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DETERMINATION OF FEATURES OF COMPOSITE STEEL AND CONCRETE SLAB BEHAVIOR UNDER FIRE CONDITION

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Methods for calculating the fire resistance of steel-reinforced concrete slabs made using profiled steel sheets under the influence of a standard temperature regime for more than 120 minutes are considered and analyzed.

Research has been carried out to determine the heating parameters and the stress-strain state of steel-reinforced concrete slabs made using profiled steel sheets under fire conditions for more than 120 minutes. The results of this study allow to obtain indicators of temperature distribution for assessing the fire resistance of such structures for fire resistance classes above REI 120. Accordingly, the results obtained are a scientific basis for improving the existing method for calculating the fire resistance of steel-reinforced concrete slabs made using profiled steel sheets.

The temperature distribution in the cross-section of structures was obtained using a general theoretical approach to solving the problem of heat conduction using the finite element method. Using the obtained temperature distributions, the parameters of the stress-strain state were determined based on the method of limiting states.

To carry out the calculations, appropriate mathematical models were created that describe the effect of the standard temperature regime of a fire, to determine the temperature distribution at every minute in the sections of steel-reinforced concrete slabs with profiled steel sheets. A method is proposed for dividing the section into zones to take into account the decrease in the indicators of the mechanical properties of concrete and steel.

A simplified method for the design assessment of steel-reinforced concrete slabs made using profiled steel sheets is proposed, which is consistent with the current EU standards and can be effectively used to analyze their fire resistance when establishing their compliance with the fire resistance class REI 120 and higher

Keywords: steel-reinforced concrete slabs, slab fire resistance, heat-insulating ability, stress-strain state, bearing capacity

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1. Introduction

The current state of the construction industry is characterized by the intensification of the development and implementation of innovative technical solutions in all areas of construction. However, despite the high level of construction technologies, fires at construction sites still pose a significant danger. The danger of fires at construction sites is characterized by the risk of the appearance and action of dangerous fire factors, with which it is associated and which directly relates to the possibility of destruction of building structures or their loss of their enclosing functions. In such conditions, the fire resistance of building structures plays an important role in the overall assessment of the fire safety of construction facilities. The main aspects of fire safety, to which fire resistance is directly related, include the safe evacuation of people, the relatively safe work of emergency rescue units, as well as the preservation of property and material values. Considering this, it can be said that the assessment of the fire resistance of building structures is an important component when conducting a fire safety analysis at any construction site.

Structures combining solid steel elements and reinforced concrete elements are widely used [1]. Among such structures, one can single out steel-reinforced concrete slabs formed using a steel profiled sheet as a one-piece formwork element and at the same time a reinforcing element. The work [2] is devoted to the main technological and structural aspects of steel-reinforced concrete slabs of this type, which reflects the main advantages of these structural elements. The advantages of steel-reinforced concrete slabs with profiled steel sheets according to the experience of their practical use are the best manufacturability during manufacture and installation. At the same time, these slabs, together with the frame of steel beams, form one strong system, reinforcing each other, which in turn gives an advantage in bearing capacity. Such systems have found their application in the buildings of trade, exhibition, sports, industrial and other facilities. Another significant advantage is the ability to regulate their rigidity and bearing capacity by varying the geometric parameters of the profiled sheet and the thickness of the concrete layer above it [2].

One of the important issues in the operation of buildings and structures is to ensure their fire safety. One of the important aspects of fire safety is the fire resistance of building structures, including steel-reinforced concrete slabs with profiled steel sheets. Like other building structures, fire resistance requirements for them are established by the standards.

The design of such slabs, the design of which must provide the necessary fire resistance, is carried out according to the recommendations given in the national norms of the states and, in particular, the current standards of Ukraine [3]. The necessary requirements for fire resistance establish the time that a particular structural element must withstand under the thermal effect of a fire until one of the limiting states occurs. With regard to the enclosing structures, they must also perform bearing functions, the boundary states are established by the loss of bearing capacity, integrity and thermal insulation capacity. The time before the onset of any limiting state describes the fire resistance limit of the structure [4]. The necessary fire resistance requirements for a particular building are established taking into account the degree of responsibility of buildings, the area and number of fire compartments, evacuation time and other factors. This algorithm is somewhat formalized, but this is the only approach that is used for practical use. This procedure is less laborious in comparison with the determination of the actual limit of fire resistance of building structures. The most versatile and comprehensive method for establishing fire resistance is the method of fire tests [5]. This method is applied without regard to the material of the structure and is universal for all types of structures and makes it possible to comprehensively establish the conditions for the occurrence of all three types of boundary states. However, this method has a number of disadvantages associated with labor intensity, cost and the impossibility of testing building structures with all types of limiting conditions that correspond to the structural schemes of buildings. In addition, the process of preparation, testing and disposal of samples and materials during testing is long in time and may also have environmental consequences [6].

