*The object of research is the fire resistance of reinforced concrete ribbed slabs. The subject of research is the effect of the level of mechanical load on the fire resistance of the studied reinforced concrete ribbed slab under the influence of fire. Currently, the assessment of the fire resistance of such structures using the tabular method is significantly limited by certain geometric parameters of these plates. It is also not considered possible to apply the zone method, since reinforced concrete ribbed slabs consist of components that receive thermal effects according to various scenarios and geometric parameters, which is not taken into account in Eurocode 2.*

*Experimental calculations carried out in the current work using a refined procedure involving the finite element method allow solving the actual scientific and technical problem related to the determination of the dependence of the fire resistance of these structures on the level of load applied.*

*The calculation of the temperature spread over a reinforced concrete ribbed slab under the influence of the standard temperature regime of fire was carried out using convection and radiant heat exchange, which is recommended by Eurocode 2. The iterative implicit Newton-Raphson method was used to solve the mechanical problem. Evaluation of fire resistance of reinforced concrete ribbed slabs was carried out according to the onset of signs of the limit state of fire resistance due to the loss of load-bearing capacity. According to the results, it was established that at 100 % load level of the structure under investigation, the critical deflection of more than 268 mm and the rate of growth of deformation exceeding 18 mm/min were recorded simultaneously on minute 43.9.*

*According to the results of the research, the regularity of the limit of fire resistance of reinforced concrete ribbed slabs from the level of the applied mechanical load was established. This will make it possible to design and build buildings and structures using the specified building structures with guaranteed fire resistance classes, which improves the level of safety for people at the facilities*

*Keywords: reinforced concrete ribbed slabs, fire resistance, iterative Newton-Raphson method, finite element method*

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# REVEALING PATTERNS IN THE BEHAVIOR OF A REINFORCED CONCRETE SLAB IN FIRE BASED ON DETERMINING ITS STRESSED AND DEFORMED STATE

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## 1. Introduction

The use of industrial and warehouse buildings and facilities involves large areas of premises without supporting structures, which forces builders to design ceilings or coverings with large spans. One of the types of structures that makes it possible to cover large spans is reinforced concrete ribbed slabs [1]. Due to design features that increase the rigidity and load-bearing capacity of these structures, namely the arrangement of longitudinal and transverse ribs, reinforced concrete ribbed slabs are able to cover large spans without passing to the limit states of the 1st and 2nd groups.

Such structures are designed to absorb constant load from natural weight, equipment, as well as periodic load from rainfall.

The main principles of modern construction are to guarantee the safety of people who plan to use construction facilities and buildings for the required period [2]. In addition, it is necessary to provide comfort, predicting the most rational financial costs for the implementation of relevant construction projects. One of the decisive directions for guaranteeing people's safety during a fire is to reduce the risk of a threat during evacuation before the onset of critical indicators of dangerous fire factors. To achieve this goal, it is necessary to guarantee the operation of especially responsible structures for a certain time under the thermal influence of fire with minimal risks, regarding the threat to human life and health. The implementation of this aspect is implied, including when assessing the fire resistance of building structures. There are several methods for assessing the fire resistance of structural elements of buildings. The principles of these methods involve determining the time from the beginning of thermal exposure according to the standard fire temperature regime to the onset of one of the limit states of fire resistance. The possibilities of full-scale and experimental tests are limited by the arrangement of the necessary configurations of furnaces for conducting similar studies [3, 4]. At the same time, the cost and labor-intensiveness of these works in comparison with calculation methods are significantly exceeded and have a negative impact on the environment.

The computational method using simulation involving the finite element method provides an opportunity to fully reproduce the operating conditions of the building structure during a fire [5, 6]. This variant of research involves the application of various geometric parameters of structures, the application of any level of load, using various theories of the strength of various materials, which opens up the possibilities of computational experiments. Accordingly, it is difficult to overestimate the objectivity of the results regarding the determination of fire resistance of building structures, obtained with the help of simulation.

Thus, the assessment of fire resistance of reinforced concrete horizontal structures using the finite element method is relevant.

