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CALCULATION OF FIRE RESISTANCE OF FIRE PROTECTED REINFORCED CONCRETE STRUCTURES

A finite-element model was developed for thermal engineering calculation of a fire-resistant multi-cavity reinforced concrete floor in the ANSYS software complex. With the help of the developed model, a thermal engineering calculation of a fire-resistant reinforced concrete multi-hollow floor slab was carried out, the essence of which was to solve the problem of non-stationary thermal conductivity and was reduced to determining the temperature of the concrete of the reinforced concrete floor at any point of the cross section at a given time (including at the place of installation of the fittings).A comparison of the results of numerical modeling with the results of an experimental study of fire resistance was carried out. An approach is proposed that allows taking into account all types of heat exchange by specifying cavities as a solid body with an equivalent coefficient of thermal conductivity. The model makes it possible to study stationary and non-stationary heating of both unprotected and fire-protected reinforced concrete structures. At the same time, with the help of the developed model, it is possible to take into account various factors affecting fire-resistant reinforced concrete structures: fire temperature regimes, thermophysical characteristics of reinforced concrete structures, coatings for fire protection of reinforced concrete structures. The adequacy of the developed model was tested, as a result of which it was established that the calculated values of temperatures satisfactorily correlate with experimental data. The largest area of deviation in temperature measurement is observed at the 100 th minute of calculation and is about 3 ºC, which is 9 %. The workability of the developed model for evaluating the fire resistance of fire-resistant reinforced concrete structures and its adequacy to real processes that occur during heating of fire-resistant reinforced concrete structures with the application of a load under the conditions of fire exposure under the standard fire temperature regime have been proven.

Keywords: fire resistance, reinforced concrete structures, thermal engineering calculation, numerical modeling, fire protection, fire protection coating, ANSYS

1. Introduction

Despite technical progress in construction and fire fighting technologies, the latter have not become less dangerous. Fires claim thousands of lives and cause billions in damages. About 51 % of all fires in the countries of the world occur in buildings and structures and on transport. At the same time, 90 % of all fire victims die indoors. The above factors create a need for human protection against the effects of the outlined threats. At the same time, one of the most dangerous factors are fires in the premises of buildings and structures. Ensuring the safety of people and material assets must be carried out taking into account all stages of the life cycle of objects, such as scientific support and monitoring, design, construction, operation, as well as exclude the occurrence of fires. The occurrence of fire can be prevented by technical means and organizational measures, under which the probability of occurrence and development of fire does not exceed the normalized permissible value. A condition for reducing the irreversible consequences of fires at objects of various purposes is the preservation of the load-bearing capacity of construction, technological structures and communications.

The stated requirements for stability are ensured by a set of measures, provided both by the production technology and by the use of effective fire-resistant coatings for fire protection of building structures.

Therefore, in the conditions of globalization and increasing threats to humans, the first place is played by the preservation of the stability of buildings and structures in the conditions of fires and other natural disasters, as well as the preservation of 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.

In [1] 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 [2] 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 [3] 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 proble 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 [4] 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 [5] 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 [6] 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 [7] 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 [8], 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 tasks of the research

The purpose of the work is to evaluate the fire resistance of fire-resistant reinforced concrete structures using the developed model, implemented in the ANSYS software complex, for thermal engineering calculation of fire-resistant reinforced concrete multi-hollow floor slabs under the influence of elevated fire temperatures.

To achieve the set goal, the following tasks needed to be solved:

– to develop a finite-element model of a fire-resistant multi-cavity reinforced concrete floor in the ANSYS software complex;

– perform heat engineering calculation of fire-resistant multi-hollow reinforced concrete floor in the ANSYS software complex;

– to check the adequacy of the developed finite element model of a fire-resistant multi-hollow reinforced concrete floor.

4. Development of a model of the thermal state of a fire-resistant multi-cavity 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. The plate has a load-bearing steel frame, which consists of five lower longitudinal load-bearing reinforcing bars of 12 mm (rebar brand: prestressed A500C) and reinforcing wire of 4 mm Vr1. Concrete C12/15.The average value of the thickness of the protective layer of concrete to the lower load-bearing reinforcement was 20 mm. According to the manufacturer, the limit of fire resistance of the slab is REI 45. A layer of fire-resistant coating material (plaster) with a thickness of 25,5 mm (sample № 1) and 26,4 mm (sample № 2) was applied to the samples from the bottom and sides of the slabs using a plaster unit. The average value of the application thickness is 25,9 mm (Fig. 1).