Calculation methods for assessing the fire resistance of building structures are a reasonable alternative to experimental methods [7]. These methods are much less costly, laborious, more versatile, have a shorter duration and do not have a harmful effect on the environment [8]. At the same time, these methods make it possible to quite effectively obtain the result in the analysis after the onset of the limiting states of the loss of heat-insulating ability and loss of bearing capacity [9]. However, computational methods for analyzing the long-term effects of fire on structures in critical and multi-functional buildings are not presented. Considering that it is not always possible to use fire retardant systems to protect structures, since it is not advisable from the point of view of infrastructure configuration, planning and architectural solutions of objects, computational methods are constantly being improved [10]. For the analysis of the onset of loss of integrity, such methods are generally limited and insufficiently developed [11]. This largely applies to steel-reinforced concrete slabs with profiled steel sheets, the design of which determines that the profiled sheet is directly exposed to fire and this affects their bearing capacity in such conditions. In addition, the profiled steel sheet blocks the escape of water vapor from the concrete surface, which can create dangerous vapor pressure in the pores of the concrete. In this connection, the occurrence of destruction of the concrete surface and disruption of adhesion between it and the profiled sheet in the slab is possible.

Therefore, for the use of steel-reinforced concrete slabs with profiled steel sheets in fireproof floor structures with increased requirements for their fire resistance, it is relevant to study and develop simplified calculation methods for assessing their fire resistance.

2. Literature review and problem statement

Calculation methods for assessing fire resistance are currently well developed. Among the existing ones, two types of calculation methods can be distinguished – simplified [11] and refined methods [12]. Simplified methods are used at their core by simplifying hypotheses and assumptions that make it possible to obtain simple calculated ratios, but the results of such calculations have a significant margin [13], which implies the consumption of unnecessary material and economic irrationality [14]. The refined methods give the results more accurate in comparison with the simplified methods [15], but there is no single universal method for determining the fire resistance for steel-reinforced concrete slabs with profiled steel sheets. At the same time, the technique described in [16] makes it possible to calculate the maximum fire resistance class REI 120. The main provisions for the implementation of these methods for steel-reinforced concrete slabs with profiled steel sheets are given in the recommendations of European standards [16]. Traditionally, these methods are divided into two separate tasks – the thermal task and the strength task. To solve the heat problem, it is allowed to use the tables, nomograms and regression dependences presented in the recommendations. When solving the strength problem, tables, regression dependences or formulas based on hypotheses of the strength of materials, structural mechanics, deformation models of concrete, reinforced concrete and steel-reinforced concrete are also used. The main disadvantage of these methods is the established design data of structures, leading to large margins of fire resistance and in some cases this leads to unjustified consumption of materials and increased material costs [17]. With this in mind, these methods are mostly hierarchical. Accordingly, provided that the required fire resistance is not ensured as a result of the calculation using the simplest method, then it is possible to establish such a correspondence with the required fire resistance class using a more accurate simplified method. Based on the results of a positive conclusion, it can be recognized that the fire resistance of such a structure is ensured. With respect to steel-reinforced concrete slabs with profiled steel sheets, this approach cannot be used, since the recommendations offer only one calculation method. This method implies a separate analysis of the onset of the boundary states of thermal insulation capacity and integrity and a separate analysis of the onset of the boundary state of the loss of bearing capacity. When analyzing the problem of assessing fire resistance upon the onset of the state of loss of heat-insulating ability, the regression dependence of the time of the onset of this limiting state is used [19]. The regression dependence includes the geometric parameters of the section and the length of the slab. According to the logic of this approach, if the limiting state of loss of heat-insulating ability does not occur, then the limiting state of loss of integrity also does not occur, since it is believed that the onset of this state can occur only due to brittle fracture [20]. Under normal conditions, in the absence of moisture supersaturation in concrete, brittle fracture does not occur.

When analyzing the problem of the onset of the limiting state of the loss of bearing capacity, this method can be divided into the solution of the thermal problem and the problem of strength. It should be noted that in this case the thermal problem is solved only when determining the temperature of the reinforcement, the temperature of the steel profiled sheet and the points of passage of the critical temperature isotherm. Moreover, these characteristics are determined by regression relationships [21]. However, in this case, such dependences lead to a significant overestimation of the data on fire resistance. The regression dependences given in [22] do not allow them to be applied for the entire range of values from a number of fire resistance classes for critical buildings, such as high-rise buildings, underground garages and others.

According to certain parameters of the heating temperature of elements of steel-reinforced concrete slabs with profiled steel sheets, the coefficients of reducing the mechanical characteristics of their elements are determined. Using the boundary state method, the bearing capacity is determined in the form of the greatest bending moment of the slab section. The obtained value of the maximum bending moment is compared with the bending moment from the acting loads. Comparison of these values establishes the compliance of the studied steel-reinforced concrete slab with profiled steel sheets with the established requirements for its fire resistance. This method is very convenient, because with a small amount of simple algebraic calculations, it makes it possible to establish the correspondence of a steel-reinforced concrete slab with profiled steel sheets as a rather complex structure to the requirements for its fire resistance.

Among the disadvantages of this method, the following should be highlighted, in particular:

1. The use of this method in the analysis of fire resistance at the onset of the limiting state of the loss of bearing capacity is limited to 120 minutes of thermal effect of the standard temperature regime of the fire.
2. When using the definition of the fire resistance limit by the loss of heat-insulating ability, the possibility of using the proposed regression dependence remains uncertain.
3. Inability to correct the existing dependencies to take into account the required fire resistance with long time intervals for 120 minutes.

The indicated disadvantages represent a serious obstacle when using these slabs for multifunctional buildings of the 1st degree of fire resistance and the device of fire-prevention ceilings of the first type. Based on the results of the review, it was found that these structures demonstrate significant advantages in manufacturing and installation technology.

