steel density, ρ_s=7850 kg/m^3;

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

– θ_0 – initial temperature, θ_0=20 °C;

– Poisson coefficient of steel ν=0.3; modulus of elasticity $E_s=2.1 \cdot 10^5$ MPa;

– ρ_c – density of concrete, ρ_c=2300 kg/m^3;

– α_{ct} (250 °C)=$9 \cdot 10^{-6}$ °C^{-1} coefficient of thermal expansion of concrete [EN 1992-1-2 Eurocode 2];

– $E_{c,\theta}=1.2 \cdot 10^4$ MPa initial modulus of concrete elasticity [EN 1992-1-2 Eurocode 2].

The effect of a fire flame on a reinforced concrete structure is a non-stationary process, therefore, non-stationary thermal analysis is used to obtain the distribution of temperature fields in a fireproof reinforced concrete structure. The design of the fireproof reinforced concrete slab was carried out in the module «Thermal conductivity» of the LIRA-CAD software.

To calculate the uneven temperature distributions in the cross-section of the fireproof reinforced concrete ceiling, a mathematical model of non-stationary thermal conductivity was used, the mathematical apparatus of which is implemented in the LIRA-CAD software. The model is a differential equation of thermal conductivity, which takes into account radiation-convective heat transfer from the gaseous medium to the heated surface of the fireproof ceiling (boundary conditions of the III kind), conductive heat transfer in the ceiling, and radiation-convective heat transfer from the side of the non-heated surface of the ceiling (boundary conditions of the III kind). To solve the thermal conductivity equation, the finite-element method implemented in the LIRA-CAD software was used, for which most verification tests for bending structures give an error within 5 %, and for rods – less than 1 %.

As a result of numerical modeling, temperature distributions were obtained in a fireproof multi-hollow ceiling on minute 120 of fire exposure under a standard temperature regime of the fire (Fig. 4).

Fig. 5 shows the temperature distribution in a fireproof reinforced concrete ceiling slab on minute 240 of the test.

Particular emphasis in the study of temperature fields shown in Fig. 5, 6, should be paid to the heating of the cavities of a multi-hollow reinforced concrete ceiling. The correctness of setting the thermophysical and mechanical characteristics of this particular layer most of all affects the accuracy of the simulation. It should be noted that to find the equivalent coefficient of thermal conductivity of a layer with cavities, there are several approaches. The first approach is based on setting air in cavities with its characteristics. In the second approach, it is possible to realize the absence of convective and radiation heat transfer, but this leads to large errors. And the third approach makes it possible to take into account complex radiation-convective heat transfer by specifying cavities as a solid with an equivalent coefficient of thermal conductivity, which in each case is calculated separately. The coefficient value for the calculations was calculated in [5, 25] and is equal to 3.18 W/m·°C, at which the greatest proximity of calculated and experimental temperatures was observed on the surface of the ceiling that is not heated.

The results of numerical modeling of the non-stationary heating of fireproof reinforced concrete ceilings in the LIRA-CAD software were tested with experimental tests in a fire furnace. The data shown in Fig. 5, namely the temperatures from the unheated surface of the fireproof reinforced concrete ceiling, coincide with the results of the experiment. This is confirmed by the data shown in Fig. 6, which shows the temperatures from the non-heated surface of the fireproof reinforced concrete ceiling, obtained experimentally and as a result of numerical modeling. Fig. 6 shows that experimental (T1aver.) and calculated (T1aver.calc.) temperatures have satisfactory convergence, as can be seen from the curves of temperature dependence on the time of fire exposure according to the standard temperature regime of the fire.

