

The Influence of the Level of Mechanical Load on the Fire Resistance Limit of a Reinforced Concrete Wall

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Abstract. The work investigates the influence of the level of applied mechanical load on the fire resistance limit of a reinforced concrete wall under the conditions of a standard temperature fire regime. For this purpose, a geometric and finite element model of a wall fragment was developed, taking into account the joint operation of concrete and reinforcement. Numerical modeling was performed using temperature-dependent thermophysical and mechanical characteristics of materials in accordance with the provisions of EN 1992-1-2 in the ANSYS WB software package. At the first stage, a thermal calculation was carried out, the results of which established a significant unevenness of the temperature field in the cross-section of the structure and the formation of a temperature gradient between the heated and unheated surfaces. It was shown that the temperature in the area of the reinforcement reaches values over 600 °C, which leads to a significant decrease in its mechanical characteristics. At the second stage, the static problem was solved for load levels from the bearing capacity $\mu = 0.2$; 0.4; 0.6 and 0.8. It has been established that the limit state of the structure is determined not by the magnitude of the deformations, but by the achievement of critical compressive stresses in the concrete and the loss of convergence of the numerical solution. For load levels $\mu = 0.4$; 0.6 and 0.8 loss of convergence is observed at 12161 s, 7506 s, and 5021.5 s of fire action, respectively, while at $\mu = 0.2$ the structure retains its load-bearing capacity throughout the entire calculation time. Based on the results obtained, a nonlinear dependence of the fire resistance limit on the level of mechanical load was established. The obtained dependence allows for the assessment of the fire resistance of a reinforced concrete wall 165 mm thick, taking into account the level of applied mechanical load, and to obtain results close to experimental, within the limits of the geometric and structural parameters adopted in the study, without conducting expensive tests or using complex numerical models.

1 Introduction

Ensuring the fire resistance of building structures is one of the main conditions for guaranteeing the safe evacuation of people and the preservation of material values during a fire for the required period of time [1, 2]. In addition, a sufficient level of fire resistance of structures ensures the stability of the building, which creates the opportunity for the effective work of emergency and rescue units during fire extinguishing. [3, 4].

Load-bearing structures, in particular columns and walls, are of particular importance, since they absorb the main vertical loads from floors and coatings and ensure the spatial stability of the building [5, 6]. In case of loss of their load-bearing capacity, progressive destruction of the structural system of the building is possible [7, 8]. According to regulatory requirements [9], the fire resistance class of such structures should be R 15, R 20, R 30, R 45, R 60, R 90, R 120, R 180, R 240 and R 360.

In this work, the main attention is paid to reinforced concrete walls, which are widely used in residential, public and industrial buildings as load-bearing and enclosing elements.

Unlike columns, walls have a significant surface area that is exposed to direct thermal effects during a fire. The most common material for their manufacture is reinforced concrete [10, 11]. Under such conditions, uneven heating of the cross-section of the structure is possible, which significantly affects its stress-strain state.

Determination of the fire resistance of reinforced concrete walls can be carried out using full-scale, experimental and calculation methods [12]. Each of the above approaches has its own application features and is used depending on the research or engineering tasks. In view of this, an analysis of existing methods for assessing the fire resistance of building structures and the possibilities of their application for studying the loss of load-bearing capacity of reinforced concrete elements in fire conditions is relevant.

Analysis of methods for assessing the fire resistance of reinforced concrete walls.

Assessment of fire resistance of building structures can be carried out using field, experimental and calculation methods. One of the approaches is conducting field tests, which involve studying real structures or their fragments in conditions as close as possible to operational ones [13, 14]. Such studies allow obtaining the most reliable results, but are characterized by significant labor intensity, high cost of implementation and require the use of specialized equipment. In addition, conducting such tests may be accompanied by a negative impact on the environment [15, 16].

Another approach is experimental studies conducted in specialized fire furnaces [17,18]. However, the use of this method also has a number of limitations. In particular, during testing it is necessary to ensure compliance with the requirements of the standard temperature regime of fire, which is complicated by the limited dimensions of the furnace working space. In addition, an important factor is the need to ensure uniform heating of the surface of the structure, which is not always possible to implement when studying large-sized elements, in particular reinforced concrete walls. Among the calculation approaches to assessing the fire resistance of building structures, there are tabular, simplified and refined methods [19, 20]. These methods differ in the level of complexity of the calculation procedures, the volume of required input parameters and the accuracy of the results obtained.

The tabular method is one of the simplest methods for assessing the fire resistance of reinforced concrete walls [21]. At the same time, the use of this method has certain limitations, in particular, the level of applied load on the structure should be within 35–70% of its calculated bearing capacity. In addition, there are limitations when using the tabular method itself, which consist in the limited geometric parameters of the structure, namely the width of the wall and the distance to the axis of the reinforcement. For example, to ensure the fire resistance class REI 150 under one-sided thermal exposure and the load level in a fire $\mu = 0.35$, the minimum wall thickness should be 165 mm, and the distance to the axis of the reinforcement should be at least 33 mm.

When the load level during fire is increased to $\mu = 0.70$, the minimum wall thickness to ensure the same fire resistance class must be at least 185 mm, and the distance to the reinforcement axis must be at least 43 mm.

Thus, the use of the tabular method is accompanied by a certain margin, which leads to increased requirements for the geometric parameters of the structure to ensure compliance with the declared fire resistance class. This is due to the fact that to guarantee compliance with the fire resistance requirements, the tabular data provides for an increased margin for the geometric parameters of the structure.

The simplified (zonal) method for assessing the fire resistance of reinforced concrete walls [22], unlike the tabular method, allows taking into account the cross-sectional area of the reinforcement and concrete, as well as their mechanical properties, as well as the level of mechanical load application, which makes it possible to obtain more accurate results. However, the use of this method has certain limitations, since the regulatory documents provide temperature curves only for walls with a thickness of 200 mm, which makes this approach even more limited in use compared to the tabular method.