3. The aim and objectives of research

The aim of research is to establish the regularities of heating the main elements of steel-reinforced concrete slabs with profiled steel sheets when exposed to the thermal effect of a standard temperature regime of a fire for a long time of more than 120 minutes. This contributes to the assessment of the fire resistance limit of these slabs according to the condition of fire exposure up to 180 minutes. Thus, it is possible to determine the possibility of using these structures for multifunctional buildings of the 1st degree of fire resistance and the device of fireproof ceilings of the first type.

To achieve the aim, the following objectives were set:

– to investigate the nature of the time of the onset of the limiting state of thermal insulation capacity in steel-reinforced concrete slabs with profiled steel sheets using a simplified method;

– to calculate the temperature distributions in the sections under the thermal effect of the standard temperature regime of the fire according to the refined calculation method;

– to construct regression dependences for assessing the fire resistance of steel-reinforced concrete slabs with profiled steel sheets according to the limiting state of the loss of bearing capacity.

4. Materials and methods of research

According to the recommendations [21], the time before the onset of the limiting state of the thermal insulation capacity of elements of steel-reinforced concrete slabs with profiled steel sheets is determined by:

$$t_i = a_0 + a_1 \cdot h_1 + a_2 \times \Phi + a_3 \cdot \frac{A}{L_r} + a_4 \cdot \frac{1}{l_3} + a_5 \cdot \frac{A}{L_r} \cdot \frac{1}{l_3}. \qquad (1)$$

The parameters included in (1) are defined as:

– reduced edge thickness:

$$\frac{A}{L_r} = \frac{h_2 \times \left(\frac{l_1 + l_2}{2} \right)}{l_2 + 2\sqrt{h_2^{\,2} + \left(\frac{l_1 + l_2}{2} \right)}}; \qquad (2)$$

– configuration or shape factor Φ of the upper shelf:

$$\Phi = \frac{\sqrt{h_2^{\,2} + \left(l_3 + \frac{l_1 + l_2}{2} \right)^2} - \sqrt{h_2^{\,2} + \left(\frac{l_1 + l_2}{2} \right)^2}}{l_3}. \qquad (3)$$

The geometric parameters included in (1)–(3) are determined according to the design diagram of the steel-reinforced concrete slab (Fig. 1).

Regression coefficients (1) are determined from Table 1 in accordance with [13, 16, 21, 22].

To analyze the problem of the fire resistance of these slabs in terms of the loss of bearing capacity during a long time of exposure to fire, it is necessary to exclude slabs that do not provide adequate fire resistance in terms of their thermal insulation capacity in terms of standard sizes. Analysis of the effect of section sizes on fire resistance in terms of loss of heat-insulating ability shows that the most significant parameters are the width of the profiled sheet depression l_3, the depth of the depression h_2 and the slab thickness h_1.

To carry out the calculation, (1) was considered as a function of these parameters, the variation of which was in the ranges given in Table 2.

These ranges have been selected taking into account the most common standard sizes of profiled steel sheets.

Fig. 2 shows the surfaces built for these ranges, given in Table 2.

Analysis of the surfaces in Fig. 2 shows that a change in the width of the depressions of the profiled sheet l_3 and the depth of the depressions h_2 of the slabs under study does not lead to a significant change in their fire resistance limit with a heat-insulating ability. In addition, varying the slab thickness h$_1$ at its narrowest point has a more significant effect, therefore this parameter is more important. Fig. 3 shows the graphs of the dependences of the parameters on the depth of the depression h_2 and the slab thickness h_1 in its narrow place corresponding to a certain value of the fire resistance limit according to the limiting state of the loss of thermal insulation capacity.

Table 1

Regression coefficients for determining the fire resistance limit of steel-reinforced concrete slabs with profiled steel sheets by the limit state of loss of thermal insulation capacity

Regression coefficient	a_0, min	a_1, min/mm	a_2, min	a_3, min/m	a_4, min^2	a_5, min
Normal concrete	–28,8	1,55	–12,6	0,33	–735	48,0
Lightweight concrete	–79,2	2,18	–2,44	0,56	–542	52,3

Table 2

Ranges of variation of geometric parameters of steel-reinforced concrete slabs with profiled steel sheets

Depth of profiled sheet, l_3, mm	Depth of profiled sheet depression, h_2, mm	Slab thickness at the narrowest point h_1, mm
50	12÷120	50÷180
150	12÷120	50÷180
300	12÷120	50÷180

Thus, it can be concluded that a fire resistance class greater than EI 120 can be achieved if, on average, the thickness of the slab h1 at its narrowest point is ≥95 mm.

