UDC 614.841.343
DOI: 10.15587/1729-4061.2024.310520

IDENTIFYING THE EVOLUTION OF THROUGH CRACKS IN IRON-REINFORCED HOLLOW SLABS UNDER THE INFLUENCE OF A STANDARD FIRE TEMPERATURE MODE

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The object of this study is the fire resistance of reinforced concrete hollow slabs at the onset of the limit state of loss of integrity. The problem of accurate modeling of the formation and development of cracks in concrete was investigated.

The paper reports an analysis of the results of the stress-strain state of a reinforced concrete hollow slab during fire exposure for devising a method for evaluating the fire resistance of such structures upon the onset of the limit state of loss of integrity.

According to EN 1992-1-2, the determination of fire resistance of structures is provided by calculation methods, however, there is no such procedure for reinforced concrete hollow slabs. Many scientific works offer refined methods for evaluating only the loss of load-bearing and heat-insulating capabilities, leaving aside the issue of loss of integrity. Thus, this can lead to a biased evaluation of reinforced concrete hollow floor slabs according to the criterion of the limit state of loss of integrity, which in turn can put under a threat to the fire safety of buildings, which threatens the life and health of people.

According to the results of the calculation, a parameter has been determined, according to which the onset of the limit state of fire resistance, in particular, the loss of integrity, was established. Summarizing the damage distributions, it was assumed that in the case of reaching the critical plastic deformation of 2.5e-3 in concrete finite elements, they are excluded from the general set of finite elements. Thus, in the case of the formation of through cracks, the removal of finite elements is taken as a parameter to identify the onset of the limit state of loss of integrity. According to the results of the computational experiment, it was established that through cracks in a fragment of a reinforced concrete hollow slab are formed in 44 min. According to the results of the research, the method of evaluating the fire resistance of such structures based on the onset of the limit state of loss of integrity has been substantiated. Such a method could be applied during design, which provides an opportunity to determine the limit of fire resistance in reinforced concrete hollow slabs

Keywords: fire resistance, integrity, hollow slab, combustion products, through cracks, finite element model

Received date 03.06.2024
Accepted date 16.08.2024
Published date 29.08.2024

***How to Cite:** Sidnei, S., Myroshnyk, O., Kovalov, A., Veselivskyi, R., Hryhorenko, K., Shnal, T., Matsyk, I. (2024). Identifying the evolution of through cracks in iron-reinforced hollow slabs under the influence of a standard fire temperature mode. Eastern-European Journal of Enterprise Technologies, 4 (7 (130)), 70–77. https://doi.org/10.15587/1729-4061.2024.310520*

1. Introduction

The optimal selection of soils for the construction of various structures and buildings is one of the priorities in modern construction. This is due to the limited possibilities when using heavy building structures made of reinforced concrete. Therefore, reducing the weight of the building contributes to a greater choice of soil, and can also lead to a reduction in the volume of construction work, a reduction in its cost and simplification of implementation, which allows for faster implementation of the planned project solution.

One of the most original solutions for the installation of a strong and at the same time lightweight floor covering is reinforced concrete hollow slabs [1]. The originality of reinforced concrete hollow floor slabs is their design, which combines strength and lightness. They have cavities that reduce the weight of the plate but retain its ability to withstand significant loads. This solution makes it possible to reduce the weight of the structure without losing its load-bearing capacity, which reduces the load on the foundation and reduces the cost of materials, while maintaining the necessary operational characteristics. In addition, reinforced concrete hollow slabs also improve the heat and sound insulation properties of inter-floor ceilings, which makes these slabs a popular choice for modern construction. The production of hollow slabs with holes can require less materials compared to traditional slabs, which can reduce the environmental footprint of construction projects [1].

Therefore, the development of a calculation method for evaluating the fire resistance of reinforced concrete hollow slabs according to the limit state of loss of integrity is an important step in improving the fire safety of construction structures and buildings in general. This is explained by the fact that in the case of conducting research into this area, it is possible to determine which limit state of fire resistance will occur first, that is, to determine the time of onset of the loss of integrity in reinforced concrete hollow slabs, and then compare the obtained results with the time of onset of the remaining limit states. Such data will make it possible to obtain information about the formation of "critical" cracks, wherever the spread of dangerous fire factors is possible. This threatens human life and health, and also creates obstacles during rescue operations.

2. Literature review and problem statement

One of the main aspects of ensuring the safety of humankind during the operation of buildings is the use of building structures of the required fire resistance class [2]. The most reliable determination of this indicator is usually carried out with the help of full-scale fire tests, since when conducting such works, neither a fragment of the structure nor a separate structure is displayed, but the building as a whole [3, 4]. But it is difficult to record signs of the onset of the limit state of loss of integrity during practical tests in accordance with EN 1363-1:2020 since the unheated surface of reinforced concrete floor slabs is covered with loads to reproduce the conditions of mechanical loading during the operation of a real structure [4]. In addition, it is important to consider that during these works, a significant concentration of CO_2 and harmful combustion products are released into the environment [3]. This leads to atmospheric pollution and can significantly affect the environmental safety of places where similar works are carried out [3]. In addition, conducting such tests is very expensive and requires a lot of effort. There is also an experimental method of fire tests, which also has an impact on the ecological safety of the environment [5].