The refined method for assessing the fire resistance of reinforced concrete walls [23] allows taking into account arbitrary cross-sectional geometry, different structural materials and any level of

applied load, which ensures obtaining results that are as close as possible to experimental or full-scale tests. At the same time, the use of such an approach requires special skills in working with software complexes and largely depends on the performance of the computing equipment on which the calculation is performed. Therefore, the use of this method in practice is more complicated compared to simplified calculation approaches.

Thus, establishing the pattern of loss of bearing capacity of a reinforced concrete wall in fire conditions depending on the level of applied load is an urgent scientific task. The implementation of this approach will allow determining the fire resistance indicators of reinforced concrete walls without conducting laborious experimental tests or using complex refined numerical methods that require significant computing resources and specialized software. In this case, it is expected to obtain results close in accuracy to experimental data.

Engineering tools and their limitations. In this study, a refined approach was used to analyze the influence of the applied load level on the fire resistance of a reinforced concrete wall. Its application allows for a more complete consideration of the thermomechanical behavior of the structure under fire conditions and to obtain results that are close in accuracy to experimental data. At the same time, the obtained dependence has certain limitations, which consist in the possibility of its application only for reinforced concrete walls with the cross-section adopted in this study.

The chosen approach justification. The choice of the refined approach is due to the need to more fully consider the influence of the applied load level on the process of loss of bearing capacity of a reinforced concrete wall under fire conditions. The use of such an approach allows taking into account the geometric parameters of the structure, the cross-sectional area of materials, as well as the change in their mechanical properties under the influence of temperature.

To study the influence of the load on the fire resistance of the structure, four levels of applied load were considered, which are 20%, 40%, 60% and 80% of the full design bearing capacity of the structure. This approach allows analyzing the change in the behavior of a reinforced concrete wall under fire conditions depending on the degree of its loading and establishing the corresponding pattern of loss of bearing capacity.

The study goal. The purpose of this study is to establish the pattern of changes in the fire resistance limit of a reinforced concrete wall depending on the level of applied mechanical load during exposure to a standard temperature regime of fire. To achieve this goal, the following constraints were set:

1. To create a geometric model of a fragment of a reinforced concrete wall in order to further form a finite element model based on it for conducting thermal and static calculations and determining the temperature distribution in the structure, as well as the stress-strain state of the reinforced concrete wall under conditions of thermal force influence.
2. To build a finite element model of a fragment of a reinforced concrete wall based on an imported geometric model using hexahedral finite elements.
3. To solve the thermal engineering problem of determining the temperature distribution across a fragment of a reinforced concrete wall under the influence of a standard temperature regime of a fire lasting 11,000 s.
4. To solve a static problem for a fragment of a reinforced concrete wall at load levels of 20%, 40%, 60% and 80% of its bearing capacity with an assessment of compressive stresses and deformations of the studied structure.
5. Based on the results obtained, to evaluate and analyze the influence of the level of applied mechanical load on the fire resistance limit of a reinforced concrete wall.

2 Main Part

Creating a geometric model of a fragment of a reinforced concrete wall. The selected geometry of the reinforced concrete wall fragment is justified by the need to ensure the compliance of the studied model with real structural elements of buildings and their operating conditions under fire exposure. The wall thickness of 165 mm was adopted in accordance with the requirements of regulatory documents (in particular EN 1992-1-2), which regulate the minimum geometric

parameters to ensure a given fire resistance class (for example, REI 150) under one-sided thermal exposure.

The height of the fragment of 3000 mm corresponds to the typical height of the floor of buildings, which allows taking into account the real operating conditions of the structure and the nature of the distribution of temperature and mechanical influences along its height.

The width of the model of 500 mm was chosen taking into account the need to minimize edge effects and ensure conditions close to the operation of an infinite plate under mechanical load and temperature influence.

The geometric model was created in the geometric module SpaceClaim of the ANSYS WB software complex and is shown in Fig. 1.

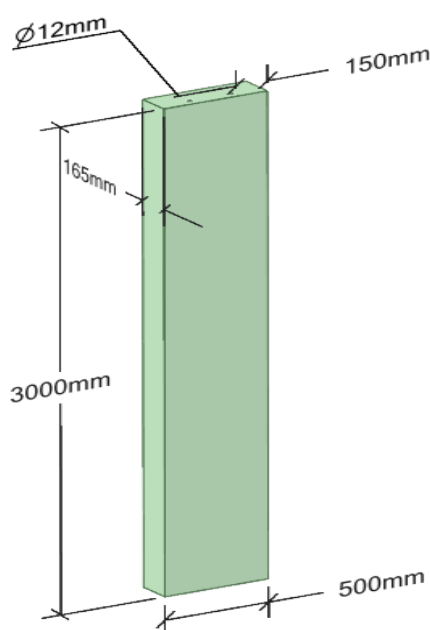


Fig. 1. Geometric model of a fragment of a reinforced concrete wall adopted for numerical modeling.

Thus, the adopted geometry of the model provides an adequate reproduction of the thermal force state of the reinforced concrete wall while maintaining the computational efficiency of numerical modeling, and also creates conditions for the correct formation of a finite element mesh using hexahedral elements without an excessive increase in computational costs.

Construction of a finite element model of a fragment of a reinforced concrete wall. Based on the developed geometric model, a finite element model of a fragment of a reinforced concrete wall was constructed using hexahedral finite elements in the ANSYS WB software package.

The finite element model of a fragment of a reinforced concrete wall was formed using a combined approach, which includes the use of volumetric and linear finite elements. The general view of the finite element mesh is shown in Fig. 2.