## 2. Literature review and problem statement

Determination of the fire resistance of reinforced concrete ribbed slabs of buildings and structures is carried out using the calculation method [7], where 3 methods are employed: tabular, simplified, and refined. However, the use of the refined method when applied to reinforced concrete ribbed slabs is not described in the cited paper, which leads to limitations in choosing methods for calculating the fire resistance of such structures. Paper [8] describes the principle of applying a generalized theoretical approach based on the non-stationary differential equation of thermal conductivity of temperature distribution across the cross-section of horizontal structures. That is, the cited paper presents a method for calculating fire resistance only based on the limit state of the loss of heat-insulating ability, without taking into account the bearing capacity. This makes it impossible to use such a technique for assessing fire resistance upon the onset of the limit state of loss of bearing capacity of reinforced concrete ribbed slabs.

In [9], the application of the tabular method is provided only for the width of the rib, the thickness of the plate itself, and the minimum distances to the armature axis. Moreover, the width of the longitudinal rib and the thickness of the ribbed plate must be at least 80 mm, which significantly limits this method. In addition, the results obtained by this method do not take into account the cross-sectional height of the main components of this slab, the class of concrete and reinforcement. Also, when applying the tabular method, one of the main criteria, which has a very significant effect on fire resistance, is not taken into account – it is the load level. Therefore, there is a limitation of the application of this method according to the geometric parameters of these structures.

The use of the zone method of checking the fire resistance indicators of ribbed reinforced concrete slabs is not considered possible at all, due to the different nature of the thermal impact of fire [10]. Therefore, longitudinal ribs are affected by fire from two sides, transverse ribs located at the edges on two sides and in the middle from three sides, and the slab directly on one side (Fig. 2). Thus, the corresponding scheme of thermal influence from a fire to reinforced concrete ribbed slabs does not make it possible to determine how the temperature will be distributed on this type of structures. Therefore, the application of the zonal method of assessing the fire resistance of reinforced concrete ribbed slabs is not possible [10].

In work [1], the method of determining the limit of fire resistance of reinforced concrete ribbed slabs by bringing the cross-section of the structure to the mark and determining the critical temperature in the working fittings is used. This approach does not provide an opportunity to monitor the stress-strain state of the structure under study during the entire calculated experiment.

The method reported in [11] describes the parametric thermal effect on reinforced concrete floor slabs. But when using this technique, the fire resistance indicators are subject to fire load, which significantly limits the limit of fire resistance for mass-produced products.

Work [12] presents a technique based on a refined method. However, this method is the most difficult to use and requires the use of powerful software packages suitable for solving non-linear thermotechnical and mechanical problems.

Thus, conducting research on determining the regularity of the limit of fire resistance of reinforced concrete ribbed slabs dependent on load level will make it possible to establish the nature of the dependence of this factor on the fire resistance indicators of these slabs.

## 3. The aim and objectives of the study

The purpose of this study is to determine the patterns of changes in the values of the fire resistance limit of the PR 63-15 reinforced concrete ribbed slab depending on the applied mechanical load at 50 %, 70 %, and 100 % of the bearing capacity of the structure. Taking into account that the level of the applied load is one of the main criteria that affects the fire resistance of the structure, the determination of the regularity will provide an opportunity to evaluate the fire resistance of the studied reinforced concrete ribbed slabs. This will make it possible to design and construct facilities using the specified building structures with guaranteed fire resistance classes, which increases the level of safety for people at the facilities.

To solve the research goal, the following tasks are set:

– to calculate the temperature distribution on the reinforced concrete ribbed slab under the influence of the standard fire temperature regime using the finite element method in the Transient Thermal module of the ANSYS WB software package;

– to calculate the distribution of normal stresses in concrete and deflection in a reinforced concrete ribbed slab during a fire at different load levels using the finite element method in the Transient Structural module;

– to determine the limit of fire resistance of a reinforced concrete ribbed slab and, based on the results, to construct a deflection diagram at the load level of 50 %, 70 %, and 100 % of the bearing capacity of the structure under study;

– to determine the regularity between the limit of fire resistance of the simulated reinforced concrete ribbed slab and the level of the applied mechanical load and construct the corresponding diagram.

## 4. The study materials and methods

The object of our research is the fire resistance of reinforced concrete ribbed slabs.

The research hypothesis assumes the possibility of determining the limit of fire resistance of reinforced concrete ribbed slabs with the help of simulation using the ANSYS WB software package.