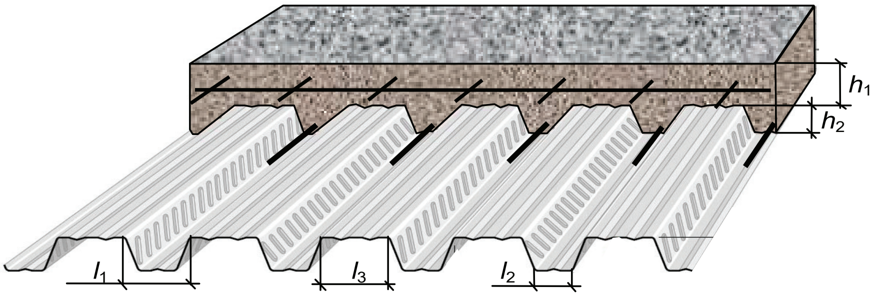


Fig. 1. Construction of a steel-reinforced concrete slab with profiled steel sheet

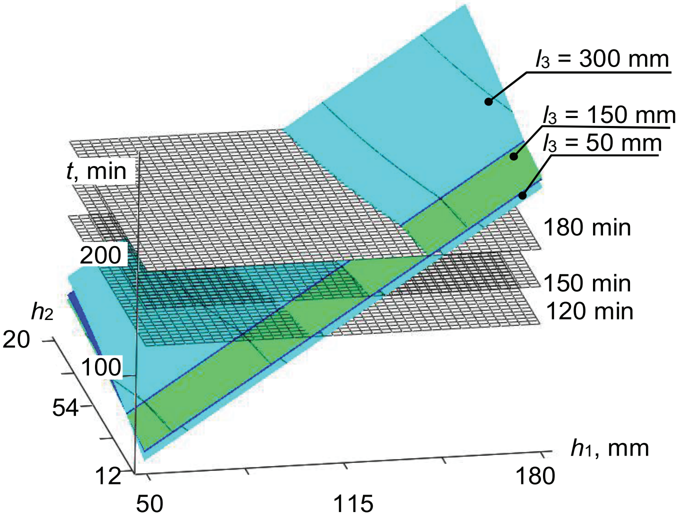


Fig. 2. Dependence of the fire resistance limit after the onset of the limiting state of loss of thermal insulation ability on the depth of the depression h_2 and the slab thickness h_1 at its narrowest point

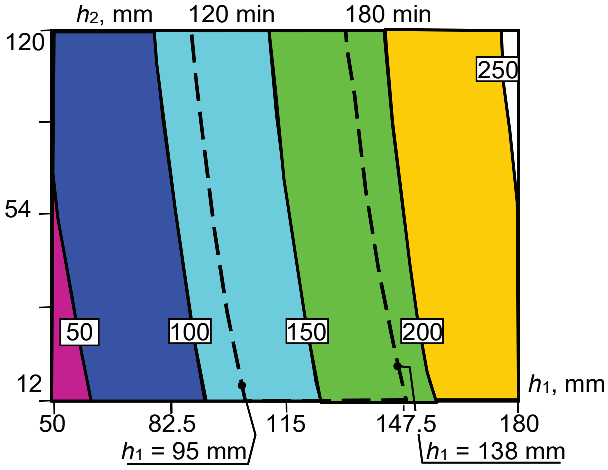


Fig. 3. The graphs of the dependences of the parameters on the depth of the depression h$_2$ and the slab thickness h$_1$ in its narrow place correspond to a certain value of the fire resistance limit according to the limiting state of the loss of thermal insulation capacity

To study the temperature distributions over the cross-section of steel-reinforced concrete slabs with profiled steel sheets, a generalized theoretical approach is applied based on a non-stationary differential equation of thermal conductivity [16]:

$$C_P(\theta)\rho\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left(\lambda(\theta)\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(\theta)\frac{\partial\theta}{\partial y}\right), \qquad (4)$$

where ρ=2500 kg/m^3 – concrete density; $C_P(\theta)$ – specific heat depending on temperature; $\lambda(\theta)$ – temperature-dependent thermal conductivity coefficient.

The formula expressing the BC of the III kind of a surface exposed to the thermal effect of a fire is as follows:

$$-\lambda(\theta)\frac{\partial\theta}{\partial r}\bigg|_{r=0}=\alpha_P(\theta_P-\theta_W), \qquad (5)$$

where θ_P, θ_W – respectively the temperature at which the thermal effect of the fire occurs, and the air temperature from the unheated side;

r – coordinate normal to the heating surface of the slab.

From the side of the slab where the surface is not heated, the formula for the BC of the III kind looks like this:

$$-\lambda(\theta)\left.\frac{\partial\theta}{\partial r}\right|_{r=b}=\alpha_n\left(20-\theta_n\right), \tag{6}$$

where α_P, α_n – respectively, the heat transfer coefficients from the side of the thermal effect of the fire and from the side of the slab, where the surface is not heated, b – coordinate of the slab surface in the normal direction to it, where there is no heating.

For the calculation, the temperature-dependent thermophysical characteristics recommended in [13, 16, 21, 22] are used, the graphs of which are shown in Fig. 4.

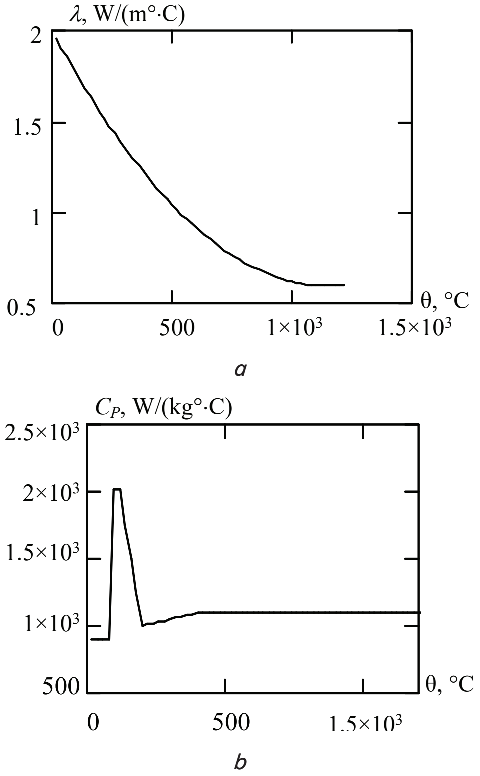


Fig. 4. Thermophysical characteristics of heavy concrete on granite aggregate: *a* – coefficient of thermal conductivity; *b* – specific heat

