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REFINING A TABULAR METHOD FOR ASSESSING THE FIRE RESISTANCE OF REINFORCED CONCRETE STRUCTURES

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This paper reports the analysis of fire resistance assessment methods of building structures. Based on the results, it was established that conducting fire tests is not expedient and harmful to the environment. The use of estimation fire resistance assessment methods for reinforced concrete staircases is not considered possible due to the lack of appropriate tables with fire resistance classes for the tabular method. The use of the estimation zone method is also impossible because of the lack of temperature nomograms of temperature distribution during exposure to the standard fire temperature regime. There are also no described procedures for applying the estimation refined method for reinforced concrete staircases. So, using mathematical models, the existing type of reinforced concrete staircase was reproduced. Employing the finite-element method, the behavior of reinforced concrete stairwells under the influence of fire was investigated.

Based on the results of these experiments, it was analyzed which structural geometric parameters of reinforced concrete stairwells have the greatest influence on their fire resistance. In this way, three independent, most significant geometric parameters of reinforced concrete stairwells were established – the height of the solid base, the thickness of the protective layer of the lower row of reinforcing bars, and the length of the span.

Therefore, the ranges of the most significant structural geometric parameters of reinforced concrete stairwells were used to build a regression dependence of the fire resistance limit on these parameters in order to design a full factorial numerical experiment.

After proving the adequacy of the results obtained according to the regression dependence, tables were constructed with the geometric parameters of reinforced concrete stairwells to determine the compliance of these structures with the required fire resistance class. The use of these tables will make it possible to reduce the risks of threats to human life and health during a fire by determining the possibility of using these structures with a guaranteed fire resistance class during design

Keywords: stairwell flight, fire, tabular method, refined method, fire tests

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1. Introduction

One of the main tasks in ensuring fire safety is to minimize the risk to human life and health during evacuation from a building in case of fire. The occurrence of dangerous fire factors complicates not only the organization of evacuation measures but also the possibility of effective actions by emergency and rescue units during the elimination of fires [1]. Accordingly, the load-bearing capacity of load-carrying building structures is an extremely important property for responsible structural elements, including in the event of a fire, maintaining their functions over the required time [2, 3].

In most residential, office, multi-story buildings with a mass presence of people, these structures are made of reinforced concrete due to the high fire resistance of this material. However, fire resistance depends not only on the material from which the structure is made but also on the geometric parameters of the section, as well as the load level.

The determination of the level of fire safety of building structures is predetermined by the fire resistance index, which is expressed in minutes from the beginning of thermal exposure under the standard fire temperature regime to the onset of one of the limit states of fire resistance [4, 5]. Accordingly, the indicator of the onset of the loss of bearing capacity under the influence of elevated temperatures from a fire directly concerns the responsible structural elements of buildings and structures, including a stairwell flight [6].

The Center for Fire Statistics of the International Association of Fire and Rescue Services, established in 1995, annually summarizes statistical data from 27–57 countries of the world, where more than 50 % of the world's population lives. In the analyzed countries [7], 3.1–4.5 million fires were registered annually, during which 24–62 thousand people died. In just 20 years, almost 1 million people became victims of 80 million fires in these countries.

The largest number of fires occurs in the USA, where 1.2–1.4 million fires are registered annually. Countries where the annual number of fires does not exceed 350,000 are followed by a large margin.

The destruction of facilities and structures built with the use of reinforced concrete structures during a fire occurs due to the action of open fire. The presence of flame and/or exposure to high temperatures causes rapid heating and, upon reaching a critical temperature, leads to the loss of the load-bearing capacity of the structure.

Most of the destruction of buildings and structures with reinforced concrete structures under fire conditions occurs as a result of the loss of bearing capacity. This is facilitated by violations of fire resistance standards, low level of technical condition of structures or buildings, unsatisfactory provision of fire safety and regulation of technological processes, exceeding the guaranteed service life of structures. The level of safety of the operation of buildings and structures is significantly reduced if the specified violations exist, and this, in turn, increases the danger to people.