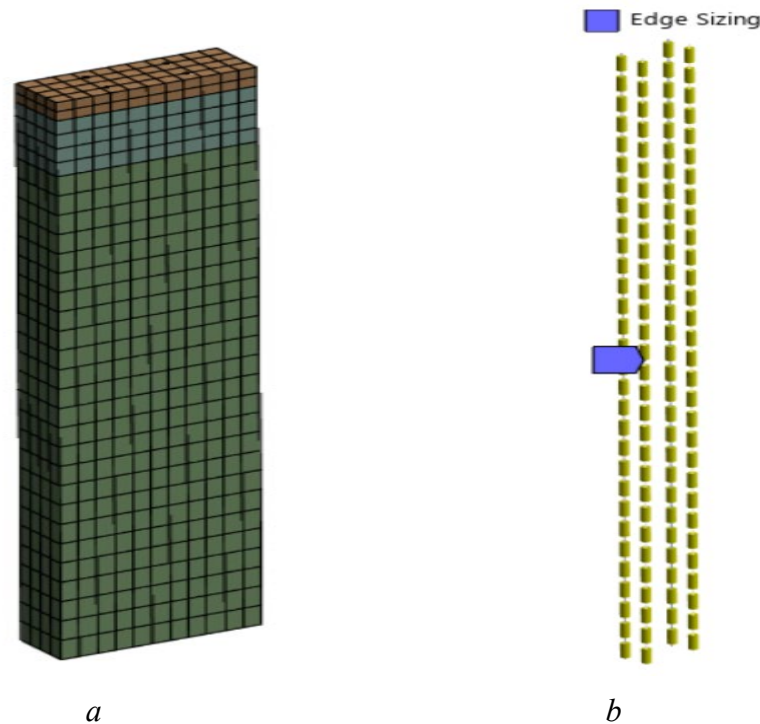


Fig. 2. Finite element mesh of a fragment of a reinforced concrete wall and reinforcement placement diagram: *a* – concrete; *b* – reinforcing bars.

The concrete part of the structure is modeled using volumetric hexahedral finite elements of the SOLID279 type, which ensure the correct reproduction of the temperature field and the stress-strain state of the structure under thermal force conditions.

The statistical indicators of the finite element mesh are presented in Table 1.

Table 1. Statistical indicators of the finite element mesh of a reinforced concrete wall.

Structural element	Finite element type	Number of finite elements (units)	Number of nodes (units)
Concrete	SOLID279	1364	7076
Rebar	linear	120	244
Total quantity	-	1484	7320

Reinforcement elements are modeled as linear finite elements, arranged according to the adopted reinforcement scheme, which are integrated into the volume of the concrete matrix and ensure the combined operation of concrete and reinforcement.

This approach to building a finite element model allows us to adequately reproduce the thermomechanical behavior of a reinforced concrete wall under fire conditions.

To ensure the accuracy of the results, mesh thickening was used at the point of application of mechanical load, which allows us to take into account the load perception by the structure in more detail.

Applying boundary conditions. To simulate the thermal impact of fire on a reinforced concrete wall, a standard fire temperature regime was used in accordance with [24, 25]. The temperature of the gas medium was set according to the standard fire temperature curve, the mathematical representation of which has the form:

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

where t – time counted from the start of the test, min.

On the heated surface of the structure a combined heat exchange is set, which includes convective (Fig. 3-a) and radiation components. (Fig. 3-b).