The finite difference method is used to approximate the heat conduction equation when determining temperature distributions. In this case, the right-hand side of equation (4) is written in the form [23]:

$$\frac{\partial}{\partial x}\left(\lambda(\theta)\frac{\partial\theta}{\partial x}\right)=a_x\theta^x_{i-1,k}-\left(a_x+b_x\right)\theta_{i,k}+b_x\theta^x_{i+1,k}, \tag{7}$$

$$\frac{\partial}{\partial y}\left(\lambda(\theta)\frac{\partial\theta}{\partial y}\right)=a_y\theta^y_{i-1,k}-\left(a_y+b_y\right)\theta_{i,k}+b_x\theta^y_{i+1,k}. \tag{8}$$

The left side of the heat equation (4), approximated by the finite difference method, has the form of the formula [23]:

$$C_P(\theta)\rho\frac{\partial\theta}{\partial t}=c\left(\frac{\theta_{i,k}+\theta_{i,k+1}}{2}\right)\cdot\frac{\theta_{i,k+1}-\theta_{i,k}}{\Delta t}. \tag{9}$$

The thermal conductivity coefficient at each integration step is determined by the formulas [23]:

$$a=\frac{\lambda(\theta_{i-1})\lambda(\theta_i)}{\left(\lambda(\theta_{i-1})+\lambda(\theta_i)\right)h^2},\quad b=\frac{\lambda(\theta_{i+1})\lambda(\theta_i)}{\left(\lambda(\theta_{i+1})+\lambda(\theta_i)\right)h^2}. \tag{10}$$

BCs of the III kind in the final differences from the heating side are written in the form [23]:

$$\frac{\lambda(\theta w_k)\lambda(\theta_{1,k})}{\lambda(\theta w_k)+\lambda(\theta_{1,k})}\cdot\frac{\theta w_k-\theta_{1,k}}{h}+$$
$$+\frac{h\cdot\rho\cdot C_P(\theta_{1,k})}{2\cdot\Delta t}\cdot\left(\theta_{1,k}-\theta_{1,k-1}\right)=$$
$$=\alpha_k\left(\theta_{1,k}-\theta_{p,k}\right)+\varepsilon\sigma\left(\left(\theta_{1,k}+273\right)^4-\left(\theta_{p,k}+273\right)^4\right), \tag{11}$$

where α_k=25 W/(m^2×°C) – the heat transfer coefficient during convection from the heating surface of the slab; h~0.02÷0.025 m – step of dividing the section; Δt=60 s – time step; ε=0.8 is the degree of emissivity of the surface of the profiled sheet; σ=5.67×10^{-8} W/(m^2 K^4) – Stefan-Boltzmann constant.

BCs of the III kind in the final differences from the unheated side are written in the form [23]:

$$\frac{\lambda(\theta w_k)\lambda(\theta_{1,k})}{\lambda(\theta w_k)+\lambda(\theta_{1,k})}\cdot\frac{\theta w_k-\theta_{1,k}}{h}+\frac{h\cdot\rho\cdot C\ (\theta_{1,}\ )}{2\cdot\Delta t}\times$$
$$\times\left(\theta_{1,k}-\theta_{1,k-1}\right)=\alpha_n\left(\theta_{1,k}-\theta_{p,k}\right), \tag{12}$$

where α_k=9 W(m^2×°C) is the heat transfer coefficient during convection from the unheated side.

The thermal effect of a fire is expressed in terms of a standard temperature regime corresponding to the formula:

$$\theta_p(t)=345\cdot\lg(8t/60+1)+\theta_0, \tag{13}$$

where θ_0=20 °C – the initial temperature of the environment and the inner layers of concrete before the start of the thermal effect of the fire.

To study the temperature distributions over the section, a boundary value problem was posed using the calculation scheme shown in Fig. 5.

The finite difference scheme of the slab is shown in Fig. 6.

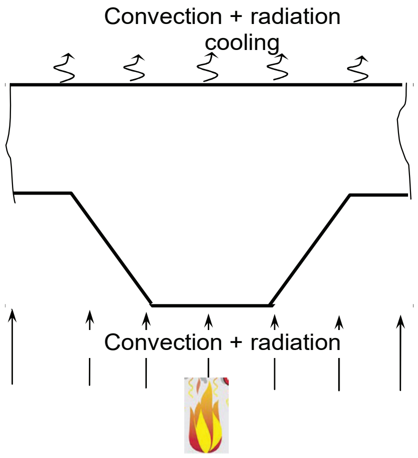


Fig. 5. Design scheme for the thermal design of a steel-reinforced concrete slab

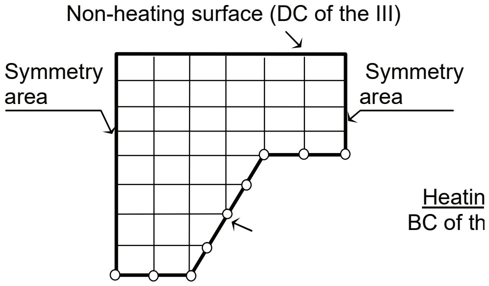


Fig. 6. Finite-difference scheme of cross-sections of a steel-reinforced concrete slab

The calculation schemes are presented in Fig. 5, 6 allow to set the boundary value problem of thermal conductivity and obtain the distribution of temperature fields of steel-reinforced concrete slabs using the method of end differences.