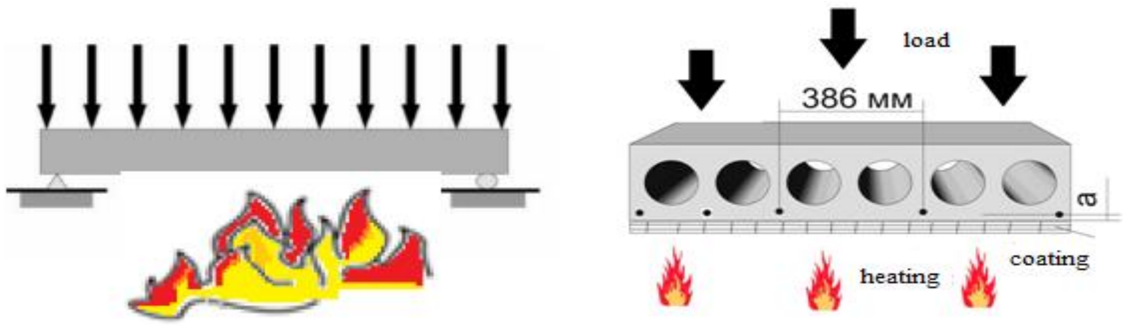


Fig. 1. Scheme of temperature loads on the plate for modeling

The samples were installed on a horizontal furnace, i.e. hinged on one side of the plate and not hinged on the other.

The loading was carried out by calibrated loads in the form of concrete blocks. The actual load on the samples was determined based on the creation of stresses in the slabs corresponding to the stresses from the specific distribution load of 570 kg/m^2.

According to the formulas, the limit value of the deflection of the samples is 220 mm (deflection b=4400 mm, the calculated thickness of the plates is 220 mm), and the limit value of the rate of growth of deformation is 9,8 mm/min.

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

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

The value of the deflection and the rate of growth of deformation of the samples for 242 min of testing were, respectively, 42 mm and 0,4 mm/min (sample № 1) and 46 mm and 0,4 mm/min (sample № 2). During the tests, there was no loss of integrity, heat-insulating ability and load-bearing capacity of both samples.

For most materials, data on performance characteristics are usually provided only at room temperature, or there is no such data at all. This fact is one of the reasons for the limited use of calculation methods based on mathematical modeling of heat exchange processes for solving the problems of thermal design of fire-resistant structures, namely fire-resistant reinforced concrete structures.

Using the results of fire resistance tests, a numerical simulation of the heating of a fire-resistant multi-hollow floor slab was carried out in the ANSYS software complex.

Solving the problem of non-stationary thermal conductivity was reduced to determining the temperature of the concrete of the fire-resistant reinforced concrete floor at any point of the cross-section at a given time.

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

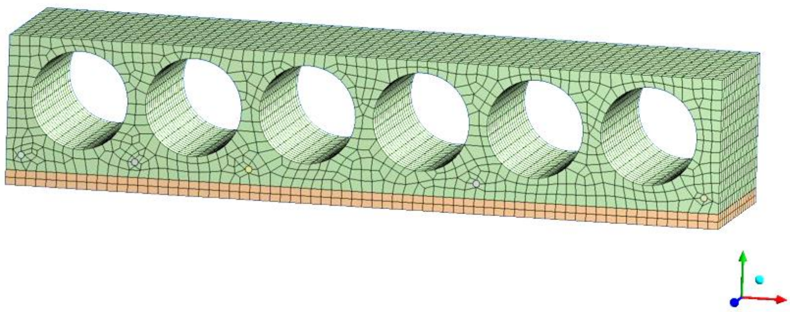


Fig. 2. Finite element model of fire-resistant multi-cavity reinforced concrete floor in 3D design

The step of dividing the section was h = 0,01 m, the time step Δt = 60 s.

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 [9].

5. Carrying out thermal engineering calculation of fire-resistant multi-cavity 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 [10] and graphs shown in Fig. 3.