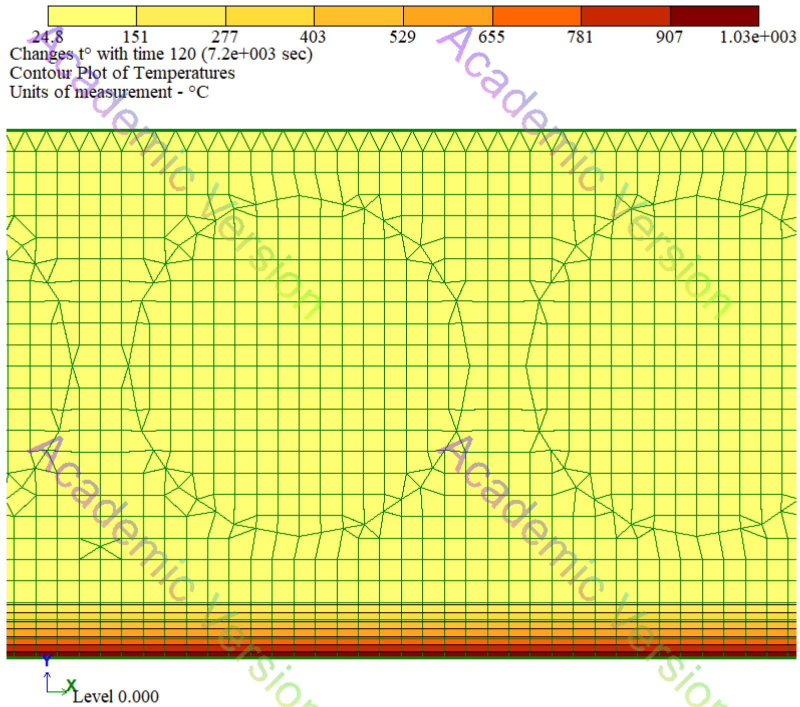

Fig. 4. Temperature distribution in a fragment of a fireproof reinforced concrete ceiling on minute 120 of the test

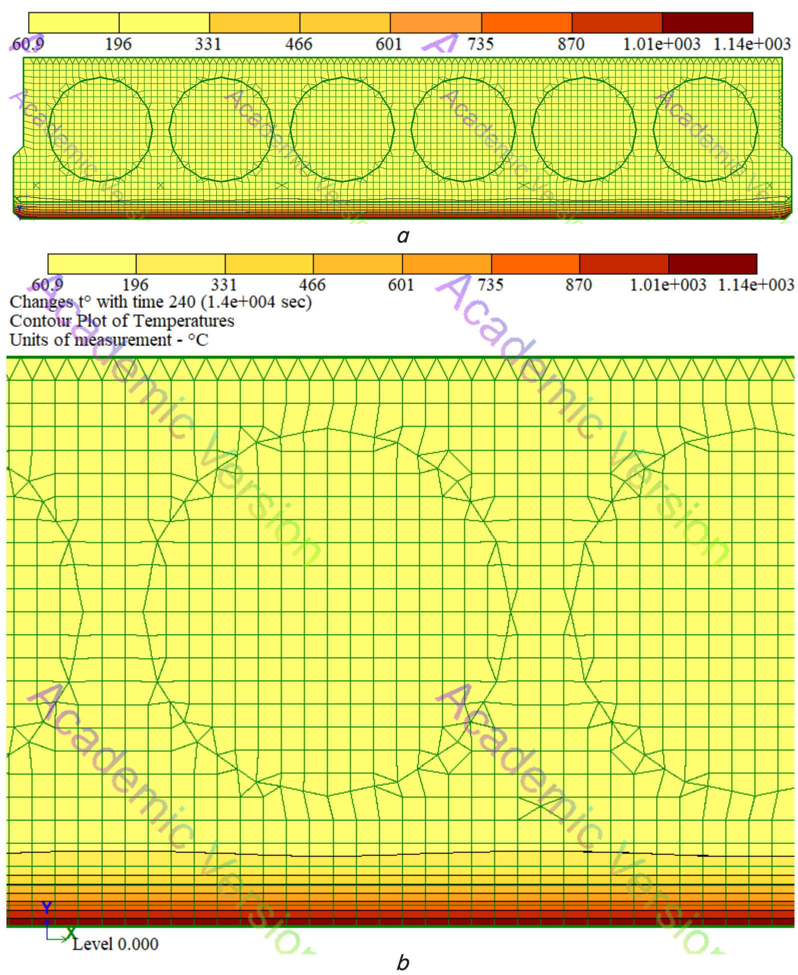

Fig. 5. Temperature distribution in a fireproof reinforced concrete ceiling slab on minute 240 of the test: *a* – fire-protected reinforced concrete ceiling; *b* – fragment of fireproof reinforced concrete ceilings