5. The results of the study of heating steel-reinforced concrete slabs with profiled steel sheets in a fire

5. 1. Investigation of the heat-insulated ability of a steel-reinforced concrete slab in case of fire

Using the mathematical models presented above, calculations were performed for 5 types of steel-reinforced concrete slabs with profiled steel sheets. These slabs differ in the type of profiled steel sheet and the thickness of the slab at the narrowest point. The main design parameters of the slabs under study are given in Table 3.

Calculations were made to determine the heating temperature of the bottom, top and side surfaces of the profiled sheet, as well as reinforcing bars.

As a result of the calculation, the temperature distributions in these slabs were obtained for the time of thermal effect of the standard temperature regime of the fire of 150 min and 180 min, shown in Fig. 7–9.

The obtained results of the temperature distribution over the structures under study show that the greatest onset of the limiting state of the loss of heat-insulating ability depends on the thickness of the steel-reinforced concrete slab in the narrowest place between the edges of the slab.

The analysis of the presented in Fig. 7–9 temperature distributions showed that the onset of the limiting state of loss of heat-insulated ability for more than 120 min of exposure to the standard temperature regime of a fire occurs only for the first two types of slabs in Fig. 7.

Table 3

Design parameters of steel-reinforced concrete slabs with profiled steel sheets.

Shelf height, h_1, mm	Edge height, h_2, mm	Large edge width, l_1, mm	Smaller edge width, l_2, mm	Shelf width between edges, l_3, mm
Steel-reinforced concrete slab No. 1 (Profiled sheet H57, axial distance from the reinforcement for the surface of 30 mm)				
90	57	143.5	93	44
Steel-reinforced concrete slab No. 2 (Profiled sheet H60, axial distance from reinforcement for a surface of 25 mm)				
115	60	161.2	122	50
Steel-reinforced concrete slab No. 3 (Profiled sheet H75, axial distance from reinforcement for a surface of 30 mm)				
135	75	137.5	92	50
Steel-reinforced concrete slab No. 4 (Profiled sheet H92, axial distance from reinforcement for a surface of 25 mm)				
158	92	265	140	40
Steel-reinforced concrete slab No. 5 (Profiled sheet H114, axial distance from reinforcement for a surface of 30 mm)				
180	114	152	104	48

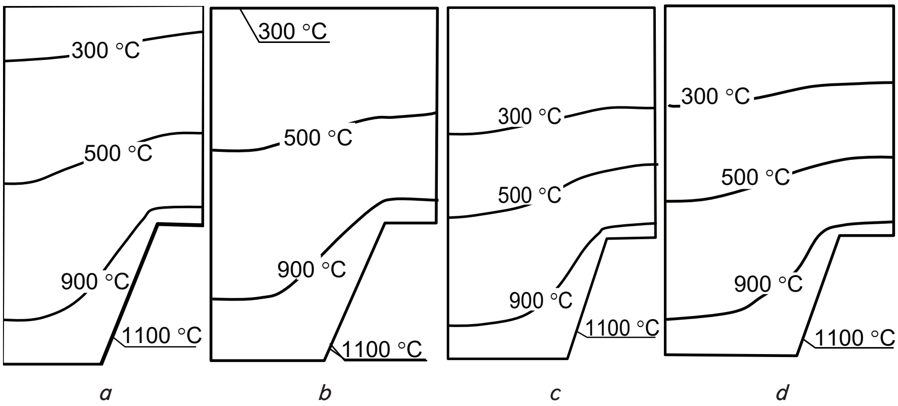


Fig. 7. Temperature distributions in the investigated slabs for the time of thermal effect of the standard temperature regime of a fire in steel-reinforced concrete slabs (SCS): *a* – SCS No. 1 150 min; *b* – SCS No. 1 180 min; *c* – SCS No. 2 150 min; *d* – SCS No. 2 180 min