In order to study the non-linear behavior of a reinforced concrete ribbed slab under mechanical load and under the conditions of thermal influence from the standard fire temperature regime, an identical reinforced concrete slab was built. External and structural schemes of the studied reinforced concrete ribbed slab are shown in Fig. 1. This design fully corresponds to the structural and geometrical parameters of a reinforced concrete ribbed plate of type PR 63-15, with a span length of 6280 mm (Fig. 1).

To implement the mathematical modeling of the researched structure, the materials were adopted in accordance with the serial type of reinforced concrete ribbed slab PR 63-15. Concrete class C 30/35 and steel reinforcement class A 400.

The thermophysical characteristics of concrete and reinforcement depending on the temperature change are accepted according to the recommendations given in [9].

Based on the results of the imported geometry of the structure under study, a finite-element grid was constructed using finite elements in the form of hexiders according to the SOLID 186 type (Fig. 2). In order to obtain reliable data during computational experiments, the nodes of the constructed finite-element grid for the concrete matrix were intersected at the locations of reinforcing bars. This was achieved by dividing the concrete composite slab into parts according to normal shapes, which ensures the creation of exactly hexahedral finite elements. The total number of nodes was 70,440 units, finite elements – 13,560. Owing to this division of the studied slab, the construction of the finite element mesh was automatic.

To model the thermal effect in the form of a temperature load on a reinforced concrete ribbed slab, a thermal problem was solved. At the same time, a quasi-linear non-stationary differential equation of thermal conductivity is applied in the form of a boundary value problem using boundary conditions of type III (Table 1) taking into account radiant and convective heat exchange of heating surfaces with a standard fire temperature regime. It is assumed that the temperature distribution in the reinforced concrete ribbed slab under the influence of the standard fire temperature regime is not affected by different load levels.

The temperature regime in the room with the fire is calculated according to the standard temperature regime of fire (1).

The thermal effect from the standard temperature regime of the fire is taken for a period of 1 hour and according to the recommendations [9, 13, 14], which is determined by the dependence:

$$\Theta_s = 345\lg(8t+1)+20, \quad (1)$$

where $t$ is the time counted from the start of the test, min; $\Theta_s$ is the temperature corresponding to time $t$, °C.

The conditions for fastening the investigated reinforced concrete ribbed slab are hinged on both sides, thereby limiting movements in the longitudinal and transverse direction of the structure.

Calculations were carried out in the ANSYS WB software package. In the Transient Thermal module, temperature distribution was determined based on the results of the influence of the standard fire temperature regime. A mechanical calculation is performed in the Transient Structural module.

Computational experiments to assess the fire resistance of a reinforced concrete ribbed slab were carried out under load conditions of 50 %, 70 %, and 100 % of the calculated load level according to the bearing capacity of the structure, which is: 2550 Pa, 3570 Pa, and 5100 Pa, respectively. The Drucker-Prager theory of concrete strength was used in the calculations, the criteria of which are given in Table 2.

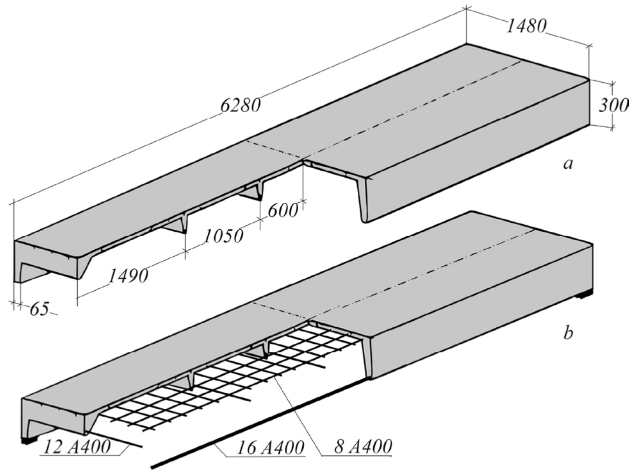



Fig. 1. The investigated reinforced concrete ribbed slab: *a* — general view; *b* — structural diagram

