Dependence of the Fire Resistance Limit of a Reinforced Concrete Bearing Wall of a Special Storage Facility on the Load Level

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Dependence of The Fire Resistance Limit of a Reinforced Concrete Bearing Wall of a Special Storage Facility on The Load Level

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Abstract. The article describes the calculation methodology for determining the fire resistance limit in a reinforced concrete bearing wall of a special storage facility using the refined method recommended by Eurocode 2. The implementation of this method involves mathematical modeling using the implicit method with the use of the finite element method. The aim of the study is to determine the dependence of the fire resistance limit of a reinforced concrete bearing wall of a special storage facility on the level of applied load by 80%, 60%, 40%, and 20% of the bearing capacity of this wall. This paper presents the results of solving the thermo-technical engineering problem of the influence of a standard fire temperature mode, as well as a static calculation under the condition of applying different levels of load (80%, 60%, 40%, and 20% of the bearing capacity) to the reinforced concrete bearing wall of a special storage facility. The obtained results were interpreted in determining the fire resistance limit of the studied structure at different load levels. The fire resistance limit of the bearing wall of a special storage facility was determined by the occurrence of the boundary states of fire resistance to loss of load-bearing capacity and heat-insulating capacity. Based on the results of the calculations, dependence was determined between the fire resistance limit and the level of load on the reinforced concrete bearing wall of a special storage facility. This dependence can be used to determine the fire resistance limit of such walls at different load levels, and it is also possible to use the described methodology in the work to determine the fire resistance limit of such types of structures by a refined approach using the finite element method.

Keywords: fire resistance assessment, finite element method, refined method.

1 Introduction

Fire resistance of building structures is an important component of fire safety aimed at reducing the risk to human life and health during the construction and use of buildings and structures [1, 2]. This is achieved by maintaining the stability of the building as a whole for a certain period of time under the impact of fire [2, 3]. In addition, it is necessary to create conditions for the effective work of emergency rescue units, which can take a long time [4, 5].

It is also necessary to ensure the fire resistance of bearing walls in order to maintain their bearing capacity, integrity and thermal insulation properties. This is due to the fact that, in addition to their main function as load-bearing elements, such structures must also contain the spread of fire hazards [6, 7]. Obviously, the most optimal material for the construction of such structures, which provides not only bearing capacity but also prevents the spread of fire, is reinforced concrete [8]. The combination of reinforcement and concrete creates a material that can effectively withstand tensile and compressive loads. However, the increased temperature from a fire affects reinforced concrete structures. A damage to the protective layer of concrete leads to the opening in the reinforcement, which accelerates the loss of bearing capacity of the elements [9, 10].

Taking into account the current situation on the territory of Ukraine, which is associated with the military actions of the aggressor country, as well as the abovementioned information, it is relevant to conduct a study to determine the fire resistance of reinforced concrete bearing walls of a special storage facility.

The fire resistance of reinforced concrete bearing walls can be determined by means of full-scale fire tests [11, 12]/ But to apply this method, it is necessary to recreate the building in its entirety, which is a very labor intensive and costly process [13, 14]. Conducting experimental fire tests, both of a fragment and a separate building structure, requires the creation of certain fire conditions in a special laboratory using special equipment [15, 16]. This is also a complex and costly process. In addition, such work, both full-scale and experimental tests, causes environmental pollution, which affects the environmental safety [17].