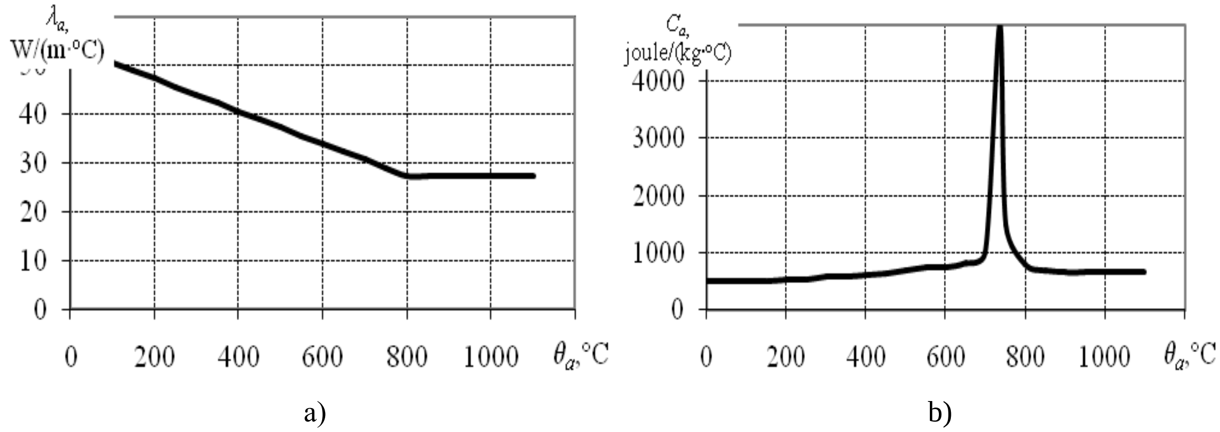


Fig. 3. Dependence of the coefficient of thermal conductivity (a) and heat capacity (b) of steel on temperature

The results of the fire resistance tests described above were used to determine the thermophysical characteristics of the studied plaster coating.

According to the data of the fire retardant manufacturers, the coefficient of thermal conductivity of the coating in the dry state is equal to 0,11 W/m·K at 20 ºC.

However, it is clear that for most flame retardant materials, thermophysical characteristics depend on temperature as a result of physicochemical processes occurring in them during heating [11–12].

The results of calculations to determine the thermophysical characteristics of the plaster composition, which depend on temperature, are shown in Fig. 4.

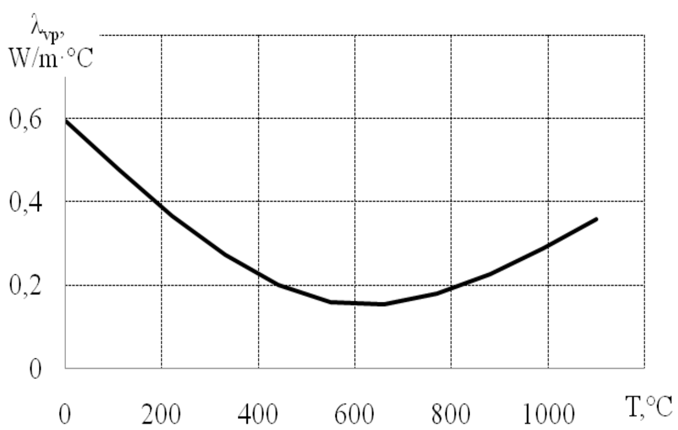


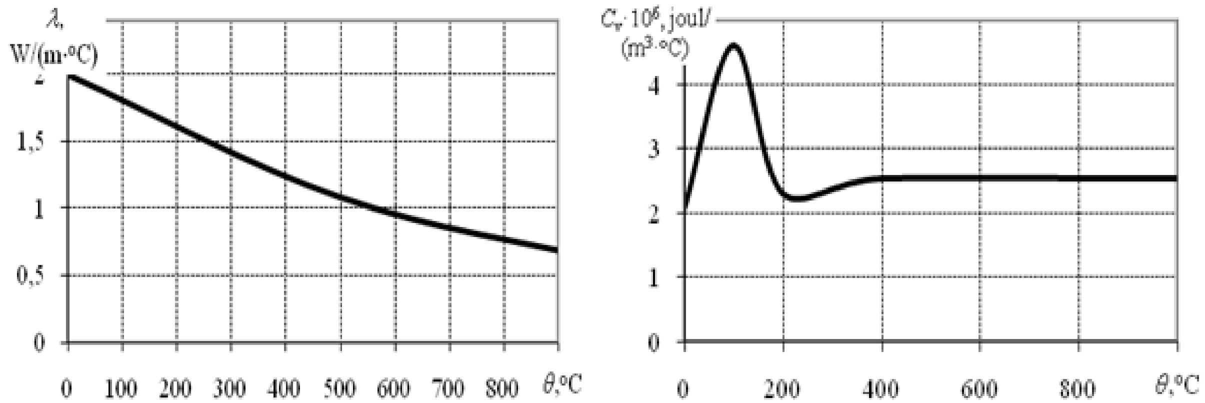
Fig. 4. Dependence of the effective coefficient of thermal conductivity of the plaster coating on temperature, found by solving inverse problems of thermal conductivity according to the data of fire resistance tests

From Fig. 4 it follows that the coefficient of thermal conductivity of the material with increasing temperature (up to 600 ºC) 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/m ^{3}·ºC. The density of the coating is ρ_p =500 kg/m^3 (manufacturer's data) and as a result the specific volumetric heat capacity of the coating was 2000 J/(kg ºC).