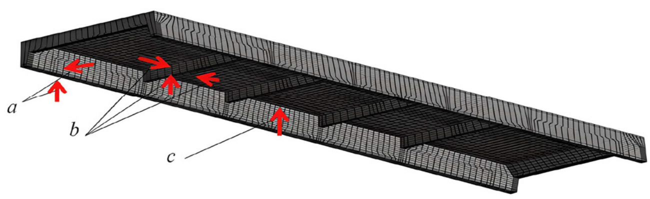



Fig. 2. Finite-element mesh model and schemes of fire influence from the standard fire temperature regime on the structural components of a reinforced concrete ribbed slab: *a* — longitudinal rib; *b* — transverse ribs; *c* — slab itself

Table 1

Parameters of boundary conditions under the influence of the standard temperature regime of fire

| Characteristic | Unit of measure | Value | Source |
|---|---|---|---|
| Parameters of the boundary conditions of the thermal task | | | |
| Coefficient of convection heat transfer on the heated surface | $W/(m^2 \cdot K)$ | 25 | [9] |
| Convection heat transfer coefficient on unheated surfaces | $W/(m^2 \cdot K)$ | 9 | [9] |
| Degree of blackness | – | 0.7 | [9] |
| The Stefan-Boltzmann constant | $W/(m^2 \cdot K^4)$ | $5.67 \cdot 10^{-8}$ | [9] |

Table 2

Criteria for Drucker-Prager concrete strength theory

| No. | Temperature, Θ, °C | Uniaxial compressive strength, $\sigma_{c1}$, MPa | Uniaxial tensile strength, $\sigma_{s1}$, MPa | Biaxial compressive strength, $\sigma_{c2}$, MPa |
|---|---|---|---|---|
| 1 | 0 | 30 | 3 | 45 |
| 2 | 100 | 30 | 3 | 45 |
| 3 | 500 | 18 | 1.8 | 27 |
| 4 | 600 | 13.5 | 1.35 | 20.25 |
| 5 | 800 | 4.5 | 0.45 | 7.25 |
| 6 | 900 | 2.4 | 0.24 | 3.6 |

Considering the difficulty of performing nonlinear mechanical calculations under the influence of the standard fire temperature regime, the load was applied step by step in

15 steps over a period of 5 minutes before the onset of thermal effects from the fire.

## 5. Results of studies on determining the patterns of influence of the load level on the fire resistance of reinforced concrete ribbed slab

### 5. 1. Results of temperature distribution calculation for the structure under study

Based on the results of calculating the influence of the standard fire temperature regime on the investigated building structure for 1 hour, our findings are shown in Fig. 3.

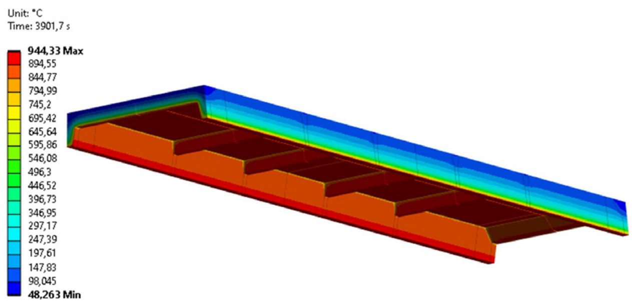



Fig. 3. Temperature distribution in a simulated reinforced concrete ribbed slab in a fire for a period of 1 hour

The maximum temperature on the heating surface of the reinforced concrete ribbed slab was 944.33 °C. According to [14], the standard temperature regime for 60 min of fire tests is 945 °C.

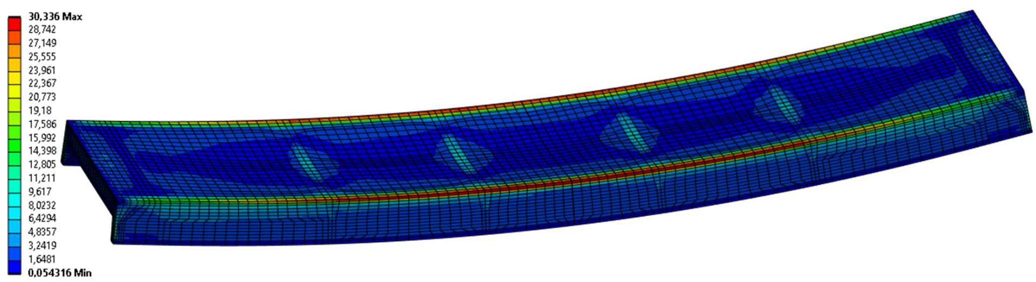
### 5. 2. Results of the calculation of the distribution of normal stresses in concrete and deflection of the slab in case of fire

The critical stresses generated in the upper part of the main load-bearing components – the longitudinal ribs of reinforced concrete ribbed slabs amount to more than 30 MPa (Fig. 4). This figure shows the results for different levels of mechanical load. Taking into account that in the modeling of the studied structure, concrete of class C30/35 was used, the obtained indicators in these ribs are critical.