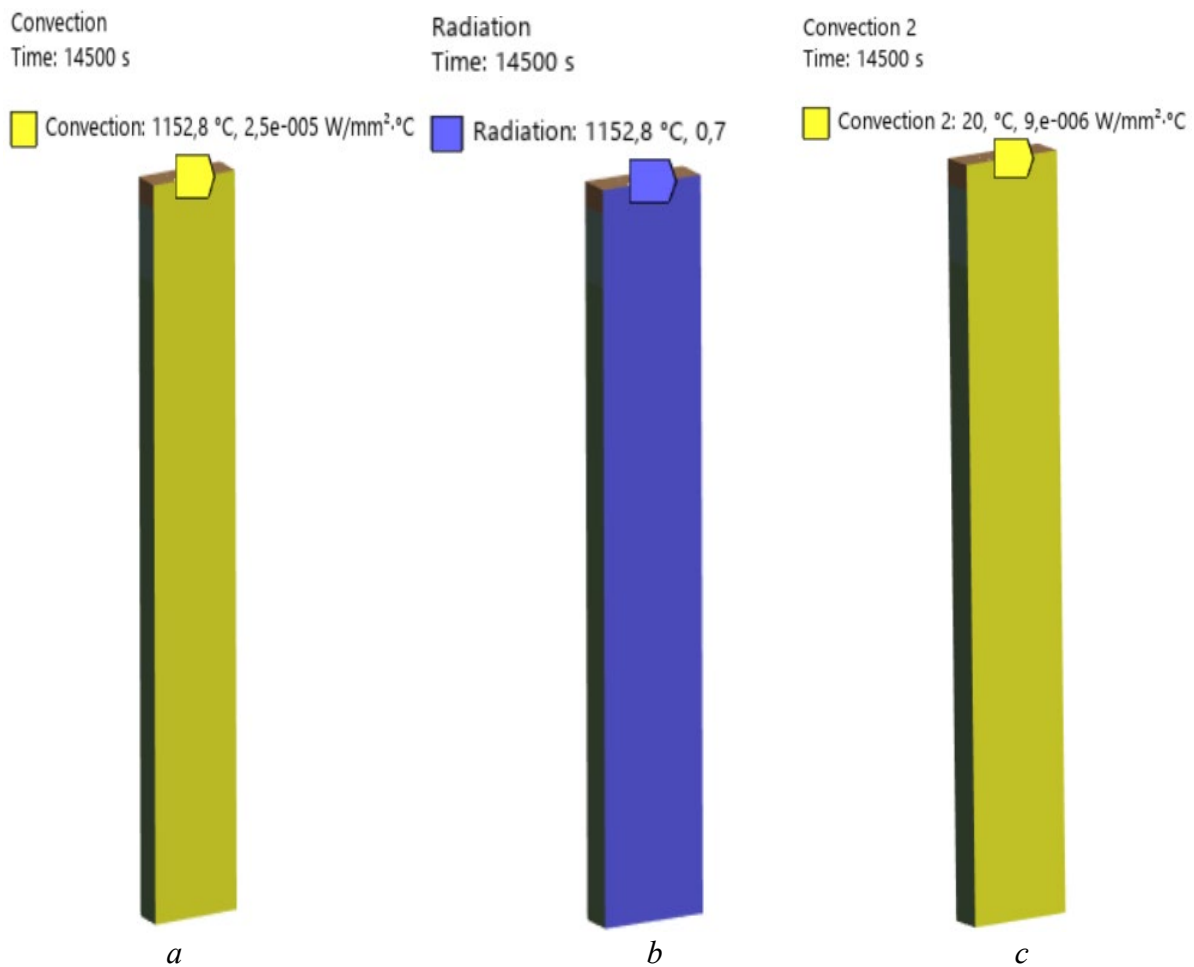


Fig. 3. Scheme for setting the boundary conditions of the thermal load: a – convective heat transfer on a heated surface; b – radiation heat transfer; c – convective heat transfer on an unheated surface.

Convective heat transfer is described by the heat transfer coefficient $\alpha = 25 \text{ W/m}^2 \cdot ^\circ\text{C}$, which corresponds to the conditions of the thermal effect of the fire, and the temperature of the gas medium changes according to the standard temperature curve of the fire. Radiative heat transfer is taken into account with the radiation coefficient $\varepsilon = 0.7$, which corresponds to the conditions of thermal radiation in the fire medium.

On the opposite (unheated) surface of the structure, convective heat exchange with the environment is set at a temperature of 20°C and a heat transfer coefficient $\alpha = 9 \text{ W/m}^2 \cdot ^\circ\text{C}$ (Fig. 3-c), which corresponds to the conditions of natural heat exchange with air.

The side and end surfaces of the model are assumed to be adiabatic, i.e., those through which there is no heat flow. This is justified by the fact that the studied fragment is considered as part of an extended wall structure, for which the thermal influence through the side surfaces is insignificant. This approach allows to exclude edge effects and to provide conditions close to the operation of an extended wall structure.

Thus, the given system of boundary conditions for solving the thermal engineering problem provides an adequate reproduction of heat transfer processes in a reinforced concrete wall under fire conditions and corresponds to modern approaches to numerical modeling of structures under thermal load.

To reproduce the mechanical load in the calculation model, appropriate boundary conditions are set. The lower face of the wall fragment is fixed from movements in all directions, which simulates

the hinged fastening of the structure (Fig. 4-a). A uniformly distributed compressive load in the form of pressure is applied to the upper face of the structure (Fig. 4-b).

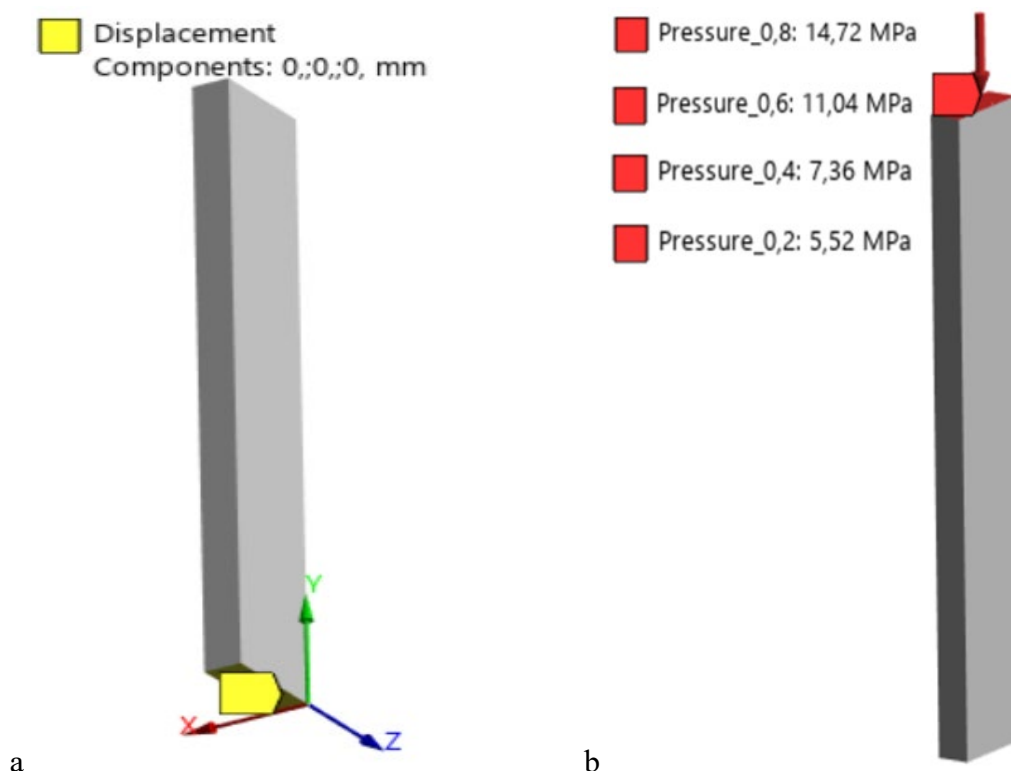


Fig. 4. Boundary conditions for reproducing mechanical load on a reinforced concrete wall:
a – fixing the lower face from displacements ($U_x = U_y = U_z = 0$), which hinged support models;
b – application of uniformly distributed pressure on the upper face.

