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The research of carrying capacity of reinforced concrete walls under uneven warming

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Abstract. The purpose of this article was to determine the dependence of the values of the boundary of the fire resistance of the bearing walls on the temperature dispersion on their heating surfaces as a scientific basis for improving the efficiency of the evaluation of the results of fire tests. In this paper, the problem of strength was determined to determine the bearing capacity of a reinforced concrete wall in a fire. During work, computational experiments using CFD and the finite element method were used. As a result of the studies, the dependence of the design values of the fire resistance of the reinforced concrete wall on the value of the maximum temperature dispersion on the heating surface of the structure during the fire tests and the error of the definition of the fire resistance limit was obtained, as well as the recommendations for creating new and improving existing furnace chambers from the tests on the fire resistance of the vertical reinforced concrete building constructions.

1. Problem statement

In the conditions of fire, the violation of the general stability of the building is always due to the destruction of individual elements in the frame of the structure. Therefore, one of the important aspects of fire safety in our time is the use of structures with a guaranteed limit of fire resistance.

To determine the limits of fire resistance, the most common is the test method in special fire test furnaces. However, the fire tests and parameters of modern test facilities are far from perfect because there are errors due to the fact that the control of the fuel system and the configuration of the furnaces do not ensure full compliance of the experimental conditions with the requirements of the standards in this field.

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2. Analysis of recent achievements and publications

There are some specific requirements for the firing furnaces, namely that the heating torch must be created with the use of liquid fuel, the flame of the torch should not touch the surfaces of the elements of the structures being heated, the volume of the heating chamber must be uniformly distributed and the temperature throughout the test in the volume of the heating chamber must vary according to the temperature of the fire defined in the standard [1]. Due to the fact that the control of the fuel system can not ensure full compliance with the heating mode of the furnace chamber to the standard temperature of the fire, there is some error in the implementation of the heating mode of the element [2, 3]. For example, in [4] eighteen large-scale slender reinforced concrete walls were tested under standard fire conditions. The test conditions included different height-to-thickness ratios, reinforcement covers, concrete strengths and mixture proportions, and varying levels of eccentric inplane load. The paper [5] summarizes research on the out-of-plane behaviour of unreinforced masonry bearing walls in buildings subjected to earthquake motions. Methods for predicting the ultimate strength of concrete bearing walls are briefly reviewed and compared described in the work [6]. The results of full-scale fire experiments on load-bearing cold-formed steel walls lined with different panels were shown in the work [7]. The paper [8] presents the effect of various factors on the fire resistance of load-bearing, gypsum board protected, steel stud wall assemblies. A detailed experimental study was conducted to evaluate the fire resistance of 14 full-scale steel stud wall assemblies.

In a previous work [9], a thermal engineering problem was solved to determine the non-uniformity of the temperature distribution on the surface of a reinforced concrete load-bearing wall when tested for fire resistance in special fire installations. The results of the calculations were used as input to solve the load-bearing wall problem. The standard [10] used to select the thermophysical characteristics of materials and the necessary coefficients.

3. Purpose

The main purpose of this article is to solve the problem of durability in determining the load-bearing capacity of reinforced concrete walls in fire conditions and, as a result, to determine the dependence of the limits of fire resistance of load-bearing walls on the dispersion of temperatures on their heating surfaces as a scientific basis for improving the efficiency of evaluating the results of such tests.

4. Method

Theoretical studies were carried out on the basis of systems of differential equations of continuous media of the type of Navier-Stokes equations and Fourier thermal conductivity equations. To solve the equations in the work, the method of finite or boundary elements, non-relation methods, Galerkin method, and optimization methods are used [10]. Computational experiments were carried out in the ANSYS CFX.

5. Consideration on methods and results

Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

Using previous studies [3-9], preconditions were created for the formulation of the strength problem with the following provisions.