There is also a method for assessing the fire resistance of walls by means of calculations [18, 19]. The calculation methods include tabular, simplified (zone) and refined methods [20, 21]. The tabular method covers a greater variability of cross-sections of bearing walls than the simplified method, but this approach is rather crude because it does not take into account the material and cross-section of concrete and reinforcement of the structure [21]. In addition, the building structures of a special storage facility have a cross-section much larger than those of conventional buildings. This makes it impossible to use this approach for reinforced structural elements of special storage facilities. The maximum wall thickness in the available tables for one-sided impact is 270 mm, with two-sided impact 350 mm [21]. In terms of accuracy, the next is a simplified (zone) method. The concept of this method is to determine the temperature in the middle of the zones of the half cross-section of concrete that is closer to the fire, as well as in the reinforcement. Taking into account the impact of temperature on concrete, its calculated section is reduced, as well as the bearing capacity of reinforcement depending on temperature. After that, a static calculation is performed to determine the bearing capacity of the structure as if under normal conditions. The reliability of the results of this simplified (zone) method exceeds the tabular method. This is because the class and cross-section of reinforcement and concrete are taken into account when checking compliance with the required fire resistance class. In addition, any load level is taken into account, unlike the tabular method. However, this method has a significant limitation due to the use of temperature curves that are applicable only for walls with a thickness of 200 mm [21]. Thus, this method is also unsuitable for reinforced concrete bearing walls of special storage facilities. At the top of the calculation methods for assessing the fire resistance of building structures is the refined method. This method can take into account any material, load level, and features of any cross-section [22]. This method is supposed to be used with the computer modeling using the finite element method [22]. The reliability of the results obtained by this method is due to the ability to reproduce all the physical processes that occur during fire tests. However, there is no described specific methodology for conducting fire resistance assessment using the refined finite element method for reinforced concrete walls, which complicates the process of fire resistance assessment of such structures. The use of the tabular and simplified methods is impossible due to the lack of the necessary tabular indicators or temperature curves.

Thus, research on assessing the fire resistance of reinforced concrete bearing walls of special storage facilities is relevant.

2 Research Methodology

The purpose of the study is to determine the dependence of the fire resistance limit of a reinforced concrete bearing wall of a special storage facility on the level of applied load by 80%, 60%, 40% and 20% of the bearing capacity of this wall.

1. To build a three-dimensional geometric model of a reinforced concrete bearing wall of a special storage facility for computational experiments to assess fire resistance at the onset of the fire resistance boundary state of loss of bearing capacity.

2. Using the constructed geometric model of the reinforced concrete bearing wall of a special storage facility, to create a finite element mesh using hexahedral finite elements.

3. To perform calculations to determine the behavior of the reinforced concrete bearing wall of the special storage facility under combined thermal and mechanical loading using the ANSYS WB software package at different load levels (80%, 60%, 40% and 20% of the bearing capacity) and determine its corresponding fire resistance limits.

4. Based on the results of determining the fire resistance limit of the reinforced concrete bearing wall of a special storage facility at different load levels (80%, 60%, 40%, and 20% of the bearing capacity), to determine the dependence between the values of the fire resistance limit of the investigated structure and the level of applied load.

To conduct computational experiments to assess the fire resistance of a reinforced concrete bearing wall of a special storage facility at the onset of the fire resistance boundary state of loss of bearing capacity, a three-dimensional geometric model of a fragment of the studied structure was constructed (Fig. 1).

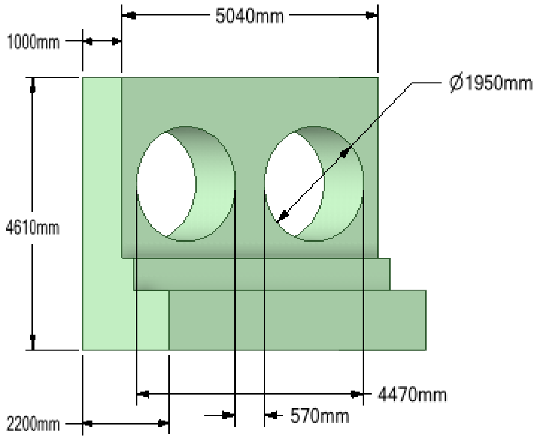
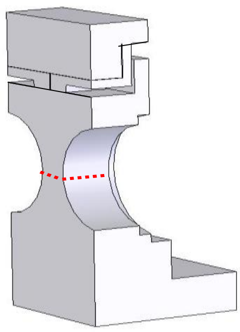
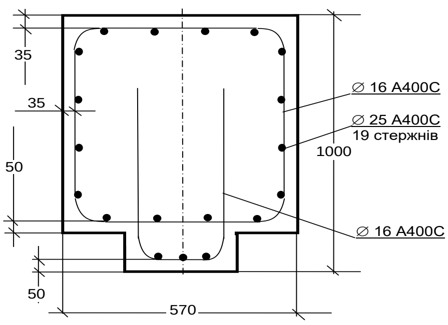


Fig. 1. Geometric model of a reinforced concrete bearing wall of a special storage facility.