The applied load level was set as a fraction of the design load-bearing capacity of the structure and was 0.2; 0.4; 0.6 and 0.8, which corresponds to pressure values of 5.52; 7.36; 11.04 and 14.72 MPa, respectively.

The mechanical load was introduced gradually during the first 100 s of the calculation, which allows to ensure the smooth formation of the stress-strain state and avoid numerical instability. After the completion of the stage of applying the mechanical load to the structure, the thermal effect of the fire was set according to the standard temperature regime.

This approach allows you to recreate the real operating conditions of the structure, under which the element first perceives the operational load and then is exposed to high temperatures.

Material properties of the model. When building a numerical model of a fragment of a reinforced concrete wall, temperature-dependent thermophysical and mechanical characteristics of materials were specified in accordance with the recommendations of EN 1992-1-2 [19, 20] for concrete and EN 1993-1-2 [26, 27] for steel reinforcement.

For the concrete part of the structure, the concrete class C30/35 was adopted. At the same time, the model took into account the change in the main thermophysical characteristics of concrete, in particular thermal conductivity, specific heat capacity and density, as well as mechanical characteristics, in particular strength and modulus of elasticity, depending on temperature [19, 20].

Reinforcing steel of class A250 was adopted for the reinforcement of the structure. Its thermophysical and mechanical characteristics were specified taking into account the temperature dependence in accordance with the regulatory recommendations for steel elements under fire conditions [26, 27]. In particular, the change in the strength and stiffness of the reinforcement during heating was taken into account [26, 27].

The adoption of reinforcement of class A250 is due to the need to ensure a conservative approach to assessing the behavior of the structure under fire conditions. This approach allows

obtaining results with a margin of safety, since the use of reinforcement with lower strength indicators compared to more common classes provides an assessment of the fire resistance of the structure under a more unfavorable scenario.

Thus, the specified material properties of the model allow for an adequate reproduction of the change in the physical and mechanical characteristics of concrete and reinforcement during heating, and also ensure the reliability of the results of numerical modeling when assessing the fire resistance of a reinforced concrete wall.

3 Results Discussion

Results of solving the heat engineering problem.

At the first stage of the study, numerical modeling of the thermal impact of fire on a fragment of a reinforced concrete wall was performed in order to determine the temperature distribution in the structure.

Fig. 5 shows the temperature distribution in the studied structure at the time point 14400 s of the standard temperature regime of fire. In this case, the initial 100 s of the calculation were allocated to reproduce the mechanical load under normal temperature conditions without thermal impact.

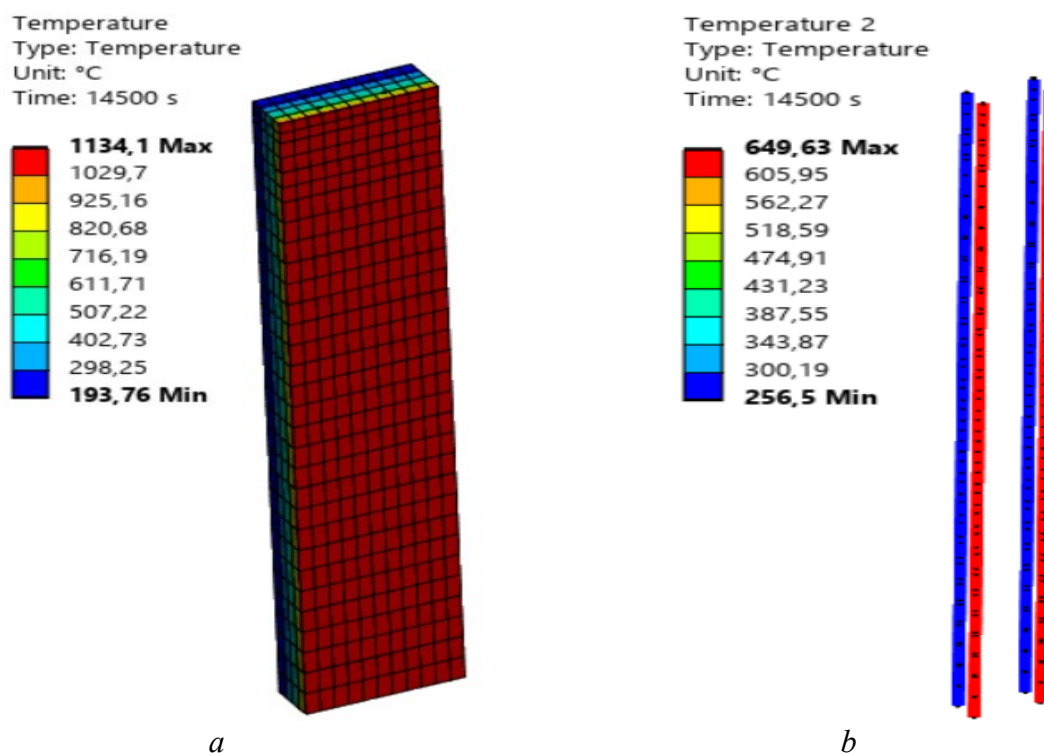


Fig. 5. Temperature distribution in a fragment of a reinforced concrete wall under the conditions of the standard temperature regime of fire for 14 400 s: a – temperature distribution in the concrete of the structure; b – temperature distribution along the reinforcing bars.

Analysis of the obtained results indicates a significant unevenness of the temperature field, characterized by the formation of a significant temperature gradient between the heated and unheated surfaces (Fig. 5-a). The maximum temperature on the heated surface reaches 1134.1 °C. At the same time, the temperature on the unheated surface is about 193.76 °C, which indicates a significant thermal insulation capacity of the concrete wall.

The temperature distribution over the thickness of the structure (Fig. 5-a), as well as in the reinforcing bars (Fig. 5-b) shows that in the area of the reinforcement location, the temperature reaches values of about 600–650 °C, which indicates a significant decrease in the strength of the

steel reinforcement due to heating. In particular, the temperature of the reinforcing bars located on the side of the thermal impact reaches 649.63 °C, while in less heated areas it is about 256.5 °C.