The coefficient of thermal conductivity of the floor concrete and specific volumetric heat capacity were also found by solving inverse problems of thermal conductivity based on the results of fire tests [13] (Fig. 5).



a) b)

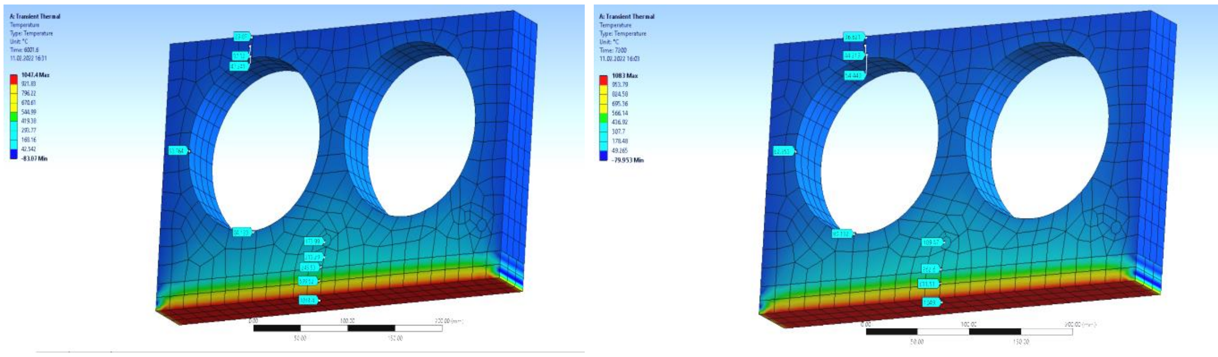
Fig. 5. Thermal conductivity coefficient (a) and specific volumetric heat capacity (b) of concrete

As can be seen from Fig. 5, the temperature-induced change in properties in concrete is much more complex than in reinforcement due to moisture migration, wet and gas exchange processes, and significant component changes in different types of concrete. Other parameters for modeling the thermal state of fire-retardant reinforced concrete floors:

Φ – is the angular coefficient, Φ=1,0; ε_m – is the coefficient of thermal radiation of the heating surface of the coating, ε_m=0,7; ε_f – is the coefficient of thermal radiation of the flame, ε_f=1,0; ρ_a – density of steel, ρ_a=7850 kg/m^3; σ – Stefan Boltzmann constant, σ=5,67 · 10^{-8} W / (m^2 · °C ^{4}); θ_0 – initial temperature, θ_0=20 ºC; density of concrete 2300 kg/m^3.

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.

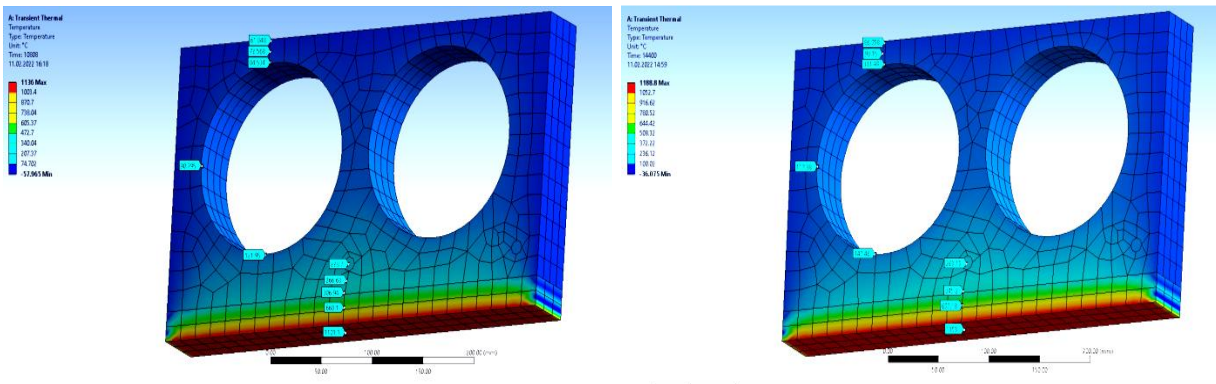
Particular emphasis in the study of temperature fields shown in Fig. 6, it is necessary to pay for heating of cavities of multihollow reinforced concrete overlapping. The correctness of setting the thermophysical and mechanical characteristics of this layer has the greatest impact on the accuracy of 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.