It is believed that the most dangerous place in the cross-section of the studied structure is a cross-section that is drawn in the transverse direction and marked with a dotted line on a fragment of the reinforced concrete bearing wall of a special storage facility (see Fig. 2-*a*).The view of the dangerous cross-section of the wall together with the reinforcement is shown in Fig. 2-*b*.



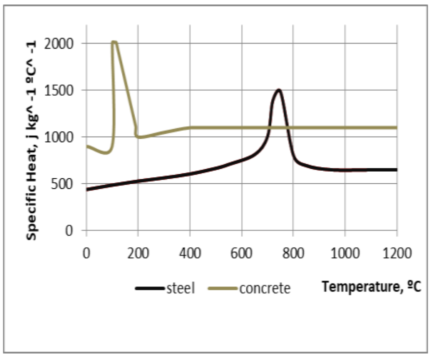
a



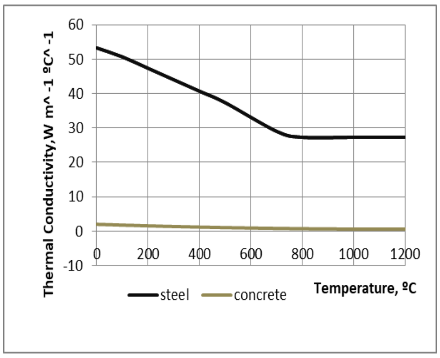
b

Fig. 2. Fragment of a reinforced concrete bearing wall of a special storage facility: *a* - the most dangerous cross-section of the wall fragment; *b* - reinforcement scheme of the dangerous cross-section of the wall fragment.

During the computational experiments, we used mathematical models of materials with thermophysical characteristics according to the recommendations [20, 21] for concrete and reinforcement Fig. 4, which change with temperature.



a



b

Fig. 3. Thermophysical characteristics: *a* - heat capacity of concrete and reinforcement, *b* - thermal conductivity of concrete and reinforcement.

Based on the results of the imported geometric model, a finite element mesh was constructed using hexahedral 8-node finite elements of the Solid type. The size of the finite elements was selected to ensure calculation performance without affecting the accuracy of the results. For the main part of the load-bearing wall, 100 mm was taken, for the secondary part 300 mm, respectively (Fig. 4).

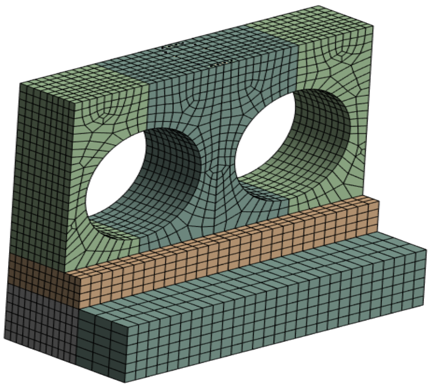


Fig. 4. Finite element mesh of the reinforced concrete bearing wall of the special storage facility.

The total number of finite elements reaches 3948 units and 19052 nodes. This was done to ensure accuracy at a high rate of computational convergence and sufficient speed of the calculation itself.

The next step in the mathematical modeling was to solve the thermal engineering problem of temperature distribution along the studied reinforced concrete bearing wall of the special storage facility under the impact of a standard fire temperature mode for a period of 10,800 s on one side.