At the same time, the temperature in the central part of the cross-section is significantly lower, which is due to the low thermal conductivity of concrete. The obtained nature of the temperature distribution along the investigated reinforced concrete wall corresponds to the physical laws of heat transfer in massive concrete structures and is consistent with the provisions of EN 1992-1-2.

At the second stage of the study, a static problem was solved taking into account a previously determined temperature field, which allowed us to assess the stress-strain state of a fragment of a reinforced concrete wall under conditions of thermal force influence. The stress state analysis was carried out using the minimum principal stress and compressive deformations, which allows us to correctly take into account the complex stress state in the structure.

The obtained deformation values (Fig. 6) do not reach the values characteristic of the loss of bearing capacity according to [28]. At the same time, the formation of the limit state is caused not by the magnitude of the displacements, but by the loss of convergence of the numerical solution, which is confirmed by the achievement of critical compressive stresses in concrete (Fig. 6).

In particular, for the mechanical load level $\mu = 0.4$, the loss of calculation convergence and the achievement of critical compressive stresses in concrete were observed at 12161 s of fire action (Fig. 6-b; 7-b), for $\mu = 0.6$ – at 7506 s (Fig. 6-c; 7-c), and for $\mu = 0.8$ – at 5021,5 s (Fig. 6-d; 7-d). For the load level $\mu = 0.2$, critical stresses in concrete did not occur, and the calculation was brought to the final fire action time of 14400 s (Fig. 6-a; 7-a).

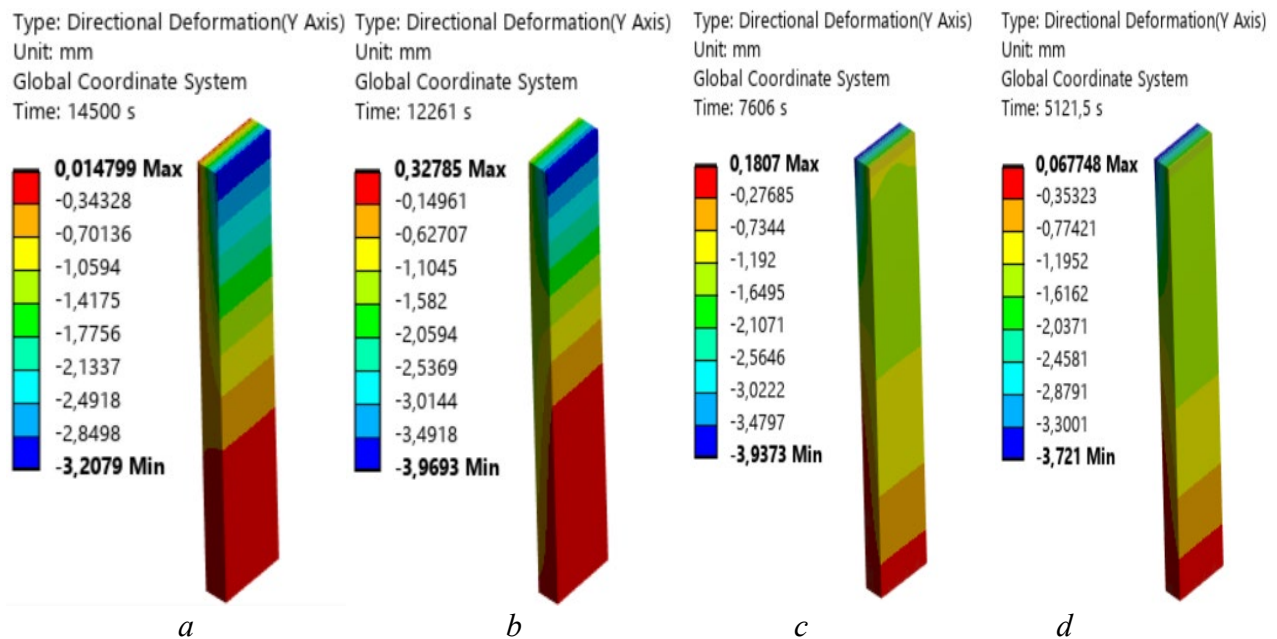


Fig. 6. Distribution of vertical deformations in a fragment of a reinforced concrete wall at different levels of mechanical loading at the moment of loss of convergence of the numerical solution or reaching the final calculation time: a – 0.2; b – 0.4; c – 0.6 and d – 0.8.