a) b)

Fig. 6. Temperature distribution in a fragment of a fire-resistant reinforced concrete floor slab at 60 (a) and 120 (b) minutes of its test at the standard fire temperature regime

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 [11–13]. In Fig. 7 shows the temperature distribution in the fire-resistant multi-hollow reinforced concrete floor slab at 180 and 240 minutes of its test.



a) b)

Fig. 7. Temperature distribution in the fragment of fire-retardant reinforced concrete slab for 180 (a) and 240 (b) minutes of its test

As can be seen from Fig. 7, the calculated temperatures are satisfactorily correlated with the experimental data.

6. Verification of the adequacy of the developed finite-element model of a fire-resistant multi-cavity reinforced concrete floor

The adequacy of the developed model is confirmed by the data in Fig. 8, which shows a satisfactory convergence of experimental and calculated temperatures.

Based on the results shown in Fig. 8, 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. 8).

As shown in Fig. 8 the largest deviation area in the measurement of temperatures is observed at 100 minutes of calculation and is about 3 ºC, 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.

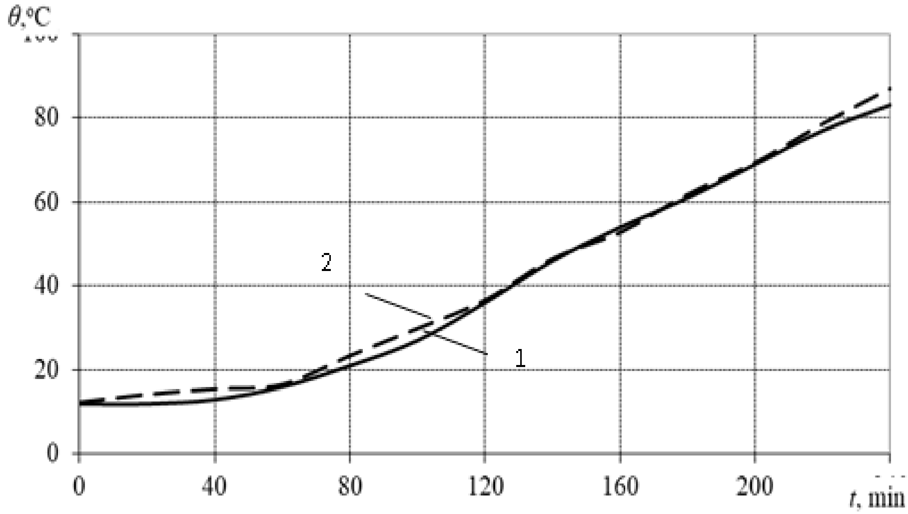


Fig. 8. Dependence of temperature on the time of fire exposure from the unheated surface of the reinforced concrete fireproof floor: 1 – experimental temperature from the unheated surface; 2 – design temperature obtained by simulation in the software package ANSYS

This does not differ from the experimental data (Fig. 8, curve 1), since the calculated curve (Fig. 8, curve 2) of the temperature change from the time of fire exposure from the unheated surface of the fire-protected ceiling correlates well with the experimental one. This, in turn, indicates the satisfactory adequacy of the developed 3D model for thermal engineering calculation of the thermal state of the fire-resistant reinforced concrete floor.

7. Discussion of the results of thermal engineering calculation of fire-resistant reinforced concrete structures

The purpose of the work was solved by evaluating the fire resistance of fire-resistant reinforced concrete structures using the developed model, implemented in the ANSYS software complex, for the thermal engineering calculation of the fire-resistant reinforced concrete multi-hollow floor slab under the influence of elevated fire temperatures. The results obtained as a result of the heat engineering calculation allow to determine the temperature of the concrete of the reinforced concrete floor at any point of the cross-section at a given time (including at the place of installation of the fittings). The obtained results satisfactorily correlate with the experimental data, which confirms the effectiveness of the developed model. This is confirmed by the data in fig. 8, which shows a satisfactory convergence of experimental and calculated temperatures. The largest area of deviation in temperature measurement is observed at the 100th minute of calculation and is about 3 °C, which is 9 %. A feature of the developed model is the possibility of taking into account all parameters when building a computer model of thermal processes in the "reinforced concrete floor – fireproof coating" system. This, in turn, opens up an opportunity to evaluate the fire resistance of fire-resistant reinforced concrete structures with the application of a load under the conditions of fire exposure under the standard fire temperature regime. The correctness of setting the thermophysical characteristics of the overlapping layer with cavities deserves special attention. It should be noted that the incorrect setting of the parameters of the layer with cavities leads to inaccuracies in the modeling. Obviously, such a mechanism for specifying the characteristics of a layer with cavities is the factor for regulating the accuracy of modeling, thanks to which it is possible to increase the convergence of the results of the calculation and experimental approach to the assessment of fire resistance. Therefore, an original approach was used, which allows taking into account all types of heat exchange by specifying cavities as a solid body with an equivalent coefficient of thermal conductivity. In this sense, of particular interest are the curves of temperature changes from the time of fire exposure from the unheated surface of the fire-resistant floor (Fig. 8), which correlate well with each other. This testifies to the correctness of the developed model, which cannot be achieved using other approaches to specifying the heat exchange in the overlap cavities. Approaches based on setting in air cavities with its characteristics and the absence of convective and radiative heat exchange lead to large errors in the calculation (up to 50 %).