To solve this problem, the boundary conditions of the 3rd kind were set with the application of convection and radiation heat exchange to the heated and unheated surfaces of the reinforced concrete bearing wall according to the recommendations of [20, 21].

Reproduction of the thermal impact in the form of a standard fire temperature mode was taken in accordance with [23]:

$$\Theta_g = 345\log_{10}(8t+1), \quad (1)$$

where t is the time counted from the beginning of the test, *min*;
Θ_g is the temperature corresponding to time t, *°C*.

Based on the results of solving the thermal engineering problem, the temperature distribution indicators were imported into the static problem solving module. This made it possible to assess the fire resistance of the reinforced concrete bearing wall of a special storage facility by the onset of the fire resistance boundary state of loss of bearing capacity. The computational experiments were carried out using the implicit Newton-Raphson method.

The mechanical load applied to the wall under study was taken in the form of pressure on the longitudinal half of the structure's cross-section from the inside (Fig. 5) to reproduce the real conditions of floor slabs' support for such storages.

In order to avoid a divergence in the solution of the combined thermal and static problems, at the initial stage, a mechanical load was applied stepwise for 300 s, i.e., before the onset of the impact of the standard fire temperature mode to reproduce the real operating conditions of the studied wall. The magnitude of the applied load was 80% (6.4 MPa), 60% (4.8 MPa), 40% (3.2 MPa), and 20% (1.6 MPa) of the wall's bearing capacity.

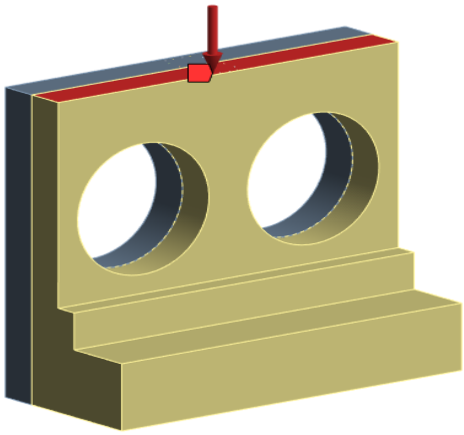


Fig. 5. Applying pressure to half of the cross-section of a reinforced concrete bearing wall of a special storage facility.

The fixing conditions are hinged with movement restriction in all directions from the bottom side of the structure. On the upper side, the settings were made to limit movement in the vertical and longitudinal directions.

3 Results and Discussion

Fig. 6 shows the temperature distribution over a fragment of the reinforced concrete bearing wall of a special storage facility based on the results of exposure to the standard fire temperature mode on one side. At 10,500 s, according to (1), the nominal temperature impact is 1110.2 °C, so the maximum temperature of the studied wall on the side of the fire exposure corresponds to the specified temperature mode [23] (Fig. 6).

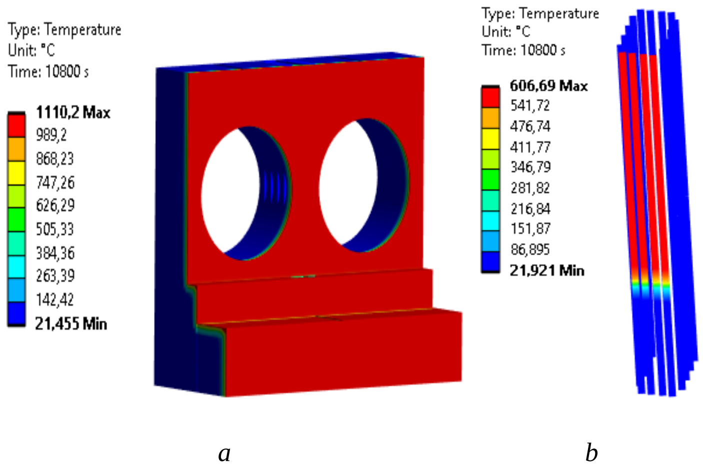


Fig. 6. Temperature distributions in a reinforced concrete bearing wall of a special storage facility after exposure to a standard fire temperature mode for 10500 s: *a* - temperature distribution in concrete, *b* - temperature distribution in reinforcing bars in the most dangerous cross-section of the wall.

