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A Method of Evaluating the Destruction of a Reinforced Concrete Hollow Core Slab for Ensuring Fire Resistance

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Abstract. Fire tests of reinforced concrete floor slabs do not allow the detection of the onset of the boundary state due to loss of entirety because blocks are installed on the unheated surface to reproduce the design load. This prevents the formation of cracks through which toxic combustion products, smoke, and temperature spread can penetrate. Determining a building structure's actual fire resistance limit was fixed at the onset of any fire resistance boundary state. It was proven that calculation methods for fire resistance assessment have significant advantages over experimental methods. To reduce the number of finite elements for a rational calculation of the fire resistance assessment of a reinforced concrete hollow core slab, a geometric model of 1/4 of this structure was built. The possibility of visualizing the studied structure at full scale was realized when obtaining the calculation results. The stress-strain state of the studied structure was evaluated based on the thermal and mechanical loading results applied to the reinforced concrete hollow core slab. Thus, the work's objective was achieved based on the calculation experiments' results. A methodology was developed for calculating the destruction of a reinforced concrete hollow core slab while assessing its fire resistance. Scientific fundamentals for determining the onset of the boundary state of loss of entirety were developed. The proposed methodology allowed for a reliable assessment of the fire resistance of such structures.

Keywords: finite element modeling, weight reduction, uniformly distributed load, temperature distribution.

1 Introduction

One of the most original design features of reinforced concrete hollow core slabs is the arrangement of hollows, mainly in the neutral zone of the cross-section [1]. This design feature significantly reduces these structures' weight while not significantly affecting their mechanical properties [2]. The reduced weight of the floor slabs makes it possible to save on the support of vertical building structures: on the method of foundation construction and the selection of soils on which construction can be carried out [3]. A comparative analysis of the cost estimates for various slabs showed that hollow core reinforced concrete slabs were the least expensive (about 7.2–16.7 %) compared to other reinforced concrete slabs. The cost estimate considered manufacturing, transportation, installation, construction, and additional work. Another significant advantage of using hollow core reinforced concrete slabs in construction is that, unlike monolithic reinforced concrete, they can be used throughout the year regardless of weather conditions. This contributes to the rapid construction of buildings [4]. In addition, hollow core slabs have a high level of sound insulation.

One of the most essential components in construction to ensure fire safety is using building structures that can perform their functions for the required time in case of exposure to high temperatures from a fire to evacuate people or material assets. In addition, it is necessary to provide for the ability of rescue units to leave the fire scene after the completion of emergency rescue operations.

In order to ensure the use of reliable building structures in fire conditions, each country has specific requirements set out in the relevant regulations [5]. They define the minimal indicators for fire resistance of building structures and buildings, which is mandatory during design and construction works. Building structures with guaranteed fire resistance is also a key to reducing the risk of threat to human life and health in case of a fire [6]. Therefore, developing a methodology for destroying a reinforced concrete hollow core slab under the influence of high temperatures from a fire is relevant.

2 Literature Review

The fire resistance indicators should be determined through practical experiments (full-scale and experimental fire tests) and calculation methods [7]. Practical experiments include determining the fire resistance limit during fire tests according to the standard BS 476-20:1987 "Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)" (incorporating amendment No. 1 and corrigendum No. 1). These experiments are accompanied by releasing harmful substances into the environment [8]. In addition, to conduct full-scale fire tests, it is necessary to recreate the building, which is very laborious and costly [9]. Experimental tests allow for evaluating a sample's fire resistance or a whole building structure [10]. This requires much work to create the conditions for the functioning of the structure in the building and to ensure the standard fire temperature mode [11, 12] in the furnace. In addition, fire tests of reinforced concrete floor slabs do not allow the detection of the onset of the boundary state due to loss of entirety because blocks are installed on the unheated surface to reproduce the design load, which prevents the formation of cracks through which toxic combustion products, smoke, and temperature spread can penetrate [13, 14].