Therefore, it is important to carry out research on the assessment of fire resistance of building structures.

2. Literature review and problem statement

Evaluation of fire resistance of building structures is possible in three main ways [8]. One of the most accurate techniques is considered to be conducting full-scale fire tests [9]. The highest accuracy according to this method is provided by the reproduction of the building in which it is necessary to determine the fire resistance indicators of a separate building structure, which makes it possible to take into account all the factors that affect the level of fire resistance of this structure. This is certainly the best method but during the tests, the environment is polluted, which threatens ecological safety, and the implementation of this method requires a colossal expenditure of money. Conducting experimental fire tests of samples of building structures also has a negative impact on the environment [10]. Obtaining reliable results using this procedure [11] is very difficult. This is due to the fact that in order to ensure the appropriate thermal effect according to the standard fire temperature regime [12], it is necessary to determine the optimal configuration of the furnace chamber. Accordingly, this requires additional design work and, accordingly, the construction of a special installation. The cost of using this method is also time-consuming and expensive.

A modern modeling approach provides an opportunity to obtain fire resistance indicators using an estimation method. The mechanism of application of estimation methods for assessing the fire resistance class of reinforced concrete structures is given in [13, 14]. However, according to [15], the use of a tabular method for checking the fire resistance class of reinforced concrete stairwells is not considered possible. The reason for this is the lack of appropriate tables with criteria for checking compliance with the required fire resistance classes for this type of building structures. A zone method is also impossible to apply [16] due to the lack of temperature curves for this type of section of reinforced concrete stairwells. For horizontal structures in Eurocode 2, only temperature curves of beams and slabs with a cross-section height of 200 mm only are available. This state of affairs significantly complicates the task of determining the fire resistance of reinforced concrete stairwells. Thus, one has to apply only the refined method of determining fire resistance indicators of reinforced concrete stairwell flights. The use of such an approach involves the use of powerful software packages, most of which are implemented through the finite-element method [17]. But the construction of mathematical models implies high requirements for the means of implementation of the calculation and the specialists who carry it out, large labor and time costs for the preparation of mathematical models and the implementation of the calculation, as well as high costs of software and hardware. In addition, there is no described procedure for using this approach.

Therefore, based on the results of the above review, it was established that conducting fire tests to assess the fire resistance of reinforced concrete stairwells pollutes the environment. In addition, additional work on the construction of special installations to ensure the standard fire temperature regime is required, which significantly complicates the assessment of the fire resistance of stairwells. Tabular data and temperature nomograms for the implementation of simplified methods do not exist, and the refined method requires high-performance and expensive software and hardware that can be used by specialists with the appropriate level of training. Thus, refining the tabular method of checking compliance with the required class of fire resistance of reinforced concrete structures will make it possible to evaluate the fire resistance of reinforced concrete stairwells.

3. The aim and objectives of the study

The purpose of this study is to improve the tabular method of assessing the fire resistance of reinforced concrete structures by constructing a table that allows establishing the minimum design parameters of reinforced concrete stairwells for assessing their fire resistance. This will make it possible to evaluate the fire resistance of reinforced concrete stairwells using a simplified method.

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

– to build a regression dependence of the fire resistance limit of reinforced concrete stairwells on the most significant structural geometric parameters of these structures;

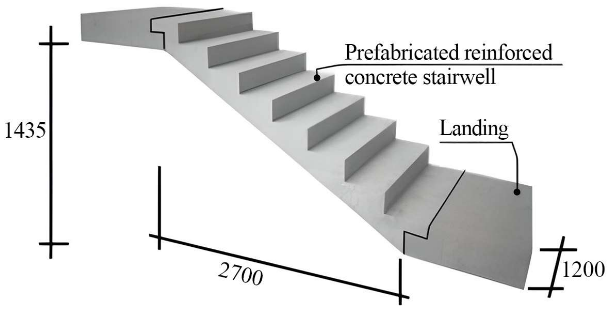
– to check the adequacy of the results of calculating the fire resistance limit of reinforced concrete stairwells, obtained by regression dependence, comparing with the fire resistance indicators of the given structures, which was obtained using the finite-element method;

– to determine the laws affecting the fire resistance of reinforced concrete stairwells, to devise a tabular method for evaluating the fire resistance of these structures in order to determine compliance with the established fire resistance class.