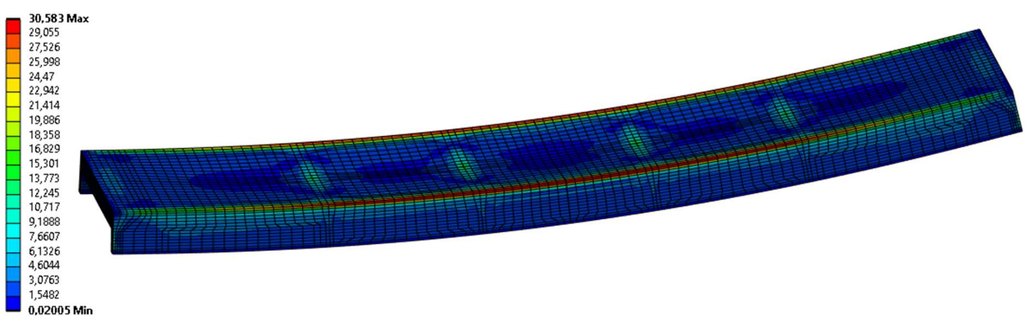
Thus, the onset of ultimate stresses of concrete in the compressive zone of the longitudinal ribs occurs on minute 57.56, 51.6, and 43.9, according to the applied mechanical loads of 50 %, 70 %, and 100 %.

Fig. 5 shows the results of deflections of the investigated reinforced concrete ribbed slab based on the results of loads of 2.55 kPa, 3.57 kPa, 5.1 kPa, which corresponds to 50 %, 70 %, 100 % of the maximum level.

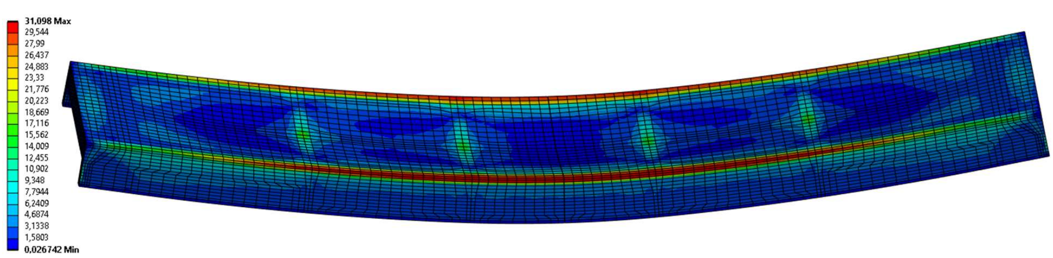
The calculation of the stress-strain state of the structure was carried out within 1 hour.




*a*




*b*




*c*

Fig. 4. Indicators of stress distribution (MPa) on a reinforced concrete ribbed slab during a fire by load levels: *a* – 2.55 kPa for 57.56 min; *b* – 3.57 kPa for 51.6 min; *c* – 5.1 kPa for 43.9 min