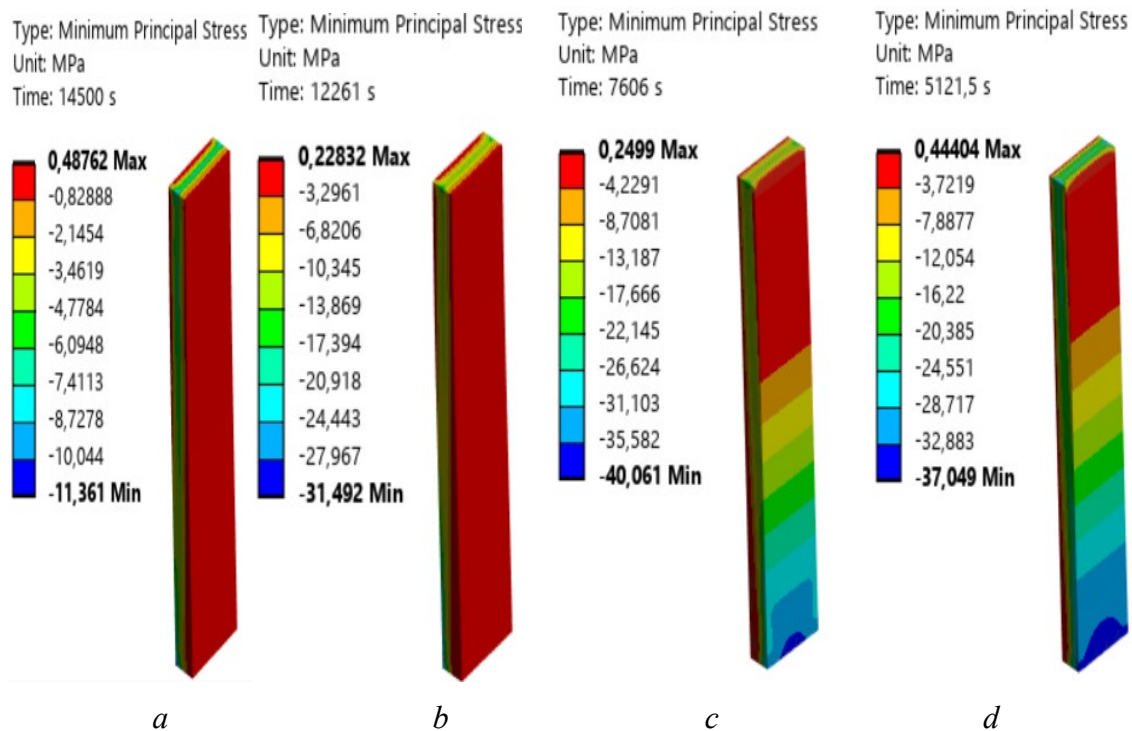


Fig. 7. Distribution of the main compressive stresses (minimum principal stress) in the concrete of a fragment of a reinforced concrete wall at different levels of mechanical loading at the moment of loss of convergence of the numerical solution or reaching the final calculation time:
a – 0.2; b – 0.4; c – 0.6 and d – 0.8.

Based on the results of the analysis of the distribution of the main compressive stresses (minimum principal stress) in the concrete of a fragment of a reinforced concrete wall, a graph of their change depending on the time of fire exposure was constructed, which is shown in Fig. 8.

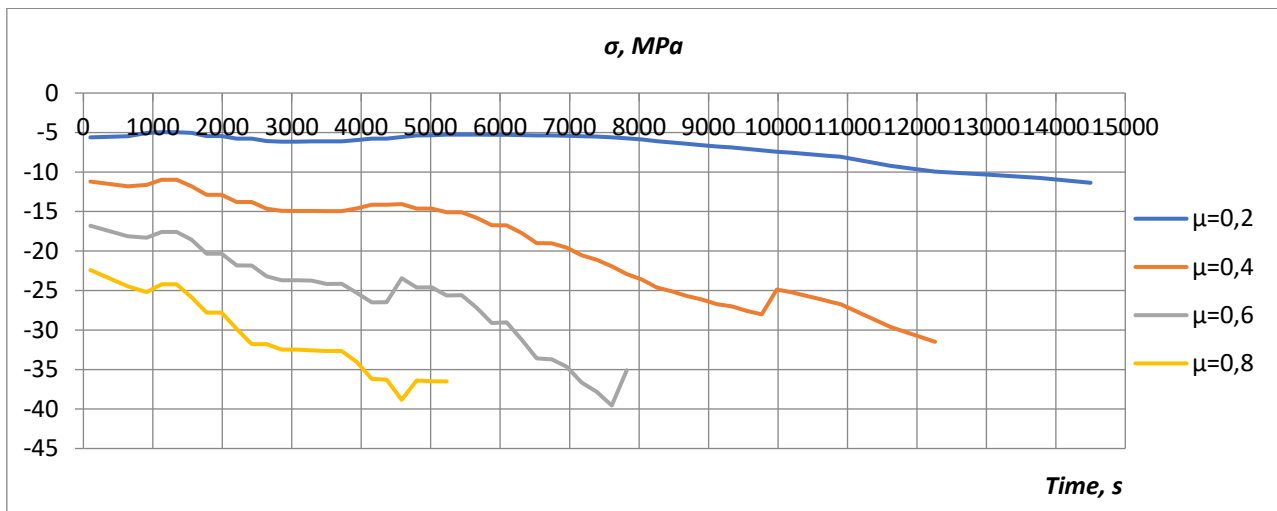


Fig. 8. Change in minimum principal stress in the concrete of a fragment of a reinforced concrete wall depending on the time of fire exposure at different levels of mechanical load.

Analysis of the obtained dependences shows that with increasing fire exposure time, there is a gradual increase in compressive stresses in concrete for all levels of mechanical loading. At the same time, the intensity of stress growth significantly depends on the load level μ .

For the load level $\mu = 0.2$, the stresses change slightly and do not reach critical values throughout the entire calculation time, which indicates the preservation of the bearing capacity of the structure. For $\mu = 0.4$, there is a more intense increase in compressive stresses, which in the later stages

approach the limiting values, which corresponds to the moment of loss of convergence of the numerical solution.

For load levels $\mu = 0.6$ and $\mu = 0.8$, a sharp increase in compressive stresses with the achievement and exceeding of the characteristic strength of concrete is typical, which is accompanied by a loss of calculation convergence. At the same time, for $\mu = 0.8$, the achievement of critical stresses occurs at much earlier stages of fire exposure than for $\mu = 0.6$, which indicates a significant decrease in the bearing capacity of the structure.

The obtained results of numerical modeling allowed us to establish the regularity of the influence of the level of mechanical load on the fire resistance of a reinforced concrete wall. As shown in Fig. 9, with an increase in the load level, a significant decrease in the time to reach the limit state is observed, and this dependence has a nonlinear character.