The results obtained as a result of the work can be used in evaluating the fire resistance of fire-resistant reinforced concrete structures of various types and configurations. The obtained results can be explained by the correctness of the development of the finite-element model of the fire-resistant reinforced concrete floor, the setting of initial and boundary conditions, the adequacy of the mathematical and physical model, and the satisfactory convergence of experimental and calculated temperatures. A feature of the developed finite element model is the possibility of taking into account the complex heat exchange in the cavities of the reinforced concrete floor. The model makes it possible to study stationary and non-stationary heating of both unprotected and fire-protected reinforced concrete structures. Moreover, taking into account the complex heat exchange in the cavities of the reinforced concrete floor opens an opportunity for modeling heat exchange processes in monolithic fire-resistant reinforced concrete structures. At the same time, with the help of the developed model, it is possible to take into account various factors affecting fire-resistant reinforced concrete structures: fire temperature regimes, thermophysical characteristics of reinforced concrete structures, coatings for fire protection of reinforced concrete structures. It should be noted that the drawback of the developed model is the lack of reliable data on the material characteristics of the reinforced concrete structure and fire-resistant coatings. This leads to the fact that designers use data available in the literature or regulatory documents. This does not always satisfy the requirements for the accuracy of calculations and may lead to an erroneous determination of the fire resistance of building structures. The disadvantages include the impossibility of calculating the fire resistance of the structural scheme of the building and failure to take into account the joint operation of the structures of the building or structure. Ignoring the specified parameters during modeling imposes certain restrictions on the use of the obtained results, which can be interpreted as shortcomings of this study. The impossibility of removing the mentioned limitations within the framework of this study creates a potentially interesting direction for further research. They can be focused on the development of a finite-element model of the structural scheme of the building using fire-resistant building structures with scientifically based parameters. The development of this research may consist in the development of a universal method that would take into account the possibility of evaluating the fire resistance of buildings and structures with the simultaneous operation of both steel and reinforced concrete fire-protected and unprotected building structures. At the same time, it is possible to face difficulties, which consist in the correct construction of a computer model, the correctness of setting the parameters of the model with scientifically based parameters. It is also of great importance to choose a description of the mathematical apparatus and build an adequate physical model of non-stationary heating of fire-resistant reinforced concrete structures when they work together in the structural scheme of the building.

8. Conclusions

1. A 3D model of a fire-resistant multi-cavity reinforced concrete floor was developed in the ANSYS software package, which allows modeling the non-stationary heating of a fire-resistant structure, taking into account the thermophysical and mechanical properties of the materials that make up the structure.

A feature of the model is the possibility of specifying the characteristics of the layer with cavities, which is an important factor in regulating the accuracy of modeling, thanks to which it is possible to increase the convergence of the results of the calculation and experimental approach to the assessment of fire resistance.

An approach is proposed that allows taking into account all types of heat exchange by defining cavities as a solid body with an equivalent coefficient of thermal conductivity, which is calculated separately in each case. The equivalent coefficient of thermal conductivity of the floor layer with cavities was calculated, equal to 3,18 W/m·°C, at which the greatest proximity of calculated and experimental temperatures from the unheated surface of the fire-resistant reinforced concrete floor is observed. At the same time, concrete and reinforcement are modeled by volumetric 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.

References

1. Zhang, H. Y., Lv, H. R., Kodur, V., Qi, S. L. (2018). Performance comparison of fiber sheet strengthened RC beams bonded with geopolymer and epoxy resin under ambient and fire conditions. Journal of Structural Fire Engineering, 9(3), 174–188. https://doi.org/10.1108/JSFE-01-2017-0023

2. Hertz, K., Giuliani, L., Sorensen, L. S. (2017). Fire resistance of extruded hollow-core slabs. Journal of Structural Fire Engineering, 8(3), 324–336.