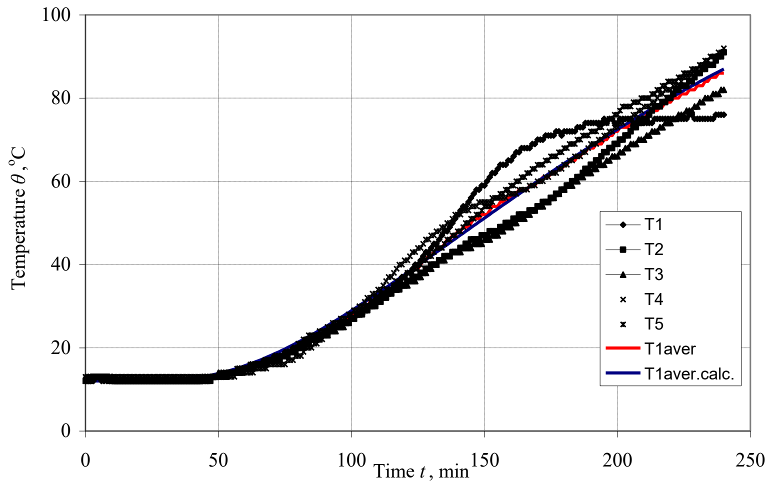

Fig. 6. Dependence of the temperature from the non-heated surface of the fireproof reinforced concrete ceiling on the time of fire exposure: T1–T5 – temperatures in the geometric centers of the quarters of reinforced concrete ceilings, obtained experimentally; T1aver. – experimental average temperature; T1aver.calc. – average temperature obtained as a result of numerical modeling

5. 3. Evaluation of the accuracy of the developed finite-element model of fireproof multi-hollow reinforced concrete ceiling

Fig. 7 shows that the estimated curve T1aver.calc. coincides with the experimental curve T1aver. At the same time, the largest temperature deviation from the experimental values was observed on minutes 160–180 of calculation and amounted to 3 °C, which corresponds to an error of not more than 4 %. This indicates the correctness of setting the parameters of the model of thermal processes in the system «reinforced concrete ceiling – fire-retardant coating».

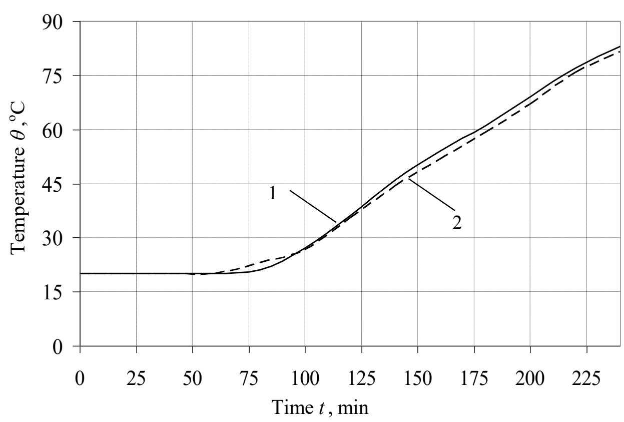

Fig. 7. Temperature from the non-heated surface of the fireproof reinforced concrete ceiling: 1 – experimental curve; 2 – estimated curve

It should be noted that the incorrect setting of the parameters of the layer with cavities leads to inaccuracies in the simulation (up to 50 %). The paper uses an approach that makes it possible to take into account complex radiation-convective heat transfer in ceiling cavities by setting cavities as solids with an equivalent thermal conductivity coefficient of 3.18 W/m °C. Obviously, such a mechanism for setting the layer of thermal conductivity coefficient of ceiling cavities is the factor in regulating the accuracy of modeling, owing to which it is possible to increase the convergence of the results of the calculated and experimental approach to assessing fire resistance.

6. Discussion of results of modeling the non-stationary heating of fire-protected reinforced concrete structures

With the help of the developed computer model (Fig. 2), the fire resistance of the fireproof reinforced concrete multi-hollow ceiling slab was assessed. The assessment of fire resistance involved solving the problem of non-stationary thermal conductivity and was reduced to determining the temperature of concrete of reinforced concrete ceiling at any point of cross-section in a given period of time (Fig. 4, 5). The results from modeling the non-stationary heating make it possible to determine the temperature of the concrete of the fireproof reinforced concrete ceiling at any point of cross-section at a given time (including at the place of installation of the reinforcement). The model developed in this work can be used in assessing the fire resistance of other types of fire-protected reinforced concrete structures, taking into account their geometry and properties. The obtained results satisfactorily correlate with the experimental data, which confirms the effectiveness of the developed computer model in the LIRA-CAD software. The results obtained as a result of numerical modeling can be explained by the correctness of the development of a finite-element model of a fireproof reinforced concrete ceiling, setting the initial and boundary conditions, the accuracy of the mathematical and physical models, and the satisfactory convergence of experimental and calculated temperatures. In this paper, accuracy of up to 5 % is accepted, which satisfies engineering calculations. This is confirmed by data in Fig. 7, which show a satisfactory convergence of experimental and calculated temperatures.