According to the recommendations of EN 1992-1-1 and EN 1992-1-2, it is envisaged to determine or check the fire resistance limit (class) of building structures using calculation methods [6, 7]. But these standards for reinforced concrete hollow slabs do not describe the methods for evaluating their fire resistance. Works [8, 9] describe the possibility of using a refined method of assessing the fire resistance of such building structures. However, in these works, only the onset of the limit state of fire resistance loss of load-bearing capacity is considered, and the onset of the limit state of loss of integrity is not paid attention to. In [10], it is shown that the formation of through cracks as a result of the formation of a fracture prism cannot be identified because the specific signs of the appearance of cracks at the integration points do not allow them to be unambiguously interpreted. Signs of the onset of the limit state of loss of integrity are not taken into account, one of them is the formation of cracks into which a probe with a diameter of 25 mm can be immersed according to EN 1363-1:2020. However, statistical data [11] show that the largest number of people died as a result of poisoning with hydrocyanic acid and combustion products. These products can penetrate through the cracks formed in the floor coverings during a fire, which threatens human life and health. Work [12] reports the results of mathematical modeling of a reinforced concrete hollow slab when assessing its fire resistance at the limit state of loss of integrity. However, the onset of this limit state was recorded at the moment of stopping the calculations due to the acquisition of plastic deformations in a large number of finite elements of the concrete matrix and their removal. There were no through cracks in [12], which is a criterion for the onset of the limit state of loss of integrity. This is explained by the application of the Drucker-Prager theory of concrete strength, which extends the plasticity criteria and is well suited for modeling plastic deformation. However, the specified strength theory may be less accurate for brittle materials that undergo cracks [13, 14]. The William-Warnke strength theory is more accurate for modeling the formation and development of cracks in concrete compared to the Drucker-Prager strength theory because it takes into account the nonlinear behavioral properties of concrete [13, 14]. Therefore, for a more accurate modeling of the formation and development of cracks in concrete, it is advisable to use the William-Warnke strength theory. This is due to the fact that this theory takes into account the non-linear behavioral properties of concrete, which makes it possible to better predict the onset of the limit state of loss of integrity, compared to the Drucker-Prager strength theory.

3. The aim and objectives of the study

The purpose of our work is to determine the possibility of identifying the formation of through cracks in a reinforced concrete hollow slab to register the onset of the limit state of fire resistance – loss of integrity. This will make it possible to ensure the reliability of structures during a fire, reduce the risk of threats to people's health and life, and also improve the efficiency of emergency rescue operations.

To achieve the goal, the following tasks were set:

– to build a finite-element model of a fragment of a reinforced concrete hollow slab with a total number of elements of no more than 2,000 units;

– to calculate the stress-strain state of a fragment of a reinforced concrete hollow slab under the conditions of combined thermal-force influence;

– to determine the parameter of the stress-strain state of a fragment of a reinforced concrete hollow slab, by which it is possible to establish the onset of the limit state of loss of integrity and justify the appropriate method for assessing the fire resistance of such structures in terms of integrity.

4. The study materials and methods

The object of our study is the fire resistance of reinforced concrete hollow slabs at the onset of the limit state of loss of integrity.

The hypothesis of the study assumes determining a parameter by which it is possible to record the signs of the onset of the limit state of fire resistance loss of integrity for reinforced concrete hollow slabs.

One of the important parameters affecting fire resistance is the level of applied load. Our work examined the load at the level of 50 % of the bearing capacity, which is an average indicator. Most structures of this type are designed for this level of load, so this assumption was adopted when determining the boundary conditions.

Since the behavior of slab and beam is the same, it was decided to use a fragment instead of a whole slab for research. This made it possible to increase the productivity of calculations without losing the reliability of results. A rectangular pipe with a cylindrical inner cavity and working reinforcing rods was used for modeling.

To describe the complex stress-strain state of a fragment of a reinforced concrete hollow slab under the conditions of thermal-force influence, the ANSYS software package was chosen, which allows performing complex calculations and modeling of such situations.

To conduct research on determining the moment of onset of this limit state of fire resistance loss of integrity, a reinforced concrete hollow slab was considered, the appearance of which is shown in Fig. 1.

In order to reduce the calculated area of the structure, the most dangerous part of the plate was chosen – the symmetrical half of the cyclic fragment of the structure in the form of a rectangular pipe with a cylindrical inner cavity and working reinforcing bars (Fig. 2).