3. Franssen, J. M., Gernay, T. (2017). Modeling structures in fire with SAFIR®: Theoretical background and capabilities. Journal of Structural Fire Engineering, 8(3), 300–323. https://doi.org/10.1108/JSFE-07-2016-0010

4. Mwangi, S. (2017). Why Broadgate Phase 8 composite floor did not fail under fire : Numerical investigation using ANSYS® FEA code. Journal of Structural Fire Engineering, 8(3), 238–257. https://doi.org/10.1108/JSFE-05-2017-0032

5. Walls, R., Viljoen, C., de Clercq, H. (2020). Parametric investigation into the cross-sectional stress-strain behaviour, stiffness and thermal forces of steel, concrete and composite beams exposed to fire. Journal of Structural Fire Engineering, 11(1), 100–117. https://doi.org/10.1108/JSFE-10-2018-0031

6. Vishal, M., Satyanarayanan, K. S. (2021). A review on research of fire-induced progressive collapse on structures. Journal of Structural Fire Engineering, 12(3), 410–425. https://doi.org/10.1108/JSFE-07-2020-0023

7. Li, S., Jiaolei, Z., Zhao, D., Deng, L. (2021). Study on fire resistance of a prefabricated reinforced concrete frame structure. Journal of Structural Fire Engineering, 12(3), 363–376. https://doi.org/10.1108/JSFE-12-2020-0039

8. Golovanov, V. I., Pekhotikov, A. V., Pavlov, V. V. (2021). Fire protection of steel and reinforced concrete structures of industrial buildings and structures. Bezopasnost' Truda v Promyshlennosti, (9), 50–56. https://doi.org/10.24000/0409-2961-2021-9-50-56.

9. Poklonskiy, V., Krukovskiy, P., Novak, S. (2021). Raschet zhelezobetonnoy plity perekrytiya pri vozdeystvii povyshennykh temperatur pozhara. Naukoviy visnik: tsivilniy zakhist ta pozhezhna bezpeka, 2(10), 69–82. https://doi.org/10.33269/nvcz.2020.2.69-82

10. ENV 1993-1-2:2005. Eurocode 3, Design of steel structures, Part 1.2, general rules – Structural fire design.

11. Kovalov, A., Otrosh, Y., Semkiv, O., Konoval, V., Chernenko, O. (2020). Influence of the fire temperature regime on the fire-retardant ability of reinforced-concrete floors coating. In Materials Science Forum (1006 MSF, 87–92). Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/MSF.1006.87

12. Kovalov, A. I., Otrosh, Y. A., Kovalevska, T. M., Safronov, S. O. (2019). Methodology for assessment of the fire-resistant quality of reinforced-concrete floors protected by fire-retardant coatings. In IOP Conference Series: Materials Science and Engineering 708. IOP Publishing Ltd. https://doi.org/10.1088/1757-899X/708/1/012058

13. Kovalov, A., Yurii, O., Surianinov, M., Tatiana, K. (2019). Experimental and computer researches of ferroconcrete floor slabs at high-temperature influences. In Materials Science Forum. 968 MSF, 361–367. Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/MSF.968.361

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РОЗРАХУНОК ВОГНЕСТІЙКОСТІ ВОГНЕЗАХИЩЕНИХ ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ

Розроблено скінченно-елементну модель для теплотехнічного розрахунку вогнезахищеного багатопустотного залізобетонного перекриття в програмному комплексі ANSYS. Проведено теплотехнічний розрахунок вогнезахищеної залізобетонної багатопустотної плити перекриття, суть якого полягав у розв'язанні задачі нестаціонарної теплопровідності і зводився до визначення температури бетону залізобетонного перекриття у будь-якій точці поперечного перерізу в заданий час (в тому числі в місці установки арматури). Проведено порівняння результатів чисельного моделювання з результатами експериментального дослідження вогнестійкості. Запропоновано підхід, що дозволяє враховувати всі види теплообміну шляхом задавання порожнин як твердого тіла з еквівалентним коефіцієнтом теплопровідності. Проведено порівняння результатів чисельного моделювання з результатами експериментального дослідження вогнестійкості. Запропоновано підхід, що дозволяє враховувати всі види теплообміну шляхом задавання порожнин як твердого тіла з еквівалентним коефіцієнтом теплопровідності. Модель дозволяє досліджувати стаціонарний та нестаціонарний прогрів як незахищених, так і вогнезахищених залізобетонних конструкцій. При цьому, за допомогою розробленої моделі можливо враховувати різні чинники, що впливають на вогнезахищені залізобетонні конструкції: температурні режими пожежі, теплофізичні характеристики залізобетонних конструкцій. Проведено перевірку адекватності розробленої моделі, в результаті якої встановлено, що розрахункові значення температур задовільно корелюють з експериментальними даними. Доведено працездатність розробленої моделі для оцінювання вогнестійкості вогнезахищених залізобетонних конструкцій та адекватність реальним процесам, що відбуваються при нагріванні вогнезахищених залізобетонних конструкцій з прикладенням навантаження в умовах вогневого впливу за стандартного температурного режиму пожежі.

