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Improvement of the Assessment Method for Fire Resistance of Steel Structures in the Temperature Regime of Fire under Realistic Conditions

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Abstract. There was researched the influence of fire temperature regimes, obtained by the proposed mathematical models, on the mechanical characteristics of metal structures. As a result, the identified patterns of the influence of the parameters of the premises with fires are shown as the slit coefficient decreases and the fire load density increases, the actual limit of fire resistance begins to decrease, as well as at values of fire load density less than 600 [MJ/m^2], there is an area where the occurrence of a boundary state is not observed and Nomograms for determining the limit of fire resistance for steel structures at standard values of critical temperature were constructed and an appropriate method was developed.

Introduction

Metal structures are often used in construction. This material is one of the most dangerous in case of fire, as it is able to melt under high temperatures. Often, fires on metal structures are accompanied by structure collapses; socioeconomic losses become the largest then. Therefore, maintaining a certain level of durability of buildings under fire is an important aspect of fire safety at any object.

Traditionally, the durability of buildings under fire is associated with fire resistance of building structures, which is subject to rigid regulation. In case of non-compliance with the requirements for building structures in the conditions of deficiency of their fire resistance, the preconditions are created for increasing the danger during evacuation of people, work of rescue teams, etc. This leads to grave consequences: human casualties and serious material loss. Therefore, ensuring that the fire resistance of metal building structures meets the requirements is a prerequisite for the fire safety of objects.

Analysis of Recent Achievements and Publications

There are many works on the behavior of metals at high temperatures. A general model, i.e. a nonlinear computer code, has been extensively used to determine the buckling load of axially loaded members, considering that the material model behaves at elevated temperatures according to the hypotheses of Eurocode 3 Part 1.2 [1], and the main results of this numerical investigation are summarised in [2]. Paper [3] includes some preliminary ideas to use the product models as a part of the fire safety concept for buildings in the future.

Article [4] was devoted to fireproof processing of steel structures. The main task was to consider different types of sections of rod elements and to choose the most effective section for a steel column from the point of view of fire protection.

Fire-resistant structures, fire-resistant insulations and a method for fire-proofing and fire-protection of permanent or temporary structures or objects were investigated in [5].

During study in work [6], 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.

In the research [7], a scientifically-substantiated sequence of procedures was created, with a detailed selection of equipment and test samples, in order to provide reliable experimental data when studying the temperature regime of a fire.

There are also other works by well-known researchers, but they do not reveal the regularities of influence of the parameters of the premises, in particular of the slit coefficient and the fire load density on the actual limit of fire resistance of metal structures.

Purpose

To investigate thermal effect of fire temperature regimes on mechanical characteristics of metal structures. To identify the regularities of influence of premises parameters: a slit coefficient, fire load density on the actual limit of fire resistance of such structures. To build nomograms for determining the limit of fire resistance for steel structures at standard values of critical temperature.

Consideration on Methods and Results

To calculate the fire resistance of steel structures, the heating temperature of these structural elements at any point of time of fire should be determined. To determine the heating temperature of unprotected steel structures, a basic method is used, based on applying the formula for determination of the temperature rise $\Delta\theta_{a,t}$ over the time interval Δt [1]:

$$\Delta\theta_{a,t} = k_{sh} \cdot \frac{A_m}{V c_a \rho_a} \cdot \dot{h}_{\text{net}} \Delta t, \qquad (1)$$

where k_{sh} — is a coefficient to account for the influence of the shadow effect;
A_m/V — cross-section coefficient for unprotected steel structures [1/m];
A_m — surface area of the structure per unit length [m^2/m];
V — volume of construction per unit length [m^3/m];
c_a — specific heating capacity of steel, [J / (kg · K)] is determined in tabl. 1 [1];
$\dot{h}_{\text{net}}$ — the calculated value of the resultant specific heat flux per area unit [W/m^2];
Δt — time interval [c];
ρ_a — steel density, [kg / m^3] is determined in tab. 1 [1].

Table 1. Thermophysical characteristics of building materials

Coefficient of thermal conductivity, $\lambda(\theta)$, [W/(m·°C)]	Volume of heating capacity, $c_p(\theta)\cdot\rho$, [J/(m^3·°C)]	Density, [kg/m^3]
Steel DSTU-N B EN 1993-1-2:2012 Eurocode 3 [1]		
$54 - 3{,}33\cdot10^{-2}\theta$ with 20 [°C] ≤ θ ≤ 800 [°C], 27,3 with θ > 800 [°C].	$425+0{,}773\theta - 1{,}69\ 10^{-2}\theta^2+2{,}22\ 10^{-6}\theta^3$ with 20 [°C] ≤ θ ≤ 600 [°C], 666–13002/(θ-738) with 600 [°C]< θ≤ 735 [°C], 545+17820/(θ-731) with 735 [°C]<θ≤ 900 [°C], 650 with 900 [°C] < θ≤ 1200 [°C]	7850

The calculated value of the resultant specific heat flux per unit area is determined by the formula [1]:

$$\dot{h}_{\mathrm{net},c} = \alpha_c \cdot (\theta_g - \theta_m), \qquad (2)$$

where $\dot{h}_{\mathrm{net},c}$ – is the resultant specific heat flux by convection;
$\dot{h}_{\mathrm{net},r}$ – resultant specific heat flux by thermal radiation.