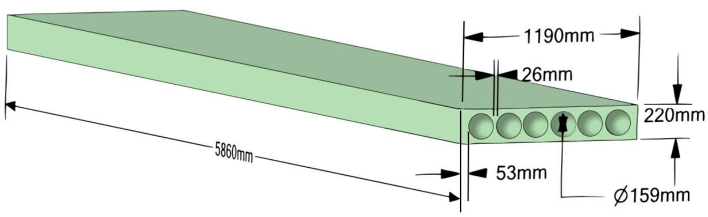


Fig. 1. Full-scale view of the investigated reinforced concrete hollow slab

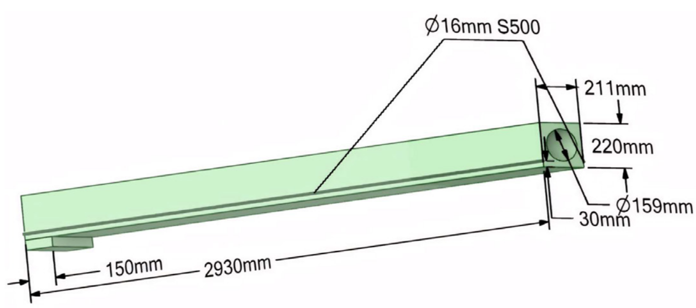


Fig. 2. Scheme of a fragment of a reinforced concrete hollow slab for carrying out calculations under conditions of combined thermal-force influence

The geometrical construction of the structure's fragment was performed in the SpaceClaim ANSYS WB geometrical module. Due to the reduction of the calculation area of the structure under study, the performance of the calculation increases.

For mathematical modeling, class C30/35 concrete with a density of 2400 kg/m^3 was used. The main steel reinforcement is of class A500 with a density of 7850 kg/m^3. Thermophysical characteristics of concrete and reinforcement are adopted according to EN 1992-1-1 and EN 1992-1-2. To take into account their deformation characteristics, "strain-stress" diagrams are used, which are also recommended by EN 1992-1-1 and EN 1992-1-2. To construct these diagrams, the ratios given in Table 1 were used.

Table 1

Mechanical characteristics of concrete and reinforcement

Stress in concrete, MPa; ultimate deformations of concrete	Stress in reinforcement, MPa; ultimate deformations of reinforcing steel
at $0<\varepsilon_c\leq\varepsilon_{c1,\theta}$: $\sigma(\varepsilon)=\dfrac{3\varepsilon_c f_{c,\theta}}{\varepsilon_{c1,T}\left(2+\left(\dfrac{\varepsilon_b}{\varepsilon_{c1,\theta}}\right)^3\right)}$, at $\varepsilon_{c1,\theta}<\varepsilon_c<\varepsilon_{c2}$: $\sigma(\varepsilon)=f_{c,\theta}-\dfrac{f_{c,\theta}\left(\varepsilon_c-\varepsilon_{c1,\theta}\right)}{\varepsilon_{c2}-\varepsilon_{c1,\theta}}$	At $0<\varepsilon_s<\varepsilon_{s0}$ $\sigma_s=E_{s,\theta}\varepsilon_s$, at $\varepsilon_{s0}<\varepsilon_s\leq\varepsilon_{sy}$ $\sigma_s=f_{sp,\theta}-c+(b/a)[a^2-(\varepsilon_{sy}-\varepsilon_s)^2]^{0.5}$, at $\varepsilon_{sy}\leq\varepsilon_s\leq\varepsilon_{st}$ $\sigma_s=f_{s,\theta}$, at $\varepsilon_{st}\leq\varepsilon_s\leq\varepsilon_{s2}$ $\sigma_s=f_{s,\theta}\,[1-(\varepsilon_s-\varepsilon_{st})/(\varepsilon_{s0}-\varepsilon_{st})]$, at $\varepsilon_{s2}<\varepsilon_s$ $\sigma_s=0$, $a^2=(\varepsilon_{sy}-\varepsilon_{sp})(\varepsilon_{sy}-\varepsilon_{sp}+c/E_{s,\theta})$, $b^2=c(\varepsilon_{sy}-\varepsilon_{sp})E_{s,\theta}+c^2$, $c=\dfrac{\left(f_{s,\theta}-f_{sp,\theta}\right)^2}{\left(\varepsilon_{sy}-\varepsilon_{sp}\right)E_{s,\theta}-2\left(f_{s,\theta}-f_{sp,\theta}\right)}$

In Table 1, the formulae include the following parameters:

ε_c – relative deformation of concrete;

$f_{c,\theta}$ – estimated compressive strength of concrete, which depends on the heating temperature of the concrete layer;

$\varepsilon_{c1,\theta}$ – relative strain to which the proportional relationship between strain and stress is valid;

ε_{c2} – ultimate relative deformation;

ε_s – relative deformation of steel;

ε_{sy} – deformation at which the yield point occurs;

ε_{st} – deformation at which the descending branch of the diagram begins;

$f_{sp,\theta}$ – limit of proportionality of reinforcing steel;

$E_{s,\theta}$ – modulus of elasticity of steel, which depends on the heating temperature.