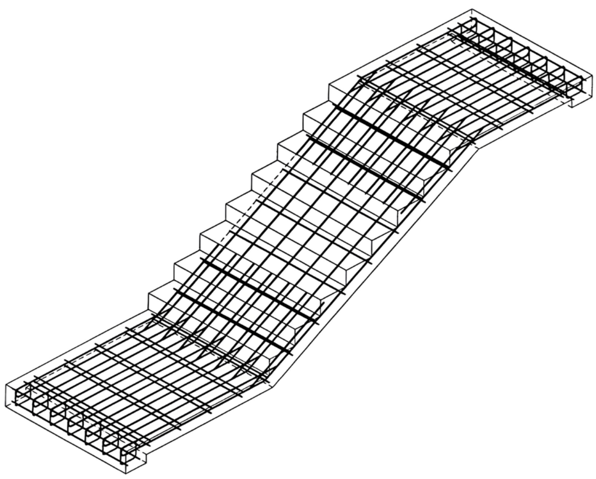
4. The study materials and methods

The object of our research is the behavior of reinforced concrete stairwells under the conditions of thermal influence of the standard fire temperature regime.

The structure of the prefabricated reinforced concrete staircase under study is made of C20/25 class concrete and with the use of A400C class rebar working rods with a diameter of 6 mm. Reinforcement of the studied reinforced concrete building structure was made with a mesh with a longitudinal step of 300 mm and a transverse step of 200 mm, respectively. The structural scheme of the prefabricated reinforced concrete stairwell and the scheme of its reinforcement are shown in Fig. 1 [18].



a



b

Fig. 1. The investigated reinforced concrete stairwell flight: *a* – structural scheme of the prefabricated reinforced concrete stairwell flight; *b* – scheme of its reinforcement

In [18], the behavior of this reinforced concrete stairwell flight under the influence of a standard temperature regime was studied using computational experiments employing the finit-element method and taking into account the nonlinear performance of materials.

Based on the results of those experiments, it was analyzed which structural geometric parameters of reinforced concrete stairwell flights had the greatest influence on their fire resistance. In this way, three independent, most significant geometric parameters of reinforced concrete stairwell flights were established – the height of the solid base of the stairwell flight, the thickness of the protective layer of the lower row of reinforcing bars, as well as the length of the flight of the stairwell flight. Table 1 gives the ranges of these parameters for their use in conducting a full factorial numerical experiment using regression dependence.

The loss of bearing capacity was considered as a criterion for the onset of the limit state. Under such conditions, the onset of other limit states for experimental reinforced concrete stairwell flights is not considered.

Table 1

Ranges of variation of the most significant structural geometric parameters of reinforced concrete stairwell flights depending on the fire resistance of these structures

The height of the solid base of the flight of stairs, mm			Thickness of the protective layer of the lower row of reinforcing rods, mm			The length of the flight of stairs, *L*, m		
Min, H_{-1}	Average, H_0	Max, H_1	Min, w_{-1}	Average, w_0	Max, w_1	Min, L_{-1}	Average, L_0	Max, L_1
100	200	300	10	20	30	1.5	3.75	6

5. Results of studying the stressed-strained state of a reinforced concrete stairwell flight under the influence of fire

5. 1. Construction of the regression dependence of the limit of fire resistance of reinforced concrete stairwell flights

The ranges of the most significant structural geometric parameters of reinforced concrete stairwell flights were used to compile a full factorial numerical experiment (Table 1).

Analysis of the curve of change in fire resistance of experimental reinforced concrete stairwell flights [18] in Fig. 2 [18] showed that it changes according to a law close to linear.

Thus, it is possible to assume that the specific regression dependence of the fire resistance limit on the limit state of the loss of bearing capacity will also have a linear character.