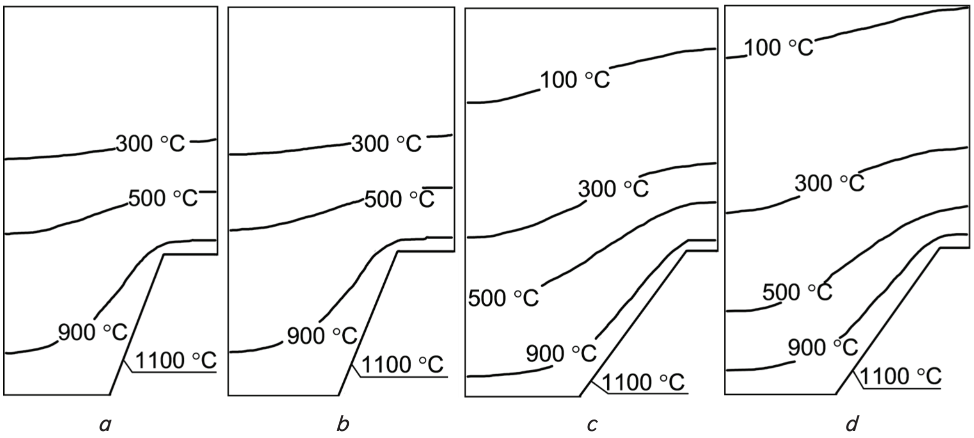
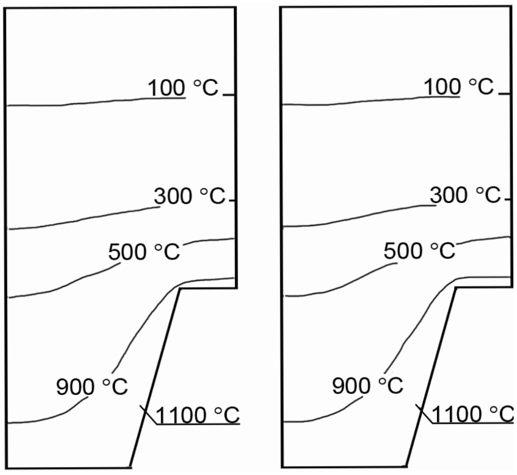


Fig. 8. Temperature distributions in the investigated slabs for the time of thermal effect of the standard temperature regime of a fire in steel-reinforced concrete slabs (SCS): *a* – SCS No. 3 150 min; *b* – SCS No. 3 180 min; *c* – SCS No. 4 150 min; *d* – SCS No. 4 180 min



a *b*

Fig. 9. Temperature distributions in the investigated slabs for the time of thermal effect of the standard temperature regime of a fire in steel-reinforced concrete slabs (SCS): *a* – SCS No. 5 150 min; *b* – SCS No. 5 180 min

5. 2. Study of temperature distributions in the cross-section of a steel-reinforced concrete slab under fire conditions

Based on the results obtained for the temperature distributions shown in Fig. 7–9, the average heating temperatures of the lower, upper and side surfaces of the profiled sheet were determined, as well as the values of the temperature of the reinforcing bars for the time of heat exposure of the standard temperature regime of the fire of 150 and 180 min, presented in Table 4.

Table 4

Temperature value of elements of steel-reinforced concrete slabs with profiled steel sheets

The time of the thermal effect of the fire, min	Lower shelf temperature, θ_l, °C	Side wall height, θ_w, °C	Top shelf temperature, θ_u, °C	Lower reinf. bar temperature θ_{sl}, °C	Upper reinf. bar temperature θ_{su}, °C
Steel-reinforced concrete slab No. 1 (Profiled sheet H57, axial distance from the reinforcement for the surface of 30 mm)					
150	1016	1008	1006	858.837	362.847
180	1114	1098	1094	904.566	420.268
Steel-reinforced concrete slab No. 2 (Profiled sheet H60, axial distance from reinforcement for a surface of 25 mm)					
150	1011	1004	1006	848.171	206.781
180	1109	1095	1096	888.581	259.514
Steel-reinforced concrete slab No. 3 (Profiled sheet H75, axial distance from reinforcement for a surface of 30 mm)					
150	1010	1003	1004	847.005	142.04
180	1108	1091	1094	886.579	175.508
Steel-reinforced concrete slab No. 4 (Profiled sheet H92, axial distance from reinforcement for a surface of 25 mm)					
150	1006	1002	1002	837.816	100.427
180	1105	1092	1092	874.197	116.32
Steel-reinforced concrete slab No. 5 (Profiled sheet H114, axial distance from reinforcement for a surface of 30 mm)					
150	1004	1005	1004	840.841	81.054
180	1102	1096	1089	879.252	95.803

5. 3. Construction of regression dependence for assessing the fire resistance of steel-reinforced concrete slabs

When determining the decrease in the parameters of the mechanical properties of concrete and steel, the temperature of the elements of the steel profiled sheet and reinforcement must be determined. The temperature values of the lower flange, wall and upper flange of a steel profiled sheet can be calculated according to [13, 16, 21, 22]:

$$\theta_a = b_0 + b_1 \cdot \frac{1}{l_3} + b_2 \cdot \frac{A}{L_r} + b_3 \cdot \Phi + b_4 \cdot \Phi^2. \qquad (14)$$

The temperature of the working valve is determined:

$$\theta_s = c_0 + c_1 \cdot \frac{u_3}{h_2} + c_2 \cdot z + c_3 \cdot \frac{A}{L_r} + c_4 \cdot \alpha + c_5 \frac{1}{l_3}. \qquad (15)$$

The parameters of the regression dependencies are determined from the Table 3 to the diagram shown in Fig. 10 and formulas (2), (3), (16).

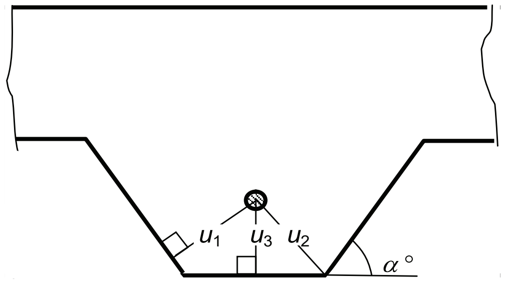


Fig. 10. Scheme for determining the geometric parameters of a steel-reinforced concrete slab when determining the temperatures of its steel elements by regression dependencies (the definition of the parameters above has been added)

The parameter *z* is determined by the formula [13, 16, 21, 22]:

$$z = \frac{\sqrt{u_1 \cdot u_2 \cdot u_3}}{\sqrt{u_1 u_2} + \sqrt{u_2 u_3} + \sqrt{u_1 u_3}}. \qquad (16)$$

data of the section of steel-reinforced concrete slabs, which are significant for determining the temperature indicators for the elements of the section.