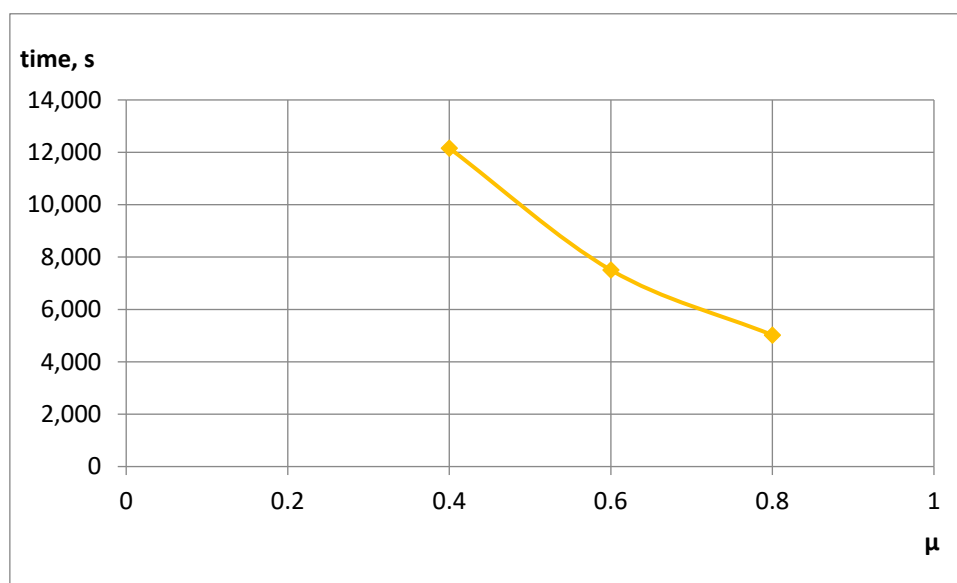


Fig. 9. Dependence of time until reaching the limit state of a reinforced concrete wall on the level of mechanical load.

Analysis of the obtained dependence shows that when moving from $\mu = 0.4$ to $\mu = 0.6$ and $\mu = 0.8$, there is a more intensive decrease in fire resistance, which is due to a decrease in the structural load capacity reserve and accelerated development of the stress-strain state under conditions of elevated temperatures. At the same time, for lower load levels ($\mu \leq 0.4$), the structure retains its operability for a long time even under significant thermal influence.

Comparison of the obtained results with the provisions of the EN 1992-1-2 tabular method showed their consistency in terms of the influence of the load level on the requirements for the geometric parameters of the structure. In particular, to ensure the fire resistance class REI 150 at $\mu = 0.35$, a wall thickness of 165 mm and a distance to the reinforcement axis of 33 mm are sufficient, while at $\mu = 0.7$ larger values are required – 185 mm and 43 mm, respectively. This confirms that with an increase in the load level, the requirements for the structure increase significantly.

At the same time, the results of numerical modeling showed that the adopted wall thickness of 165 mm is insufficient to ensure the required fire resistance at load levels $\mu \geq 0.6$, which is manifested in the loss of convergence of the numerical solution and the achievement of critical compressive stresses in concrete. In this case, the limit state of the structure is determined not by the magnitude of deformations, but by the stress state of the material and its degradation under elevated temperatures. Thus, the results obtained confirm the feasibility of taking into account the real level

of mechanical load when assessing the fire resistance of reinforced concrete structures, since the use of tabular methods without appropriate correction may lead to an overestimation of their fire resistance.

Conclusion

1. A geometric model of a fragment of a reinforced concrete wall has been developed, which adequately reproduces the real geometric parameters of the structure and its operating conditions. The model provided the possibility of correctly forming a finite element model for conducting thermal and static analysis, as well as determining the temperature distribution and stress-strain state of the structure under conditions of thermal force influence.

2. A finite element model of a fragment of a reinforced concrete wall was constructed based on an imported geometric model using hexahedral finite elements for the concrete part and linear elements for reinforcement. The generated model provided correct reproduction of the thermal and stress-strain state of the structure, as well as sufficient accuracy of calculations without excessive increase in computational costs.

3. The thermal engineering problem of determining the temperature distribution in a fragment of a reinforced concrete wall under the conditions of a standard temperature regime of fire lasting 14 400 s was solved. An uneven temperature distribution over the cross-section of the structure was established with the formation of a significant temperature gradient between the heated and unheated surfaces. It was shown that the temperature on the heated surface reaches 1134.1 °C, while on the unheated surface it is about 193.8 °C. In the area of the reinforcement location, the temperature on the side of thermal influence reaches 649.6 °C, which leads to a significant decrease in its mechanical characteristics and is one of the determining factors in the loss of the bearing capacity of the structure.

4. A static problem for a fragment of a reinforced concrete wall was solved at mechanical load levels of 20%, 40%, 60% and 80% of its bearing capacity with an assessment of compressive stresses and deformations of the structure. It was established that the obtained deformation values do not reach the values characteristic of the loss of bearing capacity, while the formation of the limit state is determined by the achievement of critical compressive stresses in concrete and the loss of convergence of the numerical solution. For load levels of 40%, 60% and 80%, the loss of convergence of the calculation was observed at 12161 s, 7506 s and 5021.5 s of fire action, respectively, while for the 20% level, critical stresses in concrete did not arise, and the calculation was brought to 14400 s.

5. Based on the results obtained, the influence of the level of applied mechanical load on the fire resistance limit of a reinforced concrete wall was assessed and analyzed. It was found that with an increase in the load level from 0.4 to 0.8, the time to reach the limit state in terms of bearing capacity significantly decreases, which indicates a nonlinear nature of the dependence of fire resistance on the level of mechanical load. Comparison with the EN 1992-1-2 tabular method showed that to ensure REI 150 at $\mu = 0.35$, a wall thickness of 165 mm and a distance to the reinforcement axis of 33 mm are sufficient, while at $\mu = 0.7$, 185 mm and 43 mm are required, respectively. This confirms that the wall thickness of 165 mm adopted in the study is sufficient for lower load levels, but is insufficient at increased μ values, which is consistent with the results of numerical modeling.

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