The selected structural geometric parameters as the most significant are independent by their nature.

Therefore, the mathematical model of the dependence of the fire resistance limit on the limit state of the loss of bearing capacity for reinforced concrete stairwell flights according to the proposed type of regression dependence, which has a linear form, and the selected most significant factors, takes the following form:

$$y=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_1x_2+ +b_5x_1x_3+b_6x_2x_3+b_7x_1x_2x_3, \quad (1)$$

where b_0–b_7 are coefficients of this regression dependence.

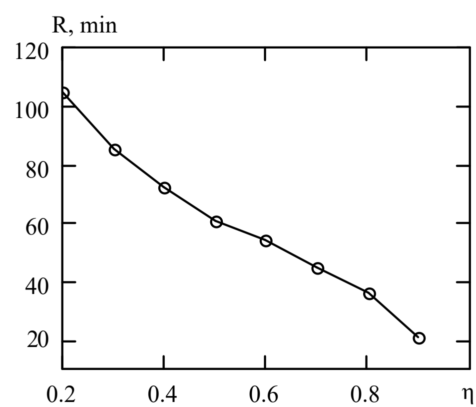


Fig. 2. Dependence of the fire resistance limit of a reinforced concrete stairwell flight on the level of its mechanical load

To calculate the regression coefficients, 8 numerical experiments were conducted according to the proposed matrix of the experimental plan, which is recorded in the form of Table 2, using parameters within the ranges of selected most significant parameters (Table 1).

Table 2

Matrix of the plan of the full factorial numerical experiment for the justification of the mathematical model

No.	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$
1	+	+	+	+	+	+	+
2	–	+	+	–	–	+	–
3	+	–	+	–	+	–	–
4	–	–	+	+	–	–	+
5	+	+	–	+	–	–	–
6	–	+	–	–	+	–	+
7	+	–	–	–	–	+	+
8	–	–	–	+	+	+	–

The results of calculations of the fire resistance limit of reinforced concrete stairwell flights, performed using the finite-element method, are given in Table 3.

Table 3

Results of calculating the fire resistance limit of reinforced concrete stairwell flights using the finite-element method

Experiment parameter set	1	2	3	4	5	6	7	8
The calculated value of the fire resistance limit of reinforced concrete stairwell flights in accordance with a set of significant parameters, y_i, min	102	74	52	38	144	121	109	66

Using the results given in Table 3, as well as the data of the matrix of the plan of the full factorial numerical experiment for substantiation of the mathematical model (Table 2), the coefficients of regression dependence were calculated according to the expressions:

$$b_0=\frac{1}{N}\sum_{i=1}^{N}y_i;\quad b_1=\frac{1}{N}\sum_{i=1}^{N}x_1y_i;\quad b_2=\frac{1}{N}\sum_{i=1}^{N}x_2y_i; \qquad (2)$$

$$b_3=\frac{1}{N}\sum_{i=1}^{N}x_3y_i;\quad b_4=\frac{1}{N}\sum_{i=1}^{N}x_1x_2y_i; \qquad (3)$$

$$b_5=\frac{1}{N}\sum_{i=1}^{N}x_1x_3y_i;\quad b_6=\frac{1}{N}\sum_{i=1}^{N}x_2x_3y_i;$$

$$b_7=\frac{1}{N}\sum_{i=1}^{N}x_1x_2x_3y_i, \qquad (4)$$

where N=8 is the number of sets of significant parameters according to the matrix of the experimental plan;

x_i is the value of the factor according to the matrix of the plan (Table 2);

y_i – the results of calculating the fire resistance limit of reinforced concrete stairwell flights in accordance with Table 3.

Using formulas (2) to (4), the regression coefficients given in Table 4 were calculated.

Thus, the constructed regression relationship establishes the regularity of the change in the fire resistance limit of reinforced concrete stairwell flights depending on the thickness of their solid base, the thickness of the protective layer of concrete, the length of the span, and takes the form:

$$y=8.5+0.352H+4.45w-1.667L-$$
$$-0.011Hw-0.038HL-0.4wL+0.002HwL, \qquad (5)$$

where H is the thickness of the solid base of the reinforced concrete stairwell flight (mm);

w – the thickness of the concrete protective layer of the reinforced concrete stairwell flight (mm);

L is the span length of the reinforced concrete stairwell flight (mm).