Besides, it should be considered that identical building structures with the same geometric parameters and materials from which they are made may have radically different fire resistance indicators [15, 16]. Thus, calculation methods not only greatly simplify the assessment of the fire resistance of building structures but also make it possible to consider various materials, geometric parameters, and load levels, which provides more reliable results [17]. Thus, calculation methods for fire resistance assessment have significant advantages over experimental methods [18]. However, after analyzing many works devoted to these areas using calculation methods, it was found that the onset of the fire resistance boundary state by loss of entirety is not monitored.

In [19, 20], the onset of fire resistance boundary states is considered only by the loss of bearing and insulation capacities, neglecting the onset of entirety [21], which indicates that unfair results are obtained. Thus, there are no calculation methods for the destruction of reinforced concrete hollow core slabs to assess their fire resistance, making it impossible to track the onset of the boundary state by losing the entirety of these building structures.

According to the standards ISO 834:1975 "Building structures. Test method for fire resistance. General requirements. Fire safety" and EN 1363-1:2020 "Fire resistance tests – Part 1: General requirements", determining a building structure's actual fire resistance limit is considered fixed at the onset of any fire resistance boundary state. In inter-floor slabs, a classification by fire resistance classes is determined by considering the onset of boundary states by the loss of bearing capacity *R*, entirety *E*, and thermal insulation capacity *I* in order to prevent critical deformations of the structure, temperature spread, toxic combustion products, and smoke during a fire.

One of the main parameters influencing the strength and destruction of building structures is the type and level of loading, geometric parameters of the structure cross-section, and materials used to construct these structures. Concepts of general strength theories are based on comparing actual values of indicators based on results of loading of structures with critical values, namely: stresses, deformations, specific energy of potential deformation, and energy of body shape change. However, it is not expected to calculate the possible nature of crack development to solve the strength problem of determining the load-bearing capacity of horizontally reinforced concrete-bearing elements in the presence of cracks.

Many studies point to the prospects of using the implicit method of integrating the static equilibrium equations for a deformed solid body to solve fire resistance problems for reinforced concrete structures. This approach makes it possible to consider the nonlinearity of the differential equations of thermal conductivity and stress-strain state, the plastic deformation during the unloading and reloading of bodies, and the deformation of the body with existing cracks. For considering the nonlinearity of the differential equations when writing them in the finite element approximation, an iterative algorithm based on the Newton–Raphson method is used to integrate them.

Thus, developing a methodology for calculating the destruction of a reinforced concrete hollow core slab is relevant when assessing its fire resistance.

3 Research Methodology

A methodology for destroying a reinforced concrete hollow core slab to assess fire resistance as scientific fundamentals for determining the onset of the boundary state of the loss of entirety includes the following stages:

1) to build a geometric model of 1/4 part of a reinforced concrete hollow core slab in three-dimensional space for further possible use of symmetry in the calculation modules of temperature distribution and action of mechanical load to reproduce this building structure in full scale when obtaining the calculation results;

2) to create a finite element mesh using finite elements of different types (SOLID186, CONTAL174, SURF154, and REINF264) when importing the geometric model of 1/4 of the reinforced concrete hollow core slab into the calculation module Transient Thermal ANSYS Workbench of temperature distribution over the reinforced concrete hollow core slab;

3) to apply symmetry to reproduce the results of the calculation experiment in the studied structure in full scale;

4) to create thermal design models with the application of boundary conditions for heat transfer under the influence of a standard fire temperature mode for 3600 s to obtain the results of temperature distribution in 1/4 of the reinforced concrete hollow core slab;

5) based on the results of the thermal calculation, import the indicators of temperature distribution over 1/4 of the reinforced concrete hollow core slab under the influence of the standard fire temperature mode for 3600 s into the calculation module Transient Structural ANSYS Workbench to study the stress-strain state under thermal and mechanical loads;

6) to apply a uniformly distributed load of 4 kPa to the unheated upper surface of 1/4 of the reinforced concrete hollow core slab in three stages, gradually, prior to exposure to the standard fire temperature mode; to perform hinge fixation of the structure and to set the direction of gravity throughout the experiment – 3600 s. Based on the results of the calculations, develop a methodology for calculating the destruction of a reinforced concrete hollow slab under the influence of a standard temperature of fire mode.