The resultant specific heat flux by convection, [W·M^{-2}], which is determined by the formula [1,8]:

$$\dot{h}_{\mathrm{net},c} = \alpha_c \cdot (\theta_g - \theta_m), \qquad (3)$$

where α_c = 25 – heat transfer by convection, [W·M^{-2}·K^{-1}];
θ_g – temperature near the structure, [°C];
θ_m – surface temperature of the structure, [°C].
The resultant specific heat flux by radiation, [W·M^{-2}], which is determined by the formula [1, 6]:

$$\dot{h}_{\mathrm{net},r} = F \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot ((\theta_g + 273)4 - (\theta_m + 273)4), \qquad (4)$$

where F = 1 – angular coefficient of irradiation;
ε_m – the degree of blackness of the structure surface;
ε_f = 1 – the degree of blackness of the fire flame;
$\sigma = 5{,}67 \cdot 10^{-8}$ [W·m^{-2}·K^{-4}] — the Stefan-Boltzmann constant.

After applying this mathematical tool, there were determined heating temperature regimes for the elements of steel structures for different values of the cross-section coefficient and the critical heating temperature, according to the standard [1]. The fig. 1 shows the heating regimes of the steel structure element with a cross-sectional coefficient A_m/V = 70 [m^{-1}] 1 in conditions of different parameters of the premises under fire.

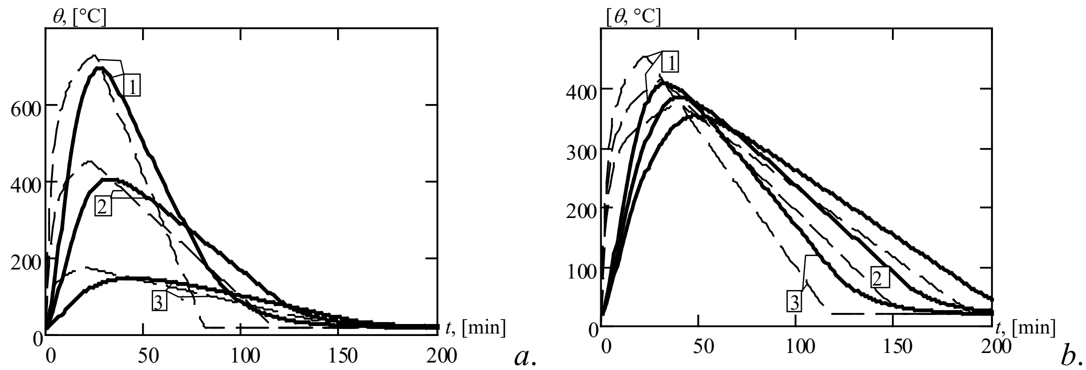

Fig. 1. Graphs of the temperature regimes of heating of a steel structure element (solid line) for temperature regimes of fire (dashed line) in premises at different values of the fire load density at a constant value of the slit coefficient O = 0.45 [m$^{0.5}$] (a) (1 – $q_{t,d}$ = 1200 [MJ/m^2], 2 – $q_{t,d}$ = 800 [MJ/m^2], 3 – $q_{t,d}$ = 400 [MJ/m^2]) and for different values of the slit coefficient at a constant value of the fire load density $q_{t,d}$ = 800 [MJ/m^2] (b) (1 – O = 0.045 [m$^{1/2}$], 2 – O = 0.055 [m$^{1/2}$], 3 – O = 0.065 [m$^{1/2}$]).

Fig. 1 shows that the temperature regime of heating of the structural element coincides with the temperature regime of the fire and allows determining the occurrence moment of one of boundary states.

To research the effect on the temperature regime of the heating element of a steel structure, depending on the coefficient of its cross section, the corresponding curves were drawn, as shown in fig. 2.