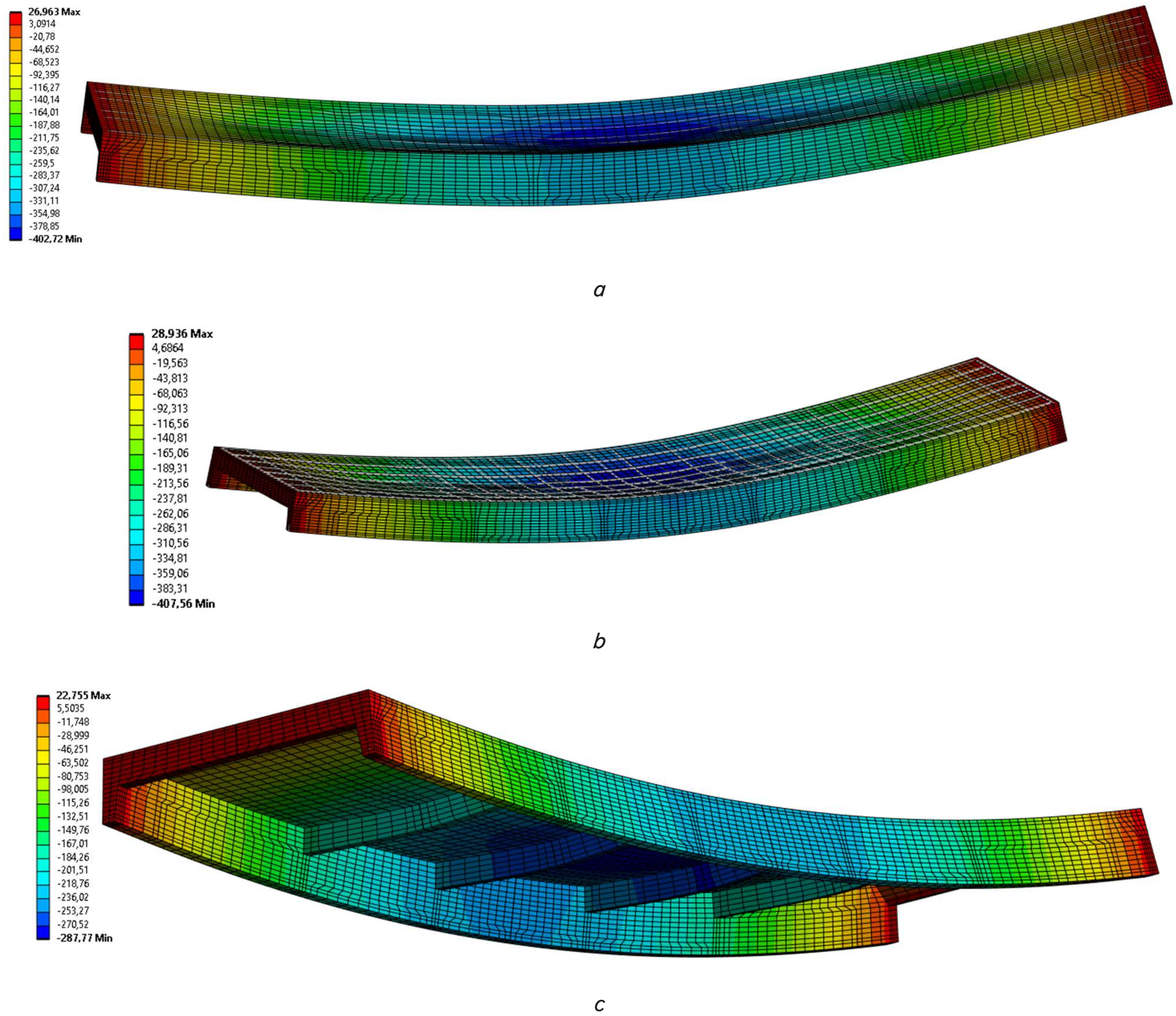



Fig. 5. Deflections of a reinforced concrete ribbed slab during a fire (mm) by load levels: *a* – 2.55 kPa; *b* – 3.57 kPa; *c* – 5.1 kPa

**5. 3. Results of the calculation of fire resistance limit of the simulated reinforced concrete ribbed slab**

Determination of the limit of fire resistance of the studied reinforced concrete structure was carried out based on the results of the onset of the limit state of fire resistance in relation to the loss of load-bearing capacity. Signs of the onset of this limit state are determined according to recommendations given in [14].

Determining the limit values of deflections and the rate of growth of deformation of the structure under study is performed according to formulas (2), (3):

$$D_{limit} = \frac{l^2}{400h}, \quad (2)$$

$$\left(\frac{dD}{dt}\right)_{limit} = \frac{l^2}{9000h}, \quad (3)$$

where $l$ is the span of the panel, mm,

$h$ is the height of the cross section of the longitudinal edge of the plate, mm.

Therefore, the critical deflection is taken to be 268.853 mm (2), and the limiting value of the rate of growth of deformation is 11.949 mm (3).

The results of computational experiments indicate that the onset of the limit state of fire resistance due to the loss of bearing capacity of the reinforced concrete ribbed panel of the coating loaded with 5.1 kPa is observed on minute 43.9 (Fig. 5). Moreover, the rate of growth of deformation was also recorded at the same time on second 2634.4 and amounted to 18.41 mm/min.