Corresponding response surfaces were constructed using the obtained regression dependence (Fig. 3).

Based on the results of the fire resistance assessment using the regression dependence of the fire resistance limit on the most significant structural geometric parameters (Table 1) of reinforced concrete stairwell flights, the corresponding dependence curves were constructed (Fig. 4). These curves provide an opportunity to study the influence of structural characteristics of reinforced concrete stairwell flights on their fire resistance limit.

For example, if it is necessary to ensure the fire resistance class R 60 for a reinforced concrete stairwell flight, the curves in Fig. 4, *a* are accepted. The minimum protective layer for a span of 6 m must be at least 25 mm while the height of the solid section of the base is at least 300 mm. The obtained data on the constructed dependences of the structural parameters allow the calculation of the minimum dimensions of the reinforced concrete stairwell flight to ensure the given level of fire resistance.

Table 4

Regression coefficients for describing the dependence of the fire resistance limit of reinforced concrete stairwell flights on experimental factors

Coefficient values	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7
Coded	88.25	13.5	22	–21.75	–0.75	–3	–0.5	4.25
Actual	8.5	0.352	4.45	–1.667	–0.011	–0.038	–0.4	0.002

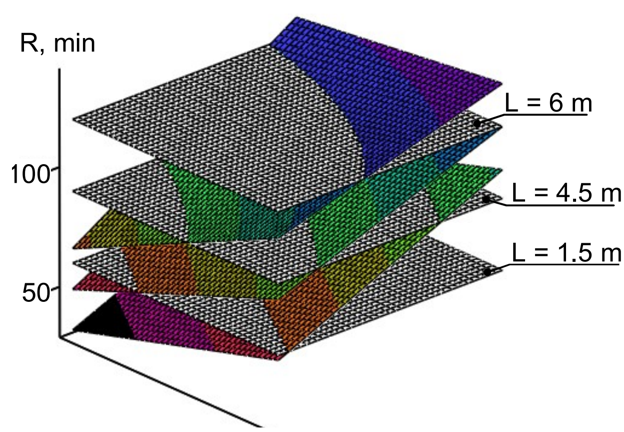
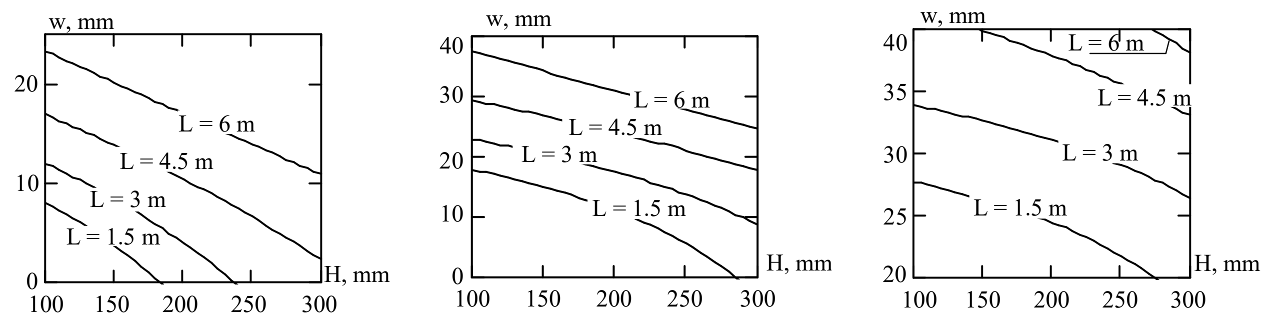


Fig. 3. Dependences of the fire resistance limit of reinforced concrete stairwell flights on their design parameters for different sizes of span length



a *b* *c*

Fig. 4. Dependences of the protective layer of concrete on the height of the solid part of the reinforced concrete stairwell flight to ensure the fire resistance limit: *a* – R 60; *b* – R 90; *c* – R 120