A mathematical apparatus was used to approximate the equations of a stress-strained body using an implicit method of integration of the equations of mechanics using the finite element method, consisting of balance equations in the nodes of the finite elements, combining the integration results for an ensemble of finite elements in which the calculation area of the studied structural element is discretized.

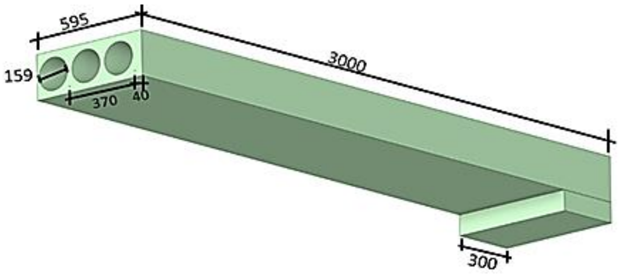
In addition to the basic mathematical model, a plasticity model was used to identify the occurrence of plastic deformations in the finite element nodes and determine the system's resistance during its unloading and reloading. In this case, it is a multilayer Besseling model with an isotropic expansion of the plasticity surface. In this case, the finite element is divided into several layers and an optionally controlled number of them (at least 3 layers), within which the plastic deformation is considered constant.

In order to reduce the number of finite elements in the finite element mesh, a geometric model of 1/4 of a reinforced concrete hollow core slab was constructed (Figure 1) to ensure the productivity of the calculations.

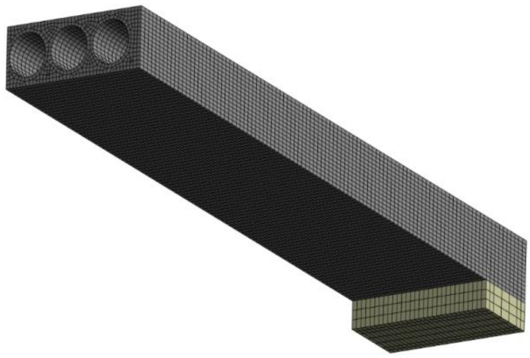
That is, reducing the actual reinforced concrete hollow core slab in length and width by half will reduce the number of finite elements by 4 times without affecting the results' reliability. Thus, the geometric parameters of the full-scale reinforced concrete hollow core slab are as follows: span length – 6000 mm, section height – 220 mm, slab width – 1190 mm, hollow core diameter – 159 mm, and 4 reinforcing bars with a diameter of 12 mm.

To obtain adequate results during the mechanical calculation, the structure under study is pivotally fixed on a 100 mm high support (Figure 1).

The structure materials were made of concrete of C30/35 class; reinforcing bars in the lower part of the slab were made of steel class A250.



a



b

Figure 1 – 1/4 part of a reinforced concrete hollow core slab in three-dimensional space (a) and its finite element model (b)

The deformation properties of the materials at elevated temperatures were taken according to the recommendations of the standard BS EN 1992-1-1:2004+A1:2014 "Eurocode 2: Design of concrete structures General rules and rules for buildings".

The Drucker–Prager theory of concrete strength was used in the calculations. The criteria are given in Table 1.

Table 1 – Criteria for the Drucker–Prager theory of concrete strength

Temperature, ºC	Uniaxial compressive strength, MPa	Uniaxial tensile strength, MPa	Biaxial compressive strength, MPa
0	30.0	3.00	45.0
100	30.0	3.00	45.0
500	18.0	1.80	27.0
600	13.5	1.35	20.3
800	4.50	0.45	7.25
900	2.40	0.24	3.60

Figure 2 shows the thermophysical characteristics of steel reinforcement used in the researched building structures for the calculation of fire resistance according to the standard EN 1992-1-2:2004 "Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design". These characteristics are the temperature dependences of the effective characteristics that describe the material as homogeneous and isotropic, which is acceptable in such calculations.