As a result of the thermal impact of the fire for 10,500 seconds, no boundary state of loss of thermal insulation capacity was recorded, since the average temperature on the unheated side remained almost unchanged from the initial one (Fig. 6-a). The maximum temperature of the reinforcing bars in the most dangerous cross-section of the studied structure fragment is 606.69 °C (Fig. 6-b).

Based on the results of the calculations to determine the behavior of the reinforced concrete wall of the special storage facility under the conditions of combined thermal and mechanical loading of the reinforced concrete bearing wall of the special storage facility, the distribution of plastic deformations was obtained (Fig. 7).

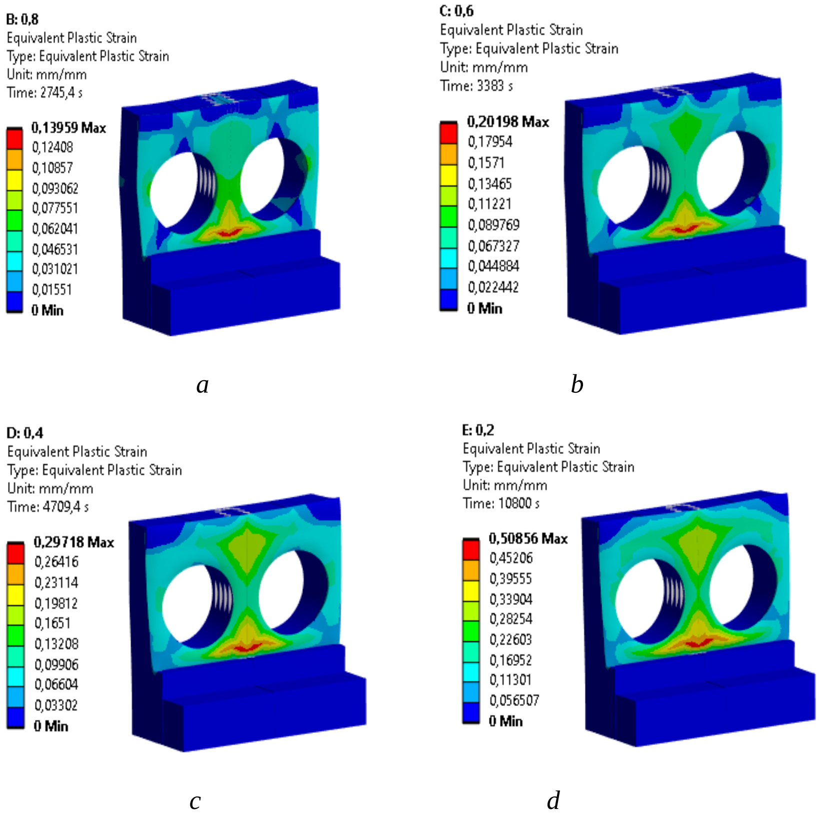


Fig. 7. Distribution of plastic deformations during calculations to determine the behavior of the reinforced concrete wall of a special storage facility under combined thermal and mechanical loading of the reinforced concrete bearing wall of a special storage facility: *a* - 80 %, *b* - 60 %, *c* - 40 %, and *d* - 20 % of the bearing capacity of the studied structure.

The values of this indicator confirm that the area of the most dangerous cross-section in the reinforced concrete bearing wall between the openings is located. However, the largest plastic deformations occur below the location shown in Fig. 2-a. This is due to the fact that in this place there is a larger volume of concrete in relation to the volume of reinforcement, and therefore the thermal impact of the fire leads to the appearance of such deformations of a greater size in the places shown in Fig. 7.

Fig. 8 shows the results of vertical compression of the reinforced concrete bearing wall of a special storage facility under thermal and mechanical loads.