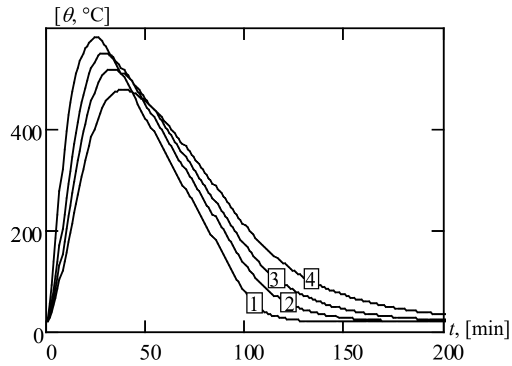

Fig. 2. Graphs of temperature regimes of heating of the elements of steel structures for premises under fire with a slit coefficient of O = 0.045 [$m^{0.5}$], fire load density $q_{t,d}$ = 800 [MJ/m^2] at different values of the cross section coefficient: 1 – A_m/V = 50 [m^{-1}]; 2 – A_m/V = 70 [m^{-1}]; 3 – A_m/V = 100 [m^{-1}]; 4 – A_m/V = 200 [m^{-1}].

The graphs in fig. 2 show that as the cross-section coefficient of the steel structure increases, its maximum heating temperature decreases and the time of its reaching and duration of fire increases. This is explained by the fact that the cross-section coefficient depends on its size in inversely proportional relationship, with respect to the increasing of size, determining this trend.

There were researched also dependences of the time occurrence of reaching the temperature when there begins the state of loss of load-bearing capacity at a certain critical temperature. The critical temperature varies according to a series of values of 350 [°C], 400 [°C], 450 [°C], 500 [°C], 550 [°C], 600 [°C], 650 [°C], 700 [°C], 750 [°C], according to the standard [1].

According to this standard, the critical temperature of this series is determined by the calculation of the load capacity according to the methods of the standard [1]. The time of reaching the boundary state of the loss of load-bearing capacity is the time of reaching this temperature.

The fig. 3 shows the time of reaching the boundary state for various critical temperatures for a steel element with a cross-section coefficient A_m/V = 70 [m^{-1}].

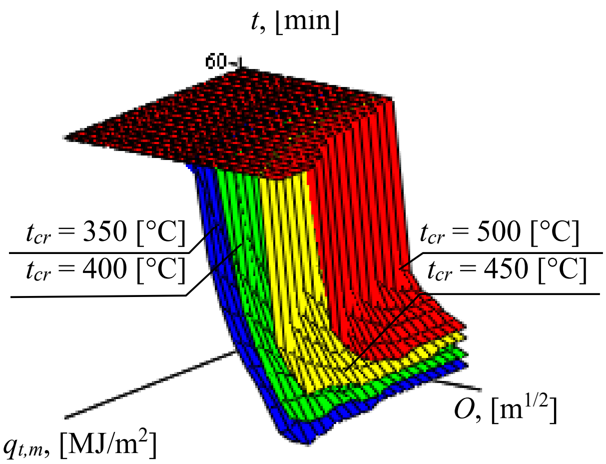

Fig. 3. Distribution of time for reaching the boundary state of losing load-bearing capacity, depending on the slit coefficient and the fire load density for various critical temperatures in a steel element with a cross-section coefficient A_m/V = 70 [m^{-1}].

Dependences of the occurrence time of the boundary state, i.e. the actual limit of fire resistance, reveal that with a certain decrease of the slit coefficient and an increase in the fire load density, the actual limit of fire resistance increases. The horizontal section of dependencies, shown in fig. 3, is a section where the occurrence of boundary state is not observed.

Similar dependences of the occurrence time of boundary state for load bearing capacity for a steel structure element were obtained for various values of the cross-section coefficient A_m/V at a constant value of the critical temperature t_{cr} = 350 [°C]. The obtained dependencies are shown in fig. 4.

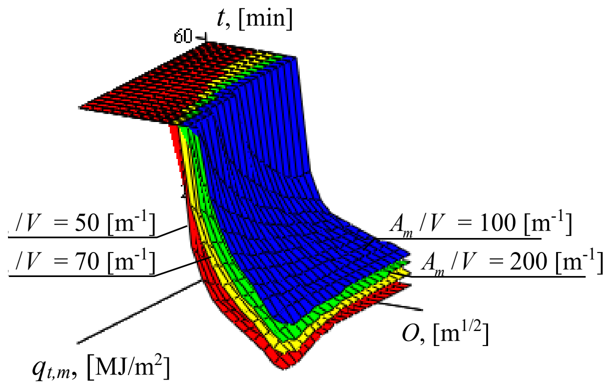

Fig. 4. Distribution of time for reaching the boundary state of the loss of load-bearing capacity, depending on the slit coefficient and the fire load density for the critical temperature t_{cr} = 350 [°C] in a steel element with various cross-section coefficients.

The obtained dependences of the occurrence time of the boundary state, i.e. the actual limit of fire resistance, shown in fig. 4, show the same features characteristic as in fig. 3.

The mathematical tool, used to obtain the abovementioned results, can be used to build nomograms to determine the actual limit of fire resistance for an element with a certain critical temperature value and a cross-section coefficient for a given steel structure. The fig. 5 illustrates similar nomograms as an example.