5. 2. Checking the adequacy of the results of calculating the fire resistance of reinforced concrete stairwell flights obtained by regression dependence

Checking the adequacy of the results of calculating the fire resistance limit of reinforced concrete stairwell flights according to the regression dependence was carried out by comparing the given results with the fire resistance indicators of the given structures, which was obtained using FEM [18]. Absolute deviation and relative deviation were used as criteria for the adequacy of the obtained results, calculated according to the regression dependence. The obtained data on the adequacy of the calculation results according to the regression dependence are given in Table 5.

Results of the adequacy analysis are given in Table 6; they indicate that the absolute deviation of the calculated estimate of fire resistance for reinforced concrete stairwell flights, calculated according to the regression dependence, does not exceed 10 min. Thus, this regression relationship can be applied to the design of flights to ensure the specified class of their fire resistance.

Table 6

Design parameters of reinforced concrete stairwell flights to ensure the required fire resistance class

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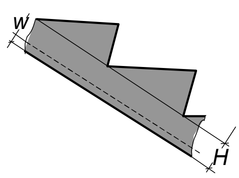
<tr><td colspan="2" rowspan="2">
</td><td rowspan="2">Conditions of use flight of stairs: height $H \geq 80$ mm; thickness t.p. $w \geq 10$ mm; area of additional reinforcement/total cross-sectional area $A_s/(A_c+A_s) \leq 5$ %</td><td colspan="7">Standard fire resistance limits</td></tr>
<tr><td>REI 30</td><td colspan="2">REI 60</td><td colspan="2">REI 90</td><td>REI 120</td><td>REI 180</td></tr>
<tr><td rowspan="2">1</td><td colspan="2">Minimum cross-sectional dimensions for span length $L \leq 2.5$ m</td><td>100</td><td>100</td><td>100</td><td>250</td><td>200</td><td>300</td><td>400</td></tr>
<tr><td colspan="2">Solid part height/protective layer thickness, H/w, (mm/mm)</td><td>10</td><td>10</td><td>20</td><td>10</td><td>30</td><td>25</td><td>60</td></tr>
<tr><td rowspan="2">2</td><td colspan="2">Minimum cross-sectional dimensions for span length $L \leq 4$ m</td><td>100</td><td>100</td><td>100</td><td>250</td><td>250</td><td>300</td><td>400</td></tr>
<tr><td colspan="2">Solid part height/protective layer thickness, H/w, (mm/mm)</td><td>10</td><td>15</td><td>25</td><td>20</td><td>35</td><td>30</td><td>65</td></tr>
<tr><td rowspan="4">3</td><td colspan="2" rowspan="2">Minimum cross-sectional dimensions for span length $L \leq 6$ m</td><td rowspan="2">100</td><td>100</td><td rowspan="2">300</td><td rowspan="2">350</td><td colspan="2" rowspan="2">400</td><td rowspan="2">–</td></tr>
<tr><td>200</td></tr>
<tr><td colspan="2" rowspan="2">Solid part height/protective layer thickness, H/w, (mm/mm)</td><td rowspan="2">10</td><td>20</td><td rowspan="2">40</td><td rowspan="2">40</td><td colspan="2" rowspan="2">60</td><td rowspan="2">–</td></tr>
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</table>

Table 5

The adequacy of results of the assessment of the fire resistance limit of a reinforced concrete stairwell flight, determined by regression dependence

Fire resistance limit calculated by FEM, min [19]	Fire resistance limit calculated by regression dependence, min	Absolute deviation, min	Relative deviation, %
Span length L=2 m, height of the solid part H=100 mm, thickness of the protective layer of concrete w=10 mm			
64	62.222	1.88	2.9
Span length L=4.5 m, height of the solid part H=100 mm, thickness of the protective layer of concrete w=10 mm			
51	43.333	7.667	14.5
Span length L=5.5 m, height of the solid part H=100 mm, thickness of the protective layer of concrete w=10 mm			
42	35.778	9.222	14.8
Average value			
–	–	6.256	10.733

5. 3. Construction of tabular data for evaluating the fire resistance of reinforced concrete stairwell flights

According to the results of a numerical full factorial experiment, using regression dependence, the minimum most significant geometric parameters of reinforced concrete stairwell flights were determined to ensure their compliance with the established fire resistance requirements. The obtained data are summarized in Table 6.