Using the ratios given in Table 2, corresponding deformation diagrams of concrete and reinforcing steel were constructed. The constructed diagrams are shown in Fig. 3.

Mathematical models for calculating the behavior of a reinforced concrete hollow slab under the conditions of combined thermal-force influence are based on the application of the implicit method of integrating differential equations of the stress-strain state using the finite element method.

Thus, the calculation process continues until an acceptable accuracy of the sought solution is reached.

At the first stage, the application of an active uniformly distributed load of 4 kPa, which is 50 % of the bearing capacity of the structure, was simulated. Fig. 4 shows the scheme of applying a mechanical load to the upper surface of a fragment of a reinforced concrete hollow slab.

To obtain convergence of the iterative process, the load was applied step by step. At the second stage, the thermal engineering problem was solved, the description of the solution method and the obtained results of the temperature distribution in a fragment of a reinforced concrete hollow slab under the influence of a standard temperature regime are given in [11]. After that, the results of temperature distribution indicators are imported to solve a compatible thermal-force problem associated with registering the onset of the limit state of fire resistance loss of integrity according to the specified parameters.

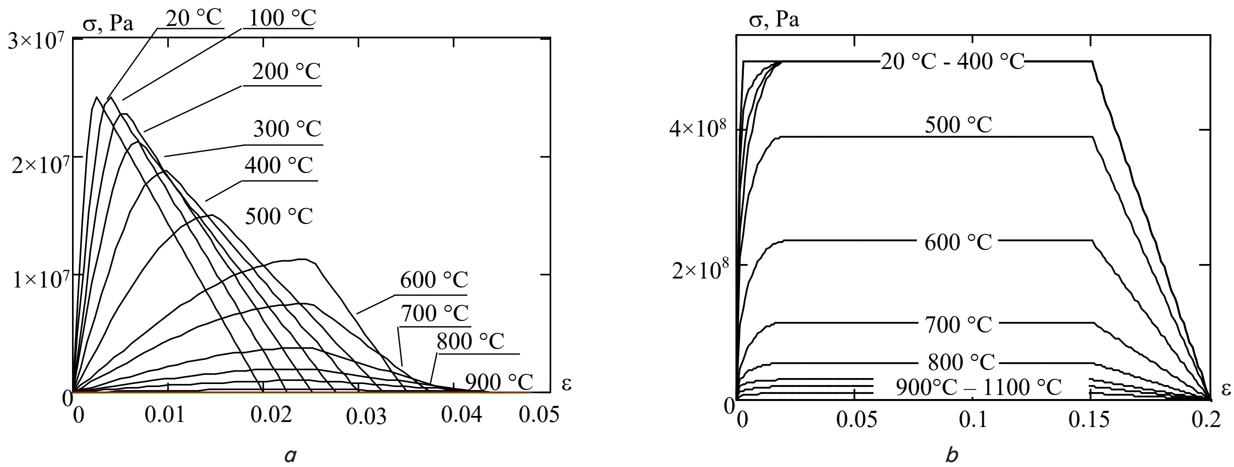


Fig. 3. Deformation diagrams of materials, which are components of reinforced concrete hollow slab: *a* — concrete; *b* — reinforcing steel

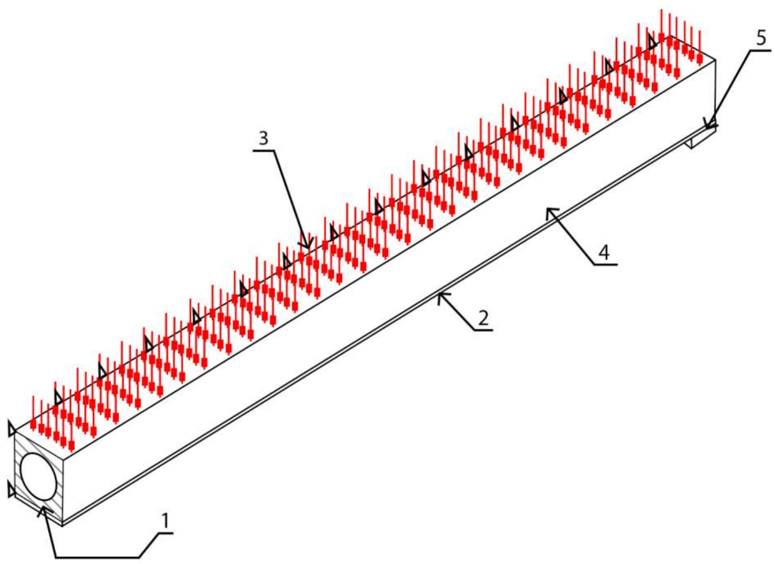


Fig. 4. Scheme of applying a mechanical load to the upper surface of a fragment of a reinforced concrete hollow slab: 1 — plane of symmetry; 2 — reinforcement; 3 — applied pressure; 4 — concrete base; 5 — support surface

5. Results of determining the fire resistance parameters of a hollow slab according to the limit state of loss of integrity

5. 1. Construction of a finite-element model of a fragment of the investigated reinforced concrete hollow slab

8-node hexahedral finite elements (hereinafter referred to as FEs) are used for modeling concrete, and 2-node rod CEs are used for modeling steel reinforcement. Such elements were chosen due to their ability to accurately reflect the behavior of concrete and reinforcement under load under thermal conditions. All FEs are Lagrangian-type physically nonlinear elements, which are shown in Fig. 5.