The onset of critical deflection in the structure under study, loaded at 50 % and 70 %, is observed on minute 51 and 57, respectively.

**5. 4. Construction of a diagram of dependence of the fire resistance limit of the investigated structure on load level**

Based on the results of calculations using simulation, the value of the deflection of the investigated reinforced concrete ribbed slab under the conditions of thermoforce influence was determined at the load levels of 2.55 kPa, 3.57 kPa, 5.1 kPa. Thus, when using (2), (3), the time of onset of critical deformations of the structure was determined during computational experiments, which indicates the onset of the limit state of fire resistance in relation to the loss of bearing capacity.

Accordingly, plots were built to determine the limit of fire resistance of a reinforced concrete ribbed slab based on the loss of bearing capacity depending on the level of applied mechanical load (Fig. 6).

Calculations of the fire resistance assessment were carried out at the onset of only the limit state for the loss of load-bearing capacity, without taking into account the formation of cracks.

Based on the results of our research, a regularity was revealed that establishes the relationship between the fire resistance limit of a reinforced concrete ribbed slab and the level of the applied mechanical load (Fig. 6).

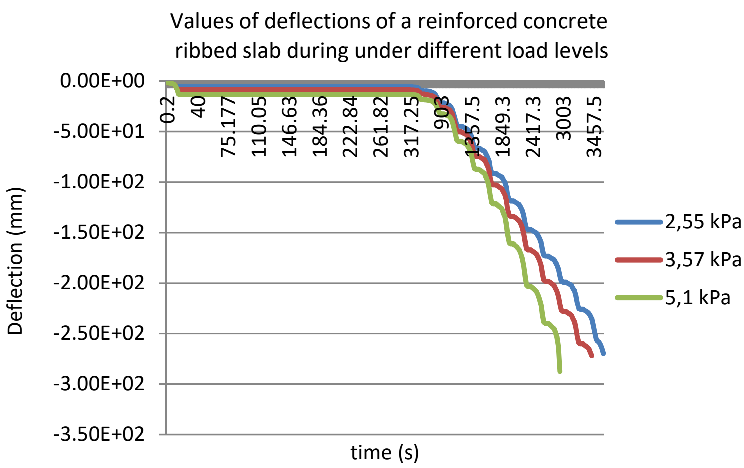



Fig. 6. Deflections of a reinforced concrete ribbed slab during a fire by levels load of 2.55 kPa, 3.57 kPa, 5.1 kPa

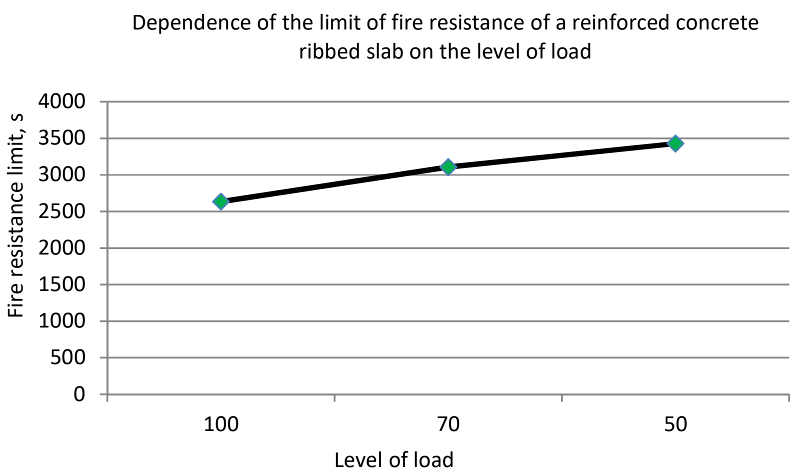



Fig. 7. Dependence of the limit of fire resistance and the level of mechanical load of a reinforced concrete ribbed slab

Thus, the established dependence of the limit of fire resistance of a reinforced concrete ribbed slab on the load level is close to linear. At a level load of 50 %, the limit of fire resistance was minute 57, 70 % – minute 51, and at the maximum limit of fire resistance – minute 43.9, respectively.