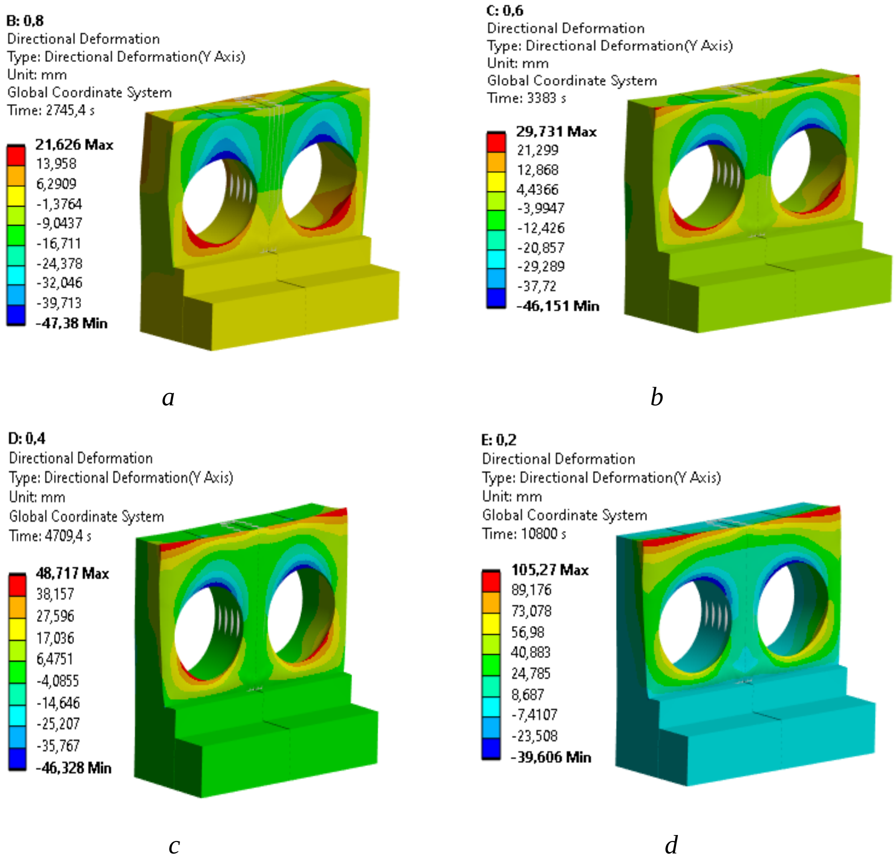


Fig. 8. Vertical compression of a reinforced concrete bearing wall of a special storage facility under combined thermal and mechanical loading at different load levels: a - 80 %, b - 60 %, c - 40 %, and d - 20 % of the bearing capacity of the studied structure.

The onset of the fire resistance boundary state (loss of bearing capacity) was determined according to [23]:

$$C_{limit} = \frac{h}{100}, \tag{2}$$

where *h* is the initial height (in millimeters) of the studied reinforced concrete wall of the special storage facility.

Thus, the ultimate vertical compression is 46.1 mm, and at a load level of 1.6 MPa (20 %), no loss of bearing capacity was recorded for a period of 10,500 s (Fig. *7-d*). This is due to the fact that the thermal expansion of concrete damped the compression of the structure under this load, which increases the fire resistance limit in terms of bearing capacity, in contrast to higher load levels.

Thus, based on the results obtained, a graph of vertical compression of the reinforced concrete bearing wall of a special storage facility at different load levels was constructed (Fig. 9).