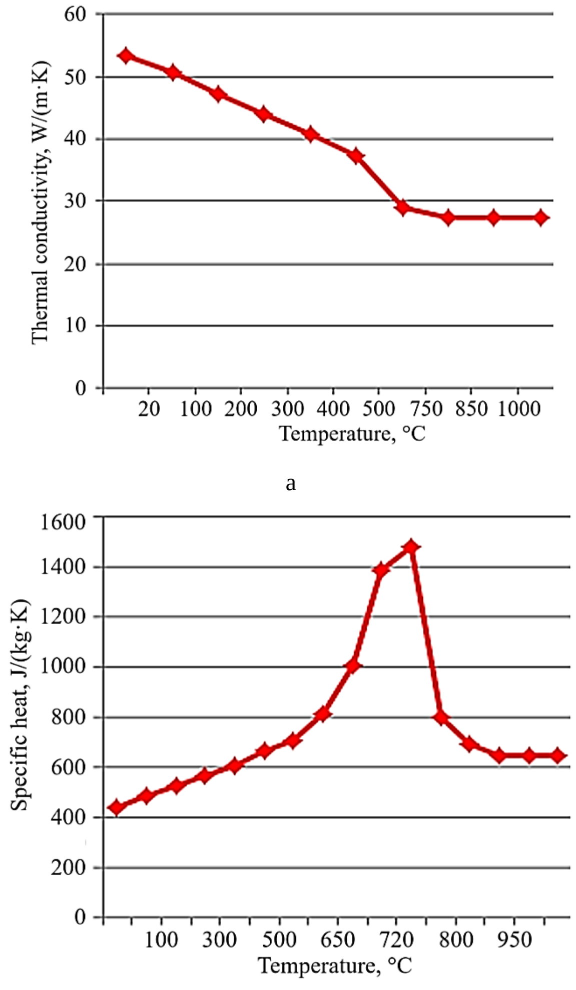


Figure 2 – Thermophysical characteristics of steel reinforcement reinforced concrete hollow core slab:
a – thermal conductivity, W/(m·K); b – specific heat, J/(kg·K)

Figure 3 shows the thermophysical characteristics of concrete used to calculate reinforced hollow slabs' fire resistance.

The finite element mesh was constructed using an imported geometric model of a 1/4 section of a reinforced concrete hollow core slab using the SWEEP method.

The total number of finite elements is $3.5 \cdot 10^4$. The finite element types used to model the concrete were SOLID186, reinforcement – REINF264, and to create contacts between concrete and reinforcement – CONTAL174, SURF154.

In order to reproduce the full scale of the reinforced concrete hollow core slab, taking into account the corresponding support on the walls, symmetry has been applied along the length and width of the slab.

The boundary conditions for ensuring heat transfer under the influence of a standard fire temperature mode on a hollow core slab are applied according to the European Committee for Standardization recommendations and are given in Table 2.

The temperature values of the thermal calculation, based on the results of exposure to the standard fire temperature mode, were imported into the module Transient Structural ANSYS Workbench to solve the mechanical problem. Moreover, there was no fire exposure during the first 15 steps for 300 s. So, it would be possible to apply a mechanical load of 4 kPa to the unheated surface of the structure under study step by step.