Ключові слова: вогнестійкість, залізобетонні конструкції, теплотехнічний розрахунок, чисельне моделювання, вогнезахист, вогнезахисне покриття, ANSYS

Література

1. Zhang H. Y., Lv H. R., Kodur V., Qi, S. L. Performance comparison of fiber sheet strengthened RC beams bonded with geopolymer and epoxy resin under ambient and fire conditions. Journal of Structural Fire Engineering. 2018. Vol. 9(3). P. 174–188. https://doi.org/10.1108/JSFE-01-2017-0023

2. Hertz K., Giuliani L., Sorensen L. S. Fire resistance of extruded hollow-core slabs. Journal of Structural Fire Engineering. 2017. Vol. 8(3). P. 324–336. https://doi.org/10.1108/JSFE-07-2016-0009

3. Franssen J. M., Gernay T. Modeling structures in fire with SAFIR®: Theoretical background and capabilities. Journal of Structural Fire Engineering. 2017. Vol. 8(3). P. 300–323. https://doi.org/10.1108/JSFE-07-2016-0010

4. Mwangi S. Why Broadgate Phase 8 composite floor did not fail under fire : Numerical investigation using ANSYS® FEA code. Journal of Structural Fire Engineering. 2017. Vol. 8(3). P. 238–257. https://doi.org/10.1108/JSFE-05-2017-0032

5. Walls R., Viljoen C. de Clercq H. Parametric investigation into the cross-

sectional stress-strain behaviour, stiffness and thermal forces of steel, concrete and composite beams exposed to fire. Journal of Structural Fire Engineering. 2020. Vol. 11 (1). P. 100–117. https://doi.org/10.1108/JSFE-10-2018-0031

6. Vishal M., Satyanarayanan K. S. A review on research of fire-induced progressive collapse on structures. Journal of Structural Fire Engineering. 2021. Vol. 12(3). P. 410–425. https://doi.org/10.1108/JSFE-07-2020-0023

7. Li S., Jiaolei Z., Zhao D. Deng L. Study on fire resistance of a prefabricated reinforced concrete frame structure. Journal of Structural Fire Engineering. 2021. Vol. 12(3). P. 363–376. https://doi.org/10.1108/JSFE-12-2020-0039

8. Golovanov V. I., Pekhotikov A. V., Pavlov V. V. Fire protection of steel and reinforced concrete structures of industrial buildings and structures. Bezopasnost' Truda v Promyshlennosti. 2021. Vol. 9. P. 50–56. doi: 10.24000/0409-2961-2021-9-50-56

9. Поклонський В., Круковский П., Новак С. Расчет железобетонной плиты перекрытия при воздействии повышенных температур пожара. Науковий вісник: цивільний захист та пожежна безпека. 2021. № 2(10). С. 69–82. https://doi.org/10.33269/nvcz.2020.2.69-82

10. ENV 1993-1-2:2005. Eurocode 3, Design of steel structures, Part 1.2, general rules – Structural fire design.

11. Kovalov A., Otrosh Y., Semkiv O., Konoval V., Chernenko O. Influence of the fire temperature regime on the fire-retardant ability of reinforced-concrete floors coating. In Materials Science Forum. 2020. Vol. 1006. P. 87–92. Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/MSF.1006.87

12. Kovalov A., Otrosh Y., Kovalevska T., Safronov S. Methodology for assessment of the fire-resistant quality of reinforced-concrete floors protected by fire-retardant coatings. IOP Conf. Series: Materials Science and Engineering. 2019. 708.012058. doi:10.1088/1757-899X/708/1/012058

13. Kovalov A., Otrosh Y., Surianinov M., Kovalevska T. Experimental and computer researches of ferroconcrete floor slabs at high-temperature influences. In Materials Science Forum. 2019. Vol. 968. P. 361–367. Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/MSF.968.361

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