## 6. Discussion of results of the study of fire resistance assessment of reinforced concrete ribbed slab

According to the results of the calculation of the influence of the standard fire temperature regime on the tested slab for 1 hour, the temperature distribution throughout the structure was determined. The maximum temperature is observed from the side exposed to heat and is 944.33 °C (Fig. 3). According to [14], the standard temperature regime for 60 min of fire tests is 945 °C. Therefore, the temperature indicators of the heating surface of the slab indicate the reliable results of the obtained heat engineering calculations, which indicates the effectiveness of the application of the employed computer model for determining the temperature distribution indicators during the fire.

According to the results of computational experiments, it was established that the loss of the load-bearing capacity of the studied structures is registered on minute 57, 51, 43.9 at 50 %, 70 %, and 100 % load levels. Signs of the onset of critical deflection were determined according to (2), (3), which is recommended in [14]. Analyzing the results of simulation, it was established that at a 100 % level of mechanical load, which is 5.1 kPa, a critical deflection of more than 268 mm and a growth rate of deformation exceeding 18 mm/min were simultaneously recorded.

At the onset of critical deformations of reinforced concrete ribbed slabs, it was established that the maximum stresses are registered in the compressive layer of the main load-bearing components of these slabs – the longitudinal ribs and amount to more than 30 MPa (Fig. 4). Accordingly, these indicators of the stress-strain state exceed the characteristic compressive strength of concrete (Table 2), which was adopted for computational experiments.

Existing calculation methods for determining the limit of fire resistance of reinforced concrete ribbed slabs involve bringing the cross-section of the structure to the standard [10]. That is, the height of the compressive layer of concrete and the critical temperature in the reinforcement during thermal exposure from the standard fire temperature regime are determined. The method used in the current work involves consideration of the entire structure under investigation, which makes it possible to obtain more objective data on the behavior of a reinforced concrete ribbed slab under conditions of thermoforce influence. In addition, this technique takes into account the effect of fire on a reinforced concrete ribbed slab at every second during the experiment, taking into account the deterioration of mechanical properties due to fire. That is, the method used in the work allows us to obtain more objective indicators of the fire resistance limit.

It should be noted that the drawback of this work is fixing the limit of fire resistance of reinforced concrete ribbed slabs only based on the loss of bearing capacity, not taking into account the limit state of loss of integrity. This is due to the limitation of theoretical ideas about the mechanisms and phenomenology of concrete deformation under the conditions of thermoforce impact during a fire. This limitation is especially evident when trying to predict through defects in reinforced concrete enclosing structures, which are associated with fixing the onset of the limit state of loss of integrity as a result of the thermal effect of a fire. Calculation methods for the limit state of the loss of integrity of reinforced concrete ribbed slabs have not yet been described and are believed to occur approximately simultaneously with the loss of bearing capacity.

Along with this, to carry out calculations according to the methodology described in this work, it is necessary to use powerful software packages, as well as computing devices. In addition, it is necessary to take into account the complexity of preparing appropriate models for calculations, which significantly complicates the conduct of such computational experiments.

At the same time, the method described in the paper can be used to conduct a full factorial numerical experiment to determine the limit of fire resistance of the structures under study using the most significant geometric parameters.

The results of this experiment will improve the tabular method described in [9], which significantly simplifies the process of evaluating the fire resistance of reinforced concrete ribbed slabs.

## 7. Conclusions

1. Based on the results of thermal engineering nonlinear calculations, the temperature distribution of the studied reinforced concrete ribbed slab under fire conditions was investigated and the maximum temperature on the heating surface of the slab was established, which is 944.33 °C.

2. According to the results of concomitant thermomechanical calculations, it was determined that the onset of critical stresses is observed in the upper part of the main load-bearing components – the longitudinal ribs of a reinforced concrete ribbed slab and amount to more than 30 MPa.

3. As a result of the research, the limits of fire resistance of the investigated structure were determined on minute 57, 51, 43.9, according to the load levels of 50 %, 70 %, 100 % of the maximum; the deflection diagrams were constructed.

4. According to the results of our research, the law of the limit of fire resistance of a reinforced concrete ribbed slab from the level of the applied mechanical load was determined and graphically constructed, which is almost linear in the range of the load level from 50 % to 100 %.

## 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 and the results reported in this paper.

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## Data availability

All data are available in the main text of the manuscript.

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