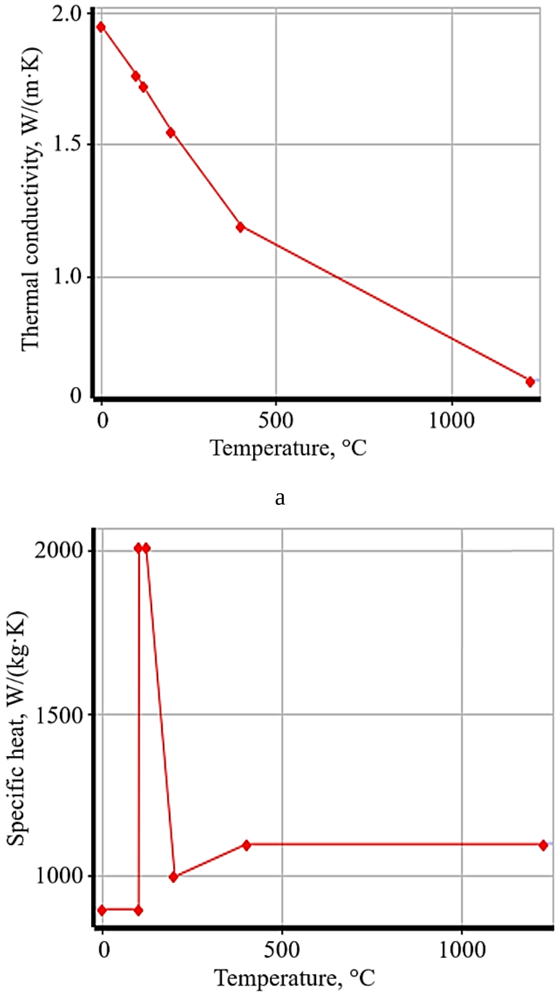


Figure 3 – Thermophysical characteristics of concrete used to calculate the fire resistance of reinforced concrete hollow slabs:
a – thermal conductivity, W/(m·K); b – specific heat, J/(kg·K)

Table 2 – Parameters of the boundary conditions

Parameter	Unit	Value
Convection heat transfer coefficient on the heated surface	$W/(m^2 \cdot K)$	25
Convection heat transfer coefficient on the unheated surface	$W/(m^2 \cdot K)$	9.0
Stefan–Boltzmann constant	$W/(m^2 \cdot K^4)$	$5.67 \cdot 10^{-8}$
Mechanical loading (pressure)	Pa	$4 \cdot 10^3$
Gravity acceleration	m/s^2	9.81
Degree of blackness	–	0.7
Nominal thermal impact, according to the standard fire temperature mode	$\Theta_s = 345 \cdot \lg(8 \cdot t + 1) + 20$	

Additionally, the criterion of concrete destruction at acquiring plastic deformations due to thermal and mechanical impacts with a value of $2.5\cdot10^{-3}$ was introduced. The standard Earth gravity acceleration of 9.81 m/s^2 is also applied to the unheated surface of the slab in the vertical direction.

4 Results

Based on the solved thermal problem results, the temperature distribution over the reinforced concrete hollow core slab for 3600 s was obtained (Figure 4).

The distribution graph of the global maximum temperature on the heating surface is presented in Figure 5.

Based on the results of compatible thermal and mechanical loading applied to the reinforced concrete hollow core slab, the stress-strain state of the studied structure was obtained.

Figure 6 shows the distribution of the von Mises equivalent stress formed in concrete during fire and mechanical stress for 2450 s.

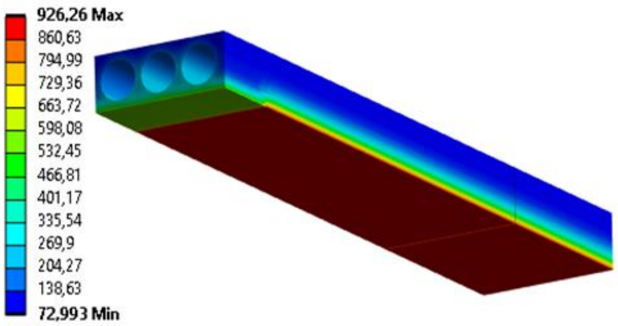


Figure 4 – The results of the thermal impact on a 1/4 for a reinforced concrete hollow core slab for 3600 s

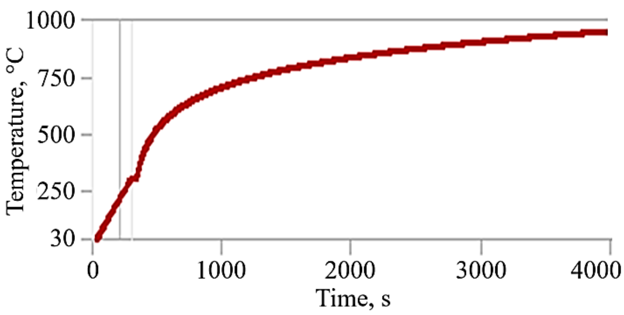


Figure 5 – The global maximum temperature on the heating surface of reinforced concrete hollow core slab for 3600 s