Table 6 makes it possible to evaluate the fire resistance of reinforced concrete stairwell flights according to the tabular method.

6. Discussion of results of the study of fire resistance assessment of a reinforced concrete stairwell flight

Using the most significant structural geometric parameters when assessing the fire resistance of reinforced concrete stairwell flights, the regression dependence of their fire resistance limits on these parameters was constructed (Table 1). According to the results, a numerical full factorial experiment was carried out, using the specified regression dependence to evaluate the fire resistance of structures under study.

Our regression dependence establishes the regularity of change in the fire resistance limit of reinforced concrete stairwell flights depending on the thickness of their solid base (H, mm), the thickness of the protective layer of concrete (w, mm), and the length of the span (L, m), takes the form (5).

The adequacy of the fire resistance values obtained by the regression dependence was checked and it was established that the absolute deviation was 6.256 min (Table 5), which is not significant. Thus, based on the results of calculations for assessing the fire resistance of reinforced concrete stairwell flights, a table was compiled to determine fire resistance classes depending on the most influential parameters of these structures (Table 6).

Determining the fire resistance of reinforced concrete stairwell flights by tabular and zonal methods is not considered possible [19, 20] since there are no corresponding tables and temperature nomograms of the temperature distribution across the section. The application of the refined method is also impossible because there is no fire resistance assessment procedure for these structures [19, 20]. Thus, the use of the proposed tabular data will allow determining the possibility of using reinforced concrete stairwell flights in accordance with the required class of fire resistance, during the design and construction works of buildings and structures.

However, the proposed method for assessing fire resistance takes into account a cross-section height of up to 300 mm and a span length of up to 6 m, which does not cover all possible options, but most structures of this type have geometric parameters within these limits. In addition, during the research, only the most influential parameters of the reinforced concrete stairwell flight were taken into account, which does not provide an opportunity to take into account all the criteria of these structures. Also, the limitation of using the proposed method is the case when higher-quality concrete and reinforcement will be used during manufacturing, which will accordingly increase the fire resistance of these structures.

The disadvantage of the devised tabular method for assessing reinforced concrete structures is that it does not take into account different levels of the applied load. Since the load level affects the fire resistance indicators, the lower the load, the better the fire resistance indicator. But this does not affect the guarantee of compliance with the required fire resistance class, due to the fact that the tabular data were obtained taking into account the maximum load level.

The next stage of research in this area may be the construction of a refined method for assessing the fire resistance of reinforced concrete stairwell flights, which could allow determining the fire resistance of any structures of this type, taking into account any material.

7. Conclusions

1. The regression dependence of the limit of fire resistance of reinforced concrete stairwell flights according to the limit state of loss of bearing capacity on the thickness of their solid base, the thickness of the protective layer of concrete, and the length of the span was built. Based on this equation, it was determined that the thickness of the concrete protective layer and the length of the span have the greatest and almost equal influence on the fire resistance limit. However, they have the opposite effect – when the thickness of the protective layer increases, the fire resistance limit increases, and when the length of the span increases, it decreases. This means that for further optimization at a given span length, the thickness of the protective layer must be increased.

2. According to the results of checking the adequacy of the results of calculating the fire resistance limit of reinforced concrete stairwell flights, which was obtained by regression dependence, it was established that the maximum absolute deviation from the results obtained when applying the refined method is 9.222 min.

3. The proposed table of structural parameters for reinforced concrete stairwell flights provides an opportunity to establish the minimum design parameters of these structures to determine compliance with the required fire resistance class, which improves the tabular method of assessing the fire resistance of reinforced concrete structures.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

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

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