The dimensions and number of FEs are given in Table 2.

The parameters that determine the mesh density are chosen to ensure satisfactory convergence of the computational process. The main equations of the finite element method:

$$[\mathbf{K}_e]\{\mathbf{u}\}=\{\mathbf{F}_e\}^{nd}+\{\mathbf{F}_e\}^{pr}+\{\mathbf{F}_e\}^{th},$$

$$[\mathbf{K}_e]=\int_V \mathbf{B}^T\mathbf{E}\,\mathbf{B}\,\mathrm{d}V,\ \{\mathbf{F}_e\}^{pr}=\int_S [\mathbf{N}_\mathbf{n}]^T\{\mathbf{P}\}\,\mathrm{d}S, \quad (1)$$

$$\{\mathbf{F}_\mathbf{e}\}^{th}=\int_V \mathbf{B}^T\mathbf{E}\{\varepsilon^{th}\}\mathrm{d}V,\ [\mathbf{K}]\{\mathbf{q}\}=\{\overline{\mathbf{p}}\}, \quad (2)$$

where $\{\mathbf{u}\}$ is the vector of nodal displacements of FEs; $\mathbf{E}$ is the matrix of elasticity coefficients; $\mathbf{B}$ is the matrix of deformations; $[\mathbf{N_n}]$ is the matrix of interpolation functions along the FE face; $\{\varepsilon^{th}\}$ is the vector of nodal temperature deformations of FEs; S and V are face areas and FE volume; $\{\mathbf{q}\}$ is a vector of displacements of nodal points; $[\mathbf{K}]$ is the stiffness matrix of the entire system; $\{\overline{\mathbf{p}}\}$ is the FE force vector.

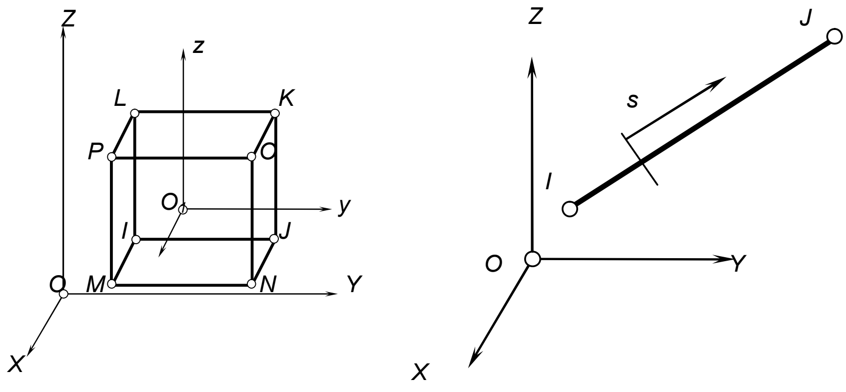
Table 2

Parameters of finite element models of test samples

Part of the model	Min. size, mm	Max size, mm	Number
Concrete base	25	100	1,740
Reinforcement	100	100	60
Supports	25	250	90
Total number of finite elements			1,890

During the mathematical modeling of the behavior of a reinforced concrete hollow slab under fire conditions, the issue of increasing the productivity of calculations and reducing the possibility of inconsistencies in the iterative process of calculations was taken into account [9, 10, 12]. A symmetrical half of a cyclic fragment of a reinforced concrete hollow slab in the form of a rectangular pipe with a cylindrical inner cavity, equipped with working reinforcing rods, was chosen for the study (Fig. 2). The positive experience of using this approach is described in [13].

When building a finite-element mesh for modeling concrete, 8-node hexahedral FEs of the SOLID186 type were used (Fig. 5, a). For modeling steel reinforcement, 2-node rod FEs of the LINK180 type (Fig. 5, b). FEs, which were used in the construction of the finite element model, are Lagrangian type elements that are physically nonlinear. The dimensions and number of FEs in the reinforced concrete hollow slab scheme are given in Table 2.



a *b*

Fig. 5. The form of finite elements: *a* – hexahedral FE (SOLID186), simulating concrete; *b* – beam FE (LINK180), simulating reinforcing bars

Fig. 6 shows the general view of the finite element model of a fragment of a reinforced concrete hollow slab, which is the corresponding calculation area.