A feature of the developed finite-element model is the possibility of modeling non-stationary heating of fire-protected reinforced concrete structures, taking into account the thermophysical characteristics of materials and taking into account the complex heat transfer in the cavities of reinforced concrete ceilings. The proposed model makes it possible to investigate the physical processes occurring precisely in fire-protected reinforced concrete structures, with scientifically based parameters of flame-retardant coatings. Such advantages that manifested in the possibility of taking into account the characteristics of flame-retardant coatings could not be achieved in works [9, 10] since it was not possible to take into account the thermophysical characteristics (thermal conductivity, heat capacity) of flame-retardant coatings in the form of temperature dependences and build a finite-element model of a fireproof structure.

The constructed model makes it possible to explore the stationary and non-stationary heating of both fire-protected and fire-protected reinforced concrete structures. Moreover, taking into account the complex heat transfer in the cavities of reinforced concrete ceilings opens up the possibility for modeling heat exchange processes in monolithic fire-protected reinforced concrete structures. It should be noted that the developed computer model makes it possible to assess the fire resistance of fire-protected reinforced concrete building structures with scientifically based parameters of flame-retardant coatings. This means that taking into account this fact opens up the possibility for effective assessment of the fire resistance of fire-protected reinforced concrete structures using modern software systems. This does not diverge from the practical data (Fig. 7, curve T1aver.), which proves the performance of the developed model.

It should be noted that the disadvantage of the developed model is the lack of reliable data on the characteristics of the material of reinforced concrete structure and flame-retardant coatings. This leads to the fact that designers use the data available in the literature or regulatory documents. This does not always satisfy the requirements for the accuracy of calculations and can lead to an erroneous determination of the fire resistance of building structures. Failure to take into account these parameters in the simulation imposes certain restrictions on the use of the results obtained.

The inability to remove these restrictions in the framework of this study gives rise to a potentially interesting area for further research. The development of this study may consist in the development of a computer model that would make it possible to assess the fire resistance of buildings and structures during the joint operation of both steel and reinforced concrete fire and fire-protected building structures. In this case, it is possible to face difficulties in describing the mathematical apparatus of the process of non-stationary heating of fire-protected reinforced concrete structures during their joint work in the structural scheme of the building.

7. Conclusions

1. A finite-element model of a fireproof multi-hollow reinforced concrete ceiling in the LIRA-CAD software environment has been developed, which makes it possible to model the non-stationary heating of a fireproof reinforced concrete structure, taking into account the thermophysical and mechanical properties of the materials that make up the structure. The model consists of 3107 nodes and 3372 elements and makes it possible to simulate non-stationary heating of a fireproof structure, taking into account the thermophysical and mechanical properties of the materials that make up the structure. The thermophysical and mechanical properties of materials are substantiated, which make it possible to predict the fire resistance of a fire-proof reinforced concrete structure with sufficient accuracy for engineering calculations.

2. With the help of the developed model, a simulation of non-stationary heating of a fireproof multi-hollow reinforced concrete ceiling was carried out under the conditions of its testing at a standard temperature regime of fire, the essence of which was to solve the problem of non-stationary thermal conductivity. As a result of the simulation, the fire-protected reinforced concrete ceiling was divided into 4 layers. Each layer was assigned with thermophysical and mechanical characteristics, found from the results of tests for fire resistance. A feature of the developed model is the correct setting of heat transfer in the cavities of a multi-hollow reinforced concrete ceiling, which involves setting an equivalent coefficient of thermal conductivity of the ceiling layer with cavities (3.18 W/m·°C). At the same time, the greatest proximity of calculated and experimental temperatures from the non-heated surface of the fire-proof reinforced concrete ceiling is observed. The model makes it possible to take into account the thermophysical characteristics of reinforced concrete structures and flame-retardant coatings, depending on temperature.

3. The accuracy of the developed model for assessing the fire resistance of fireproof multi-hollow reinforced concrete ceilings implemented in the LIRA-CAD software environment was assessed. As a result, a satisfactory convergence of experimental and calculated temperatures was established (with an accuracy of 5 %). At the same time, the largest temperature deviation from the experimental values was observed on minutes 160–180 of calculation and amounted to 3 °C, which corresponds to an error of not more than 5 %. This indicates the correctness of setting the initial and boundary conditions, the construction of a computer model of thermal processes in the system «reinforced concrete ceiling – fire-retardant coating». It is proved that the developed computer model makes it possible to simulate real processes occurring when heating fire-protected reinforced concrete structures with the application of load under fire exposure at a standard temperature regime of fire.

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Conflict of interests

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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