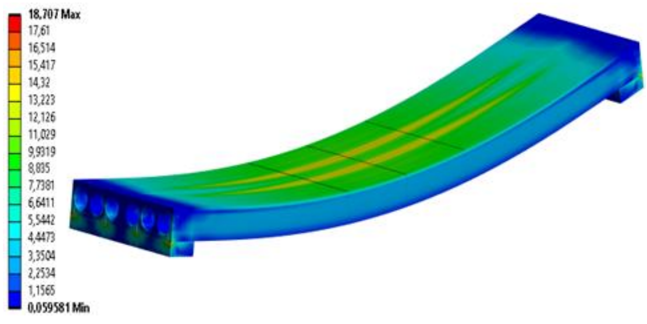


Figure 6 – The von Mises equivalent stress in concrete during the fire and mechanical stress for 2450 s

The stress-strain state of the studied structure was obtained based on the thermal and mechanical loading results applied to the reinforced concrete hollow core slab. Thus, the maximum deflection was 13.9 cm, and it was shown that the most significant number of finite elements was removed in the slab zone where the most considerable bending moment occurs (Figure 7).

Thus, the finite elements of the concrete matrix that have received such a plastic deformation value will be close to destruction and are removed from the model of a reinforced concrete hollow core slab.

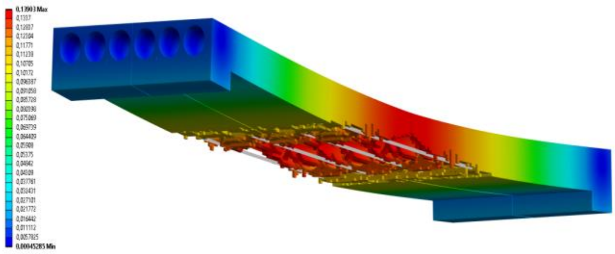


Figure 7 – Visualization of the result of thermal and mechanical calculation of a reinforced concrete hollow core slab for 2450 s

Plastic deformations that occur in concrete at 2450 s of the study reinforced concrete hollow slab during the stress-strain state without introducing the criterion of concrete destruction at the acquisition of plastic deformations, under thermal and mechanical effects, in the value of $2.5\cdot10^{-3}$ are shown in Figure 8.

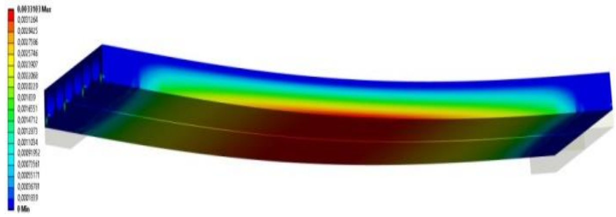


Figure 8 – Plastic deformations in concrete at 2450 s of a reinforced concrete hollow slab during the stress-strain state without introducing the criterion of concrete destruction

The onset of the boundary state in terms of loss of bearing capacity of the studied structure can be identified when the deflection or strain growth rate of the studied reinforced concrete hollow core slab:

$$f = l^2 / (400\cdot h); \quad (1)$$

$$dt = l^2 / (9000\cdot h); \quad (2)$$

where l – slab span, mm; h – cross-section height, mm.

The evaluated values are $f = 36.92$ cm and $dt = 16.4$ mm/min.

Remarkably, the distribution of the von Mises equivalent stresses formed in concrete during the fire and mechanical loads during 2450 s are observed along the central part of the structure. This can be explained by the fact that under the influence of the standard fire temperature mode, the transverse expansion of the concrete in the studied reinforced concrete slab occurs. This leads to stretching the lower and upper layers in this direction. The boundary state for the loss of thermal insulation capacity at 2450 s was not recorded. The maximum temperature on the side of the unheated surface did not exceed about 101 °C (Figure 9).