Using the data of the geometric parameters listed in Table 3, the value of the temperatures obtained during the calculation and indicated in Table 4, as well as regression dependences (14), (15), their coefficients were obtained. Thus, the found coefficients were used to calculate the temperature of the elements of the steel profiled sheet and the reinforcement of steel-reinforced concrete slabs in the analysis of fire resistance according to the REI 150 and REI 180 classes. The obtained values for the regression dependence (14) are given in Table 5, and for regression dependence (15) are given in Table 6.

The obtained results of the temperature distribution over the slabs under study show that the greatest onset of the limiting state of the loss of heat-insulating ability depends on the thickness of the steel-reinforced concrete slab in the narrowest place between the edges of the slab.

Table 5

Regression coefficients for determining the temperature in the elements of a steel profiled sheet of steel-reinforced concrete slabs

Fire resistance class	Steel profiled sheet element	b_0, °C	b_1, °C×mm	b_2, °C×mm	b_3, °C	b_4, °C
REI 150	Lower shelf	940.338	1257.58	–1.002	191.711	–130.027
	Wall	1388.66	1236.71	–0.684	–844.651	450.557
	Top shelf	1281.58	62.073	–0.319	–609.989	342.772
REI 180	Lower shelf	1008.25	1295.26	–0.931	248.557	–158.9
	Wall	1930.95	1285.77	–0.686	–1893	1054.03
	Top shelf	962.362	–619.59	–0.043	291.282	–143.636

Table 6

Regression coefficients for determining the temperature in the elements of a steel profiled sheet of steel-reinforced concrete slabs

Fire resistance class	c_0, °C	c_1, °C	c_2, °C×mm^{0,5}	c_3, °C×mm	c_4, °C/°	c_5, °C×mm
REI 150	2.962	60.191	–159.842	56.147	0.688	2940.054
REI 180	3.181	88.139	–217.848	60.302	1.183	4992.853

The analysis of the presented in Fig. 7–9 temperature distributions showed that the onset of the limiting state of the loss of heat-insulated ability for more than 120 minutes of exposure to the standard temperature regime of a fire occurs only for the first two types of slabs.

6. Discussion of the research results of the thermal effect of fire on steel-reinforced concrete slabs with profiled steel sheets

The results of calculating the temperature distribution showed (Fig. 7–9) that for the first two types of slabs there is a state of loss of thermal insulation capacity, therefore, for these types of slabs (1) should be corrected. According to the results of the analysis of temperature distributions (Fig. 7–9), it can be seen that the temperature indicators of the shelves and walls of profiled steel sheets do not differ much, which makes it possible to obtain a correct regression dependence for determining their temperature. In general, it is noticeable that profiled sheets heat up more than 1000 °C under conditions of heat exposure for more than 120 minutes of fire. This means that with a simplified determination of the fire resistance of a slab, the presence of a steel sheet can be ignored and considered as a reinforced concrete structure. The reinforcing bar in the edge of the slab also heats up to a temperature of more than 800 °C. This condition leads to a significant decrease in the strength of the tensile reinforcement inside the slab. This increases the role for the load-bearing capacity of the slab in the event of a fire lasting more than 120 minutes top reinforcement. The obtained regression dependences make it possible to calculate steel-reinforced concrete slabs with profiled steel sheets for compliance with fire resistance classes REI 150 and REI 180. The use of this technique is limited only for steel-reinforced concrete slabs with profiled sheets, the edges of which are trapezoidal and taper downward. In the future, this technique can be expanded to use it in analyzing the fire resistance of steel-reinforced concrete slabs with steel profiled sheets with trapezoidal edges expanding downward.

7. Conclusions

1. The nature of the time of the onset of the limiting state of the thermal insulating ability in steel-reinforced concrete slabs with profiled steel sheets is investigated using a simplified method. Based on the results, it is determined that the slabs for which this boundary state does not occur for more than 120 minutes should have a thickness in the narrower place between the edges of more than 95 mm.

2. The calculation of the temperature distributions in the sections under the thermal effect of the standard temperature regime of the fire is carried out according to the refined calculation method. It is shown that for steel-reinforced concrete slabs with profiled steel sheets with a thickness of less than 120 mm in the narrowest place between the edges, when exposed to a fire for more than 150 minutes, a state of loss of heat-insulating ability can occur.

3. On the basis of the obtained regularities of the influence of the design parameters of the profiled steel sheet and the thickness of the slab in the narrowest place according to the heating temperature of the steel profile and working reinforcement, regression dependences are constructed. This regression analysis is used to assess the fire resistance of these slabs based on the limiting states of loss of bearing and thermal insulation capacity at the moments of exposure to a standard fire temperature of 150 and 180 minutes. All factors included in these regression dependencies are significant and these dependencies are ready to be used in practical calculations without adjusting the input variables, but taking them from the corresponding design documentation.

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