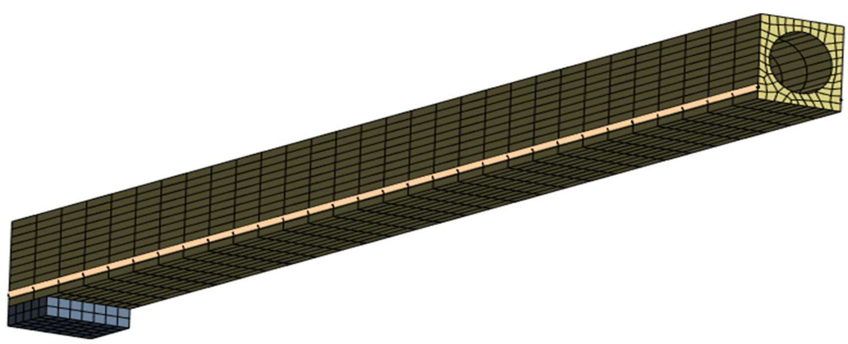


Fig. 6. Finite element model of a fragment of a reinforced concrete hollow slab

Based on the results of the generated finite element model for calculation in the ANSYS APDL software package, it was established that the total number of elements was 1890 units. This number of finite elements could ensure both the performance of the calculation and the convergence of the solver when solving the compatible thermal-force problem.

5. 2. Calculation of the stress-strain state of a fragment of a reinforced concrete hollow slab under conditions of combined thermal-force influence

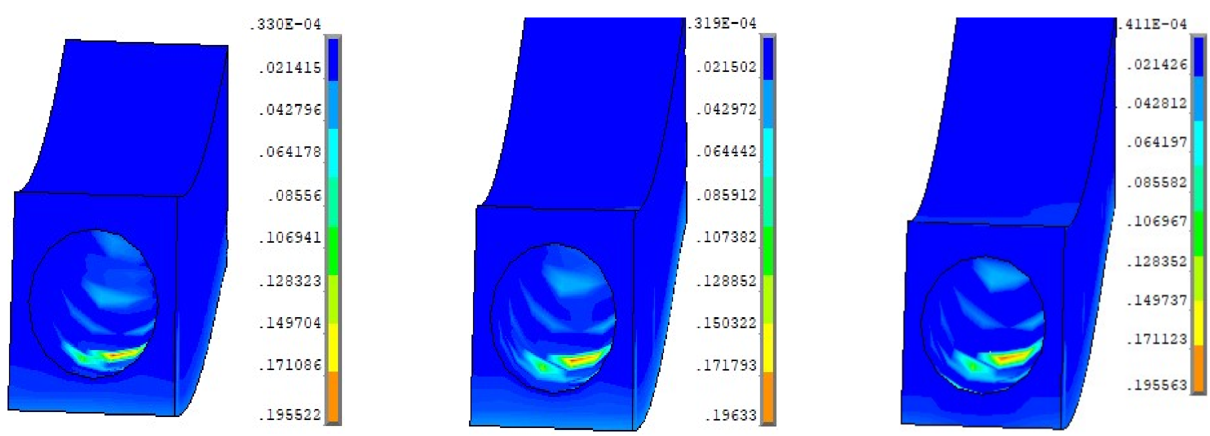
The methodology of solving the thermal engineering problem of temperature distribution over a fragment of a reinforced concrete hollow slab under the influence of the standard fire temperature regime is reported in [11]. Accordingly, the temperature distribution indicators obtained in [11] were imported to calculate the stress-strain state of a plate fragment under conditions of combined thermal-force influence.

Based on the results of our calculations, distributions of the amount of equivalent plastic deformation over the space of the concrete base of the reinforced concrete hollow slab at different time points of exposure to the standard fire temperature regime were constructed. Fig. 7 shows the constructed distributions of plastic deformation in the studied structure under the influence of thermal and mechanical load.

The largest plastic deformations are concentrated in the lower part of the reinforced concrete slab, which indicates the presence of cracks and defects there. However, this does not indicate a violation of integrity in the upper part of the plate.

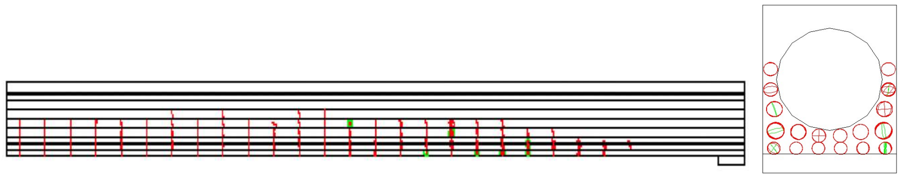
In addition, based on the results of the calculation, the distribution of cracks in a fragment of a reinforced concrete hollow slab was obtained (Fig. 8 and decoding of the crack markings, Fig. 9), which is another parameter that allows analyzing the possibility of the onset of the limit state of loss of integrity. This distribution of "cracks" is identified at the integration points when applying the William-Warnke strength theory [15].

The designations of cracks and defects in concrete are decoded in Fig. 9.