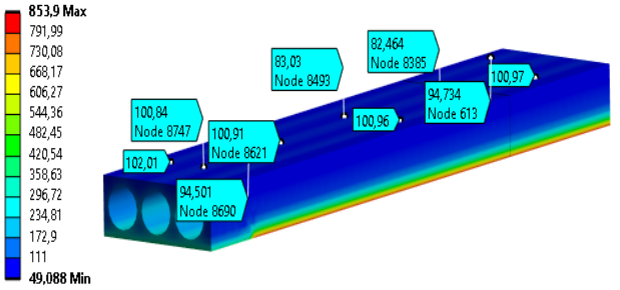


Figure 9 – Temperature distribution on the unheated surface of a hollow core reinforced concrete slab based on the results of thermal exposure at a standard fire temperature mode for 2450 s

According to the results of a calculation experiment to assess the fire resistance of a hollow core reinforced concrete slab without introducing the criterion of concrete destruction when plastic deformations occur, under thermal and mechanical effects, at a value of $2.5 \cdot 10^{-3}$, it was found that the onset of the boundary state with a loss of bearing capacity was observed at 3128 s (Figure 10).

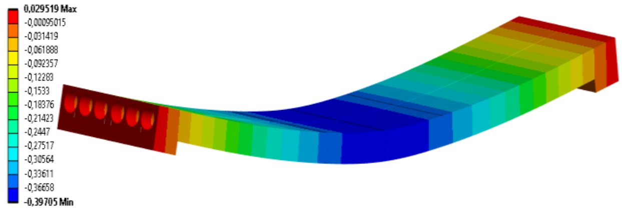


Figure 10 – The critical deflection of a reinforced concrete hollow core slab based on the results of exposure to a standard fire temperature mode for 3128 s

Thus, the value of the critical deflection of the reinforced concrete hollow core slab is 37.05 cm. It occurs later than the calculation experiment is stopped due to the acquisition of plastic deformations of many concrete matrix finite elements and their subsequent removal.

5 Discussion

The developed approach makes it possible to consider the processes of destruction of reinforced concrete hollow slabs under the influence of the standard fire temperature mode to the appearance of plastic deformations in concrete when evaluating fire resistance.

However, the proposed method does not allow determining the onset of the threshold state in terms of loss of entirety since it is necessary to determine the size of corresponding cracks.

The proposed method determines the reinforced concrete hollow slab destruction during fire resistance. That is, at which point the protective layer of the working rods of the reinforcement is destroyed, thus manifesting a significant deterioration of the mechanical properties of the reinforcement.

The obtained results indicate that the onset of the boundary state for loss of entirety occurs earlier than for loss of bearing capacity by 678 s. This poses a threat to human life and health before critical deflection occurs due to the penetration of smoke, toxic combustion products, and temperature through the cracks in the structure.

Thus, the fire resistance limit of the tested reinforced concrete hollow core slab is 40.83 minutes and does not correspond to the fire resistance class REI 45.

6 Conclusions

The following findings were performed to achieve the objective of the study. Firstly, in order to reduce the number of finite elements for a rational calculation of the fire resistance assessment of a reinforced concrete hollow core slab, a geometric model of 1/4 of this structure was built with the subsequent possibility of visualizing the studied structure in full scale when obtaining the calculation results.

Secondly, in the calculation module Transient Thermal ANSYS Workbench for calculating the temperature distribution over a reinforced concrete hollow core slab, a finite element mesh was built using the imported geometric model 1/4 of this structure, using finite elements of types SOLID186, CONTAL174, SURF154, and REINF264. In order to reproduce the results of the calculation experiment in the studied structure at full scale, symmetry was applied.

Also, the temperature distribution over the reinforced concrete hollow core slab under the standard fire temperature mode was determined for 3600 s by applying boundary conditions according to international and European standards.

Moreover, the obtained results of the thermal calculation of 1/4 of the reinforced concrete hollow core slab under the influence of the standard fire temperature mode for 3600 s were imported into the calculation module Transient Structural ANSYS Workbench to study the stress-strain state under thermal and mechanical loading.

Finally, a uniformly distributed load of 4 kPa was gradually applied to the unheated upper surface of 1/4 of the reinforced concrete hollow core slab in three steps before exposure to the standard fire temperature mode. The structure was fixed in a hinged manner, and the direction of gravity was set to 3600 s throughout the experiment.

Thus, the work’s objective was achieved based on the calculation experiments’ results. A methodology for calculating the destruction of a reinforced concrete hollow core slab while assessing its fire resistance was developed as a scientific basis for determining the onset of the boundary state of loss of entirety. The developed methodology allows a more reliable assessment of the fire resistance of these structures.

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