1. The system of stress-state equations of a solid is used for the calculation.
2. The properties of the material depend on the current deformation and temperature nonlinearly, and large deformations of structural elements that correlate with their size are also allowed.
3. To determine the temperature influence temperature distributions resulting from pre-solved problem of heating temperature curve for a standard fire is used.
4. The system of equations is solved numerically by the finite element method in combination with the Newton-Raphson method, by incrementally adding an active mechanical load at the initial stage and incrementally adding temperature loads at the final stage with an interval of 1 min.

5. For simulation of the stress-strain state of reinforced concrete in a fire, complete deformation diagrams are used for concrete and reinforcement with the descending branch.

6. The work of the damaged element and the conditions of its damage are determined by the relevant theory of concrete strength.

7. The criterion for the global destruction of an element of a reinforced concrete structure is:

- the appearance of inevitability of the computational process due to the violation of the geometric immutability of the system;
- achieving of critical plastic deformations in the finite elements of the model;
- achieving of critical magnitudes of global displacements of points of elements of reinforced concrete structures.
- achieving critical values of the rate of increase of global displacements of points of elements of reinforced concrete structures.

The temperature dependences of deformation of thermal expansion of concrete and reinforcing steel according to the recommendations of the standard were used for the calculation [2].

In order to solve the durability problem, a finite element (FE) scheme was created, which is shown in Fig. 1.

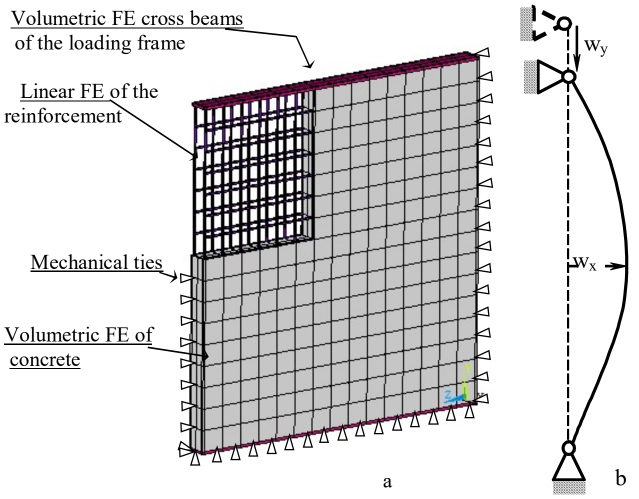

Figure 1. Finite element scheme of reinforced concrete walls and mechanical ties superimposed on its components (a) and design scheme of wall fixing (b).

Fig. 2 shows the graphs obtained for the corresponding modifications of the furnace using the results of computer simulation.

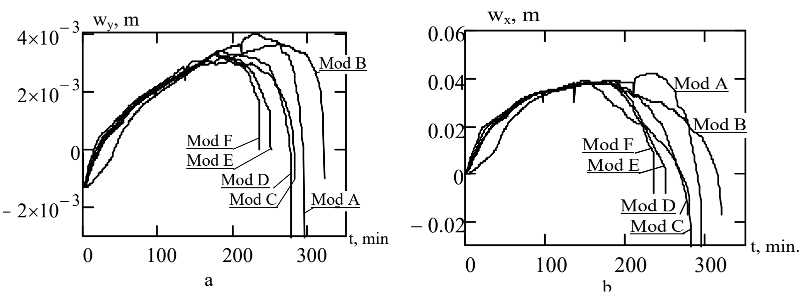

Figure 2. Graphs of maximum longitudinal movement (a) and maximum deflection (b) a reinforced concrete wall, tested in furnaces with different configurations.

Based on the data obtained in Fig. 2, the limits of fire resistance of the investigated wall under conditions of fire tests in furnaces with various modifications were determined. The algorithm described in this paper was used. The data obtained concerning fire resistance are summarized in Table. 1.

Table1. Limits of fire resistance of reinforced concrete wall tested in furnaces with different modifications.