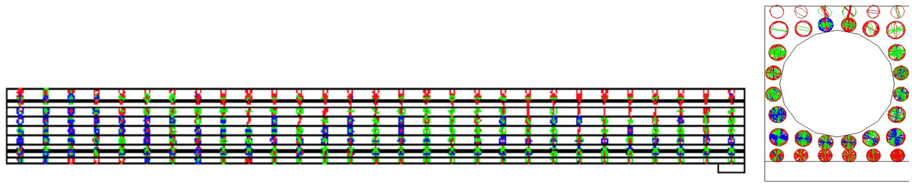


a *b* *c*

Fig. 7. Distributions of the magnitude of the equivalent plastic deformation over the space of the concrete base of the reinforced concrete hollow slab at different time points of exposure to the standard fire temperature regime: *a* – 30 min; *b* – 45 minutes; c – 55 min



a



b

Fig. 8. Distribution of cracks in the concrete of a reinforced concrete hollow slab at different moments of exposure to the standard fire temperature regime: *a* — 2 min; *b* — 46 min

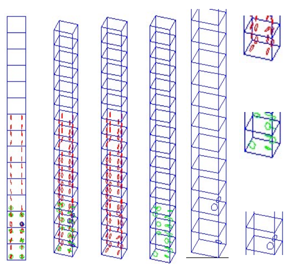


Fig. 9. Conditional designations of cracks in concrete: *a* — primary cracks (the first cracks that appear in the element); *b* — secondary cracks (the first branching of cracks that appear in the element); *c* — tertiary cracks (the second branching of cracks that appear in the element)

This distribution of cracks plays the role of an effective characteristic in order to adequately describe the behavior of reinforced concrete under the conditions of the thermal-force effect of fire. But the appearance of damage at one or more points of integration does not allow us to conclude that the cracks will be through.

5. 3. Determining the parameter of onset (limit state of loss) of integrity when evaluating the fire resistance of a hollow slab

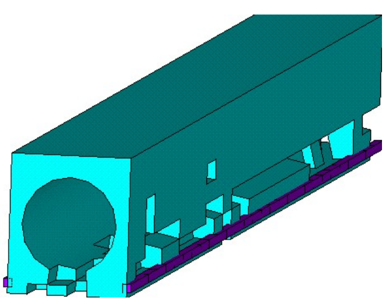
During the calculation, one more parameter of the onset of the limit state of loss of integrity was monitored. Fig. 10 shows the positions of the removed destroyed FEs, which have reached a critical plastic deformation of 2.5 *e*-3, from the calculation scheme of a reinforced concrete hollow slab.

According to the results of a computational experiment, it was established that through cracks in a fragment of a reinforced concrete hollow slab are formed in 44 minutes, which is interpreted as the onset of the limit state of fire resistance, in particular, the loss of integrity.

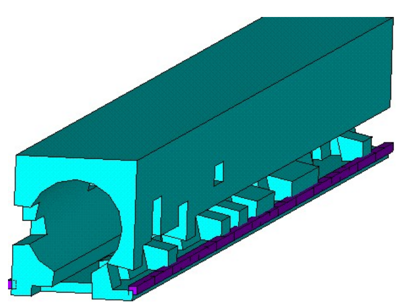
6. Discussion of results based on determining the slab integrity loss parameter during fire simulation

The geometric parameters of a full-sized reinforced concrete hollow slab are shown in Fig. 1. To perform the first task, a fragment of a reinforced concrete hollow slab was built in the geometric module of SpaceClaim ANSYS WB (Fig. 5). This fragment is a symmetrical half of a cyclic structural element in the form of a rectangular tube with a cylindrical inner cavity and working reinforcing rods. Due to the reduction of the geometric area of the structure under study, it is possible to reduce the calculation area, which increases the performance of the calculation, without affecting the reliability of the results.

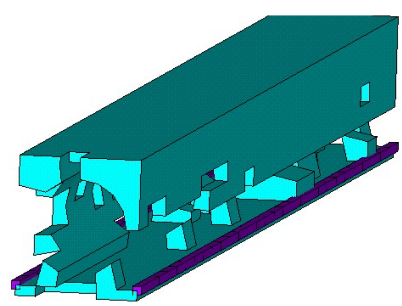
As can be seen on the finite element model shown in Fig. 6, the mesh of FEs in concrete and reinforcement is not very dense. The dimensions and number of FEs in the scheme of reinforced concrete hollow slab are given in Table 1. To reduce the possibility of inconsistencies in the iterative calculation process and increase the productivity of calculations, a finite-element model of a fragment of a reinforced concrete hollow slab with a total number of elements of no more than 2000 units was built.



a



b



c

Fig. 10. Position of the destroyed FEs removed from the design scheme of the reinforced concrete hollow slab under the influence of the standard fire temperature regime: *a* — 15 min; *b* — 30 minutes; *c* — 44 min

Analyzing the distributions of plastic deformations (Fig. 7), it can be seen that it is not possible to identify the onset of the limit state of loss of integrity by them. This is explained by the fact that the largest plastic deformations are concentrated in the lower part of the reinforced concrete slab and indicate that there is a concentration of cracks and defects, which is generally understandable. However, this does not indicate that there is a violation of integrity in the upper part.