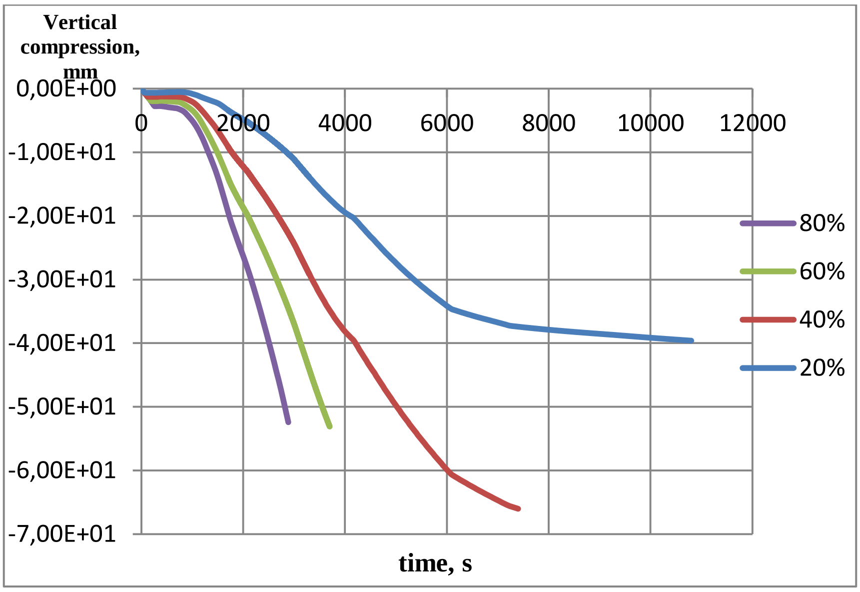


Fig. 9. Graph of longitudinal compression of the reinforced concrete bearing wall of a special storage facility at different load levels.

Thus, the dependence of the fire resistance limit of the reinforced concrete bearing wall of a special storage facility on the level of applied load was determined, and a graph was constructed based on the results (Fig. 10).

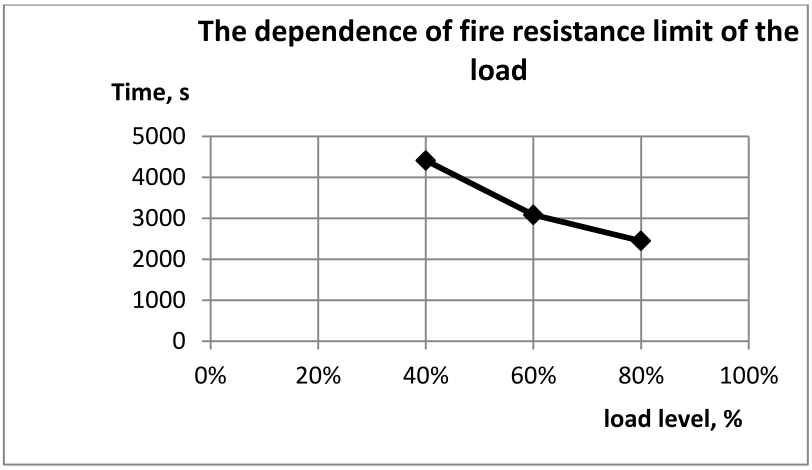


Fig. 10. Graph of the dependence of the fire resistance limit of a reinforced concrete bearing wall of a special storage facility on the level of the applied load.

Thus, the revealed dependence is close to linear, while at a load of 20% of the bearing capacity, there was no loss of bearing capacity for 10,500 s.

4 Conclusions

1. There was reproduced a geometric model of a three-dimensional model of a reinforced concrete bearing wall of a special storage facility for computational experiments to assess fire resistance at the onset of loss of bearing capacity.
2. Based on the results of the imported geometric model of the reinforced concrete bearing wall of the special storage facility, a finite element mesh was created using hexahedral finite elements.
3. Based on the results of the calculations to determine the behavior of the reinforced concrete bearing wall of the special storage facility under combined thermal and mechanical loading, the fire resistance limits of the reinforced concrete bearing wall of the special storage facility were determined, in particular:
   - 40.75 min at 80% load level;
   - 51.38 min at 60% load level;
   - 73.49 minutes at 40% load level;
   - no loss of bearing capacity was observed at 20% load level.
4. Based on the analysis of the calculation results, the dependence of the fire resistance limit of the studied structure on the level of applied load was determined.

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