Modification of the Furnace	Temperature Dispersion, S^2, ºC^2	Limit of Fire Resistance, R, min
Mod A	586.59	281
Mod B	803.557	301
Mod C	512.475	277
Mod D	406.164	271
Mod E	238.902	248
Mod F	205.295	235

According to the table 1, graphs of the calculated values of the limit of fire resistance of the reinforced concrete plate from the value of the maximum temperature dispersion on the heating surface of the reinforced concrete wall during fire tests and the error of determining the limit of fire resistance relative to its smallest value were created. These graphs are shown in Fig. 3.

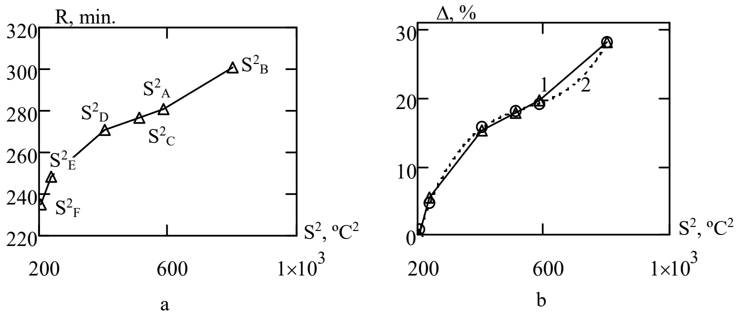

Figure 3. Dependence of calculated values of the limit of fire resistance of reinforced concrete wall on the value of maximum temperature variance on the heating surface of the structure during fire tests (a) and error of determination of the limit of fire resistance (b) (1 - obtained as a result of numerical experiment, 2 - regression dependence).

According to the graphs, the regression dependence of the limit of fire resistance of a reinforced concrete wall on the dispersion of temperatures on their heating surfaces is constructed, as well as the error of determination of the limit of fire resistance, expressed by the formula:

$$\Delta(S^2) = -42.586 + 0.307 \cdot S^2 - 5.355 \cdot 10^{-4} \cdot (S^2)^2 + 3.276 \cdot 10^{-7} \cdot (S^2)^3 \quad (3)$$

Conducted studies to identify the dependence of the limit of fire resistance of reinforced concrete wall on the dispersion of temperatures on their heating surfaces made it possible to formulate generalized recommendations for the design of new and improving the parameters of existing vertical building structures in order to achieve uniformity of the temperature field on the heating surfaces of the structures in the furnace chamber and, as a consequence, to increase the efficiency of fire resistance tests by ensuring a greater uniformity of heat flow:

1. As a basis for the construction of the installation, there must be used a furnace which geometric shape, the dimensions and construction must allow the test of samples of various building structures, in particular with fire protection elements, while ensuring the uniformity of heat flow.

2. There must be at least two openings for the combustion products to be placed symmetrically and dispersed from the center of the furnace.

3. The height of the furnace should provide the required minimum volume for the circulation of the combustion products, and thus, uniform heating of the surface of the structure.

4. The burners should be located no closer than 0.8 m from the surface of the test structure.

5. The number of temperature control devices in the furnace chamber (thermocouple) shall depend on the geometric dimensions of the furnace (one thermocouple per 1 $м^2$ of the heating surface of the analyzed building structure), but not less than five [9].

6. The value of the dispersion of temperatures over the heated surface of a reinforced concrete structure shall not exceed the critical value – 600 °C [3].

7. Fuel system management and test results must be organized with the help of computers.

6. Conclusions

1. Computational experiments to calculate the dependence of the limit of fire resistance on the maximum temperature variance over the heating surface of a vertical building structure were carried out during the tests.

2. The dependence of the values of the fire resistance of vertical reinforced concrete structures on the variance of temperatures on their heating surfaces, as well as the errors of determining the limit of fire resistance, described by the formula were obtained (3).

3. The obtained results make it possible to substantiate the parameters of the fire furnace for determining the fire resistance of vertical reinforced concrete structures, which take into account the detected dependences of the temperature dispersion on the heating surface, which will allow to increase the reproducibility of the results of such tests.

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