Analyzing the patterns of crack distributions shown in Fig. 8 (decoding of cracks in Fig. 9), it can be noted that only on the basis of these data it is impossible to unambiguously identify the appearance of through cracks. The appearance of damage in one or more integration points does not allow us to conclude that the cracks will be through. These cracks play the role of an effective characteristic in order to adequately describe the behavior of reinforced concrete under the conditions of the thermal-force effect of fire.

In contrast to [12], the William-Warnke strength theory was used for concrete modeling. The mechanical properties of the concrete used during the simulation of the combined thermal and mechanical load depend on the temperature and are given in Table 2 and Fig. 4, *a*.

The application of the William-Warnke strength theory, in contrast to the Drucker-Prager theory applied in [12], made it possible to obtain the results shown in Fig. 10. The Drucker-Prager strength theory expands the plasticity criteria, making it more universal and suitable for modeling plastic deformation. However, the Drucker-Prager strength theory may be less accurate for brittle materials that undergo cracks compared to the William-Warnke strength theory [14, 15].

Based on the results of our research, it was established that the removal of finite elements in the upper and lower parts of the structure is observed in a fragment of a reinforced concrete hollow slab on minute 44 (Fig. 10, *c*).

The removal of finite elements in the upper part of the slab is explained by the fact that during the stretching of the lower layers of concrete in the transverse direction due to the thermal expansion of concrete, the stretching of the upper layer also occurs. This leads to the occurrence of plastic deformations in the upper layer of concrete, reaching critical values and, accordingly, removing the finite elements in the upper layer of the slab.

Thus, in the case of the formation of through cracks due to the removal of finite elements with critical plastic deformation (Fig. 10, *c*), this is taken as a parameter for identifying the onset of the limit state of loss of integrity for such plates. In study [12], this was not possible due to the termination of the calculation caused by a significant amount of plastic deformation only in the lower part of the slab. Accordingly, it was not possible to obtain through cracks in a reinforced concrete hollow slab in [12]. This is also due to the large number of finite elements in [12], in which their number was 30,000 units, which is more than 15 times more compared to the model presented in this work. The obtained parameter of the onset of the limit state of the fire resistance of the loss of integrity makes it possible to evaluate the fire resistance of reinforced concrete hollow slabs, which can guarantee the specified class of fire resistance for such structures. Thus, by ensuring the integrity of the hollow slabs for the required time, harmful combustion products, flames, smoke, and high temperature will not penetrate through the cracks formed, which will prevent the spread of fire in buildings. This reduces the risk of threats to people's lives and health and enables emergency rescue units to perform functional duties during the organization of the evacuation of people and material values, as well as to act effectively during fire extinguishing.

Despite the fact that the principle of operation of the beam, as a tested slab, is almost identical to the floor slabs, in order to obtain more accurate results, it is necessary to consider the structure in its entirety. However, this significantly increases the calculation area and the number of finite elements, which significantly increases the computational complexity and can lead to the problem not being solved due to non-convergence.

The applied approach in our work is universal, practically feasible, and such that it can take into account all design features and combinations of boundary conditions. This allows solving such problems; however, there are certain shortcomings that call into question the widespread use of this computational-theoretical approach in such a modification. The indicated shortcomings are time-consuming procedures of preparation of calculation models, the theoretical aspects of their application must be worked out in detail, the need for experimental verification of model data, and the high cost of software and calculations.

A promising development of this research is to devise a tabular method for evaluating the fire resistance of reinforced concrete hollow slabs by the onset of the limit state of loss of integrity. This could significantly simplify the application of the method when checking compliance with the fire resistance class of such structures.

7. Conclusions

1. A finite-element model has been built, which uses up to 2000 elements, which is the optimal number to ensure satisfactory accuracy of calculation results for the identification of through cracks with a diameter of 25 mm.

2. According to the results of our calculation of the stress-strain state of a fragment of a reinforced concrete hollow slab, a set of parameters was obtained, under which it is possible to assume the formation of cracks, in particular:

– distributions of the amount of equivalent plastic deformation over the space of the concrete base of the structure up to values of 2.5 e-3;

– distribution of primary, secondary, and tertiary cracks in a fragment of reinforced concrete hollow slab;

– removal of finite elements from the concrete base of the slab with the formation of through cracks where a probe with a diameter of 25 mm can be inserted.

This can become the basis for the development of a method for assessing fire resistance by loss of integrity.

3. Based on the results of our research, it was possible to obtain a parameter that indicates the formation of through holes due to the removed finite elements in the amount of 28.5 % from the concrete base of the slab, which consists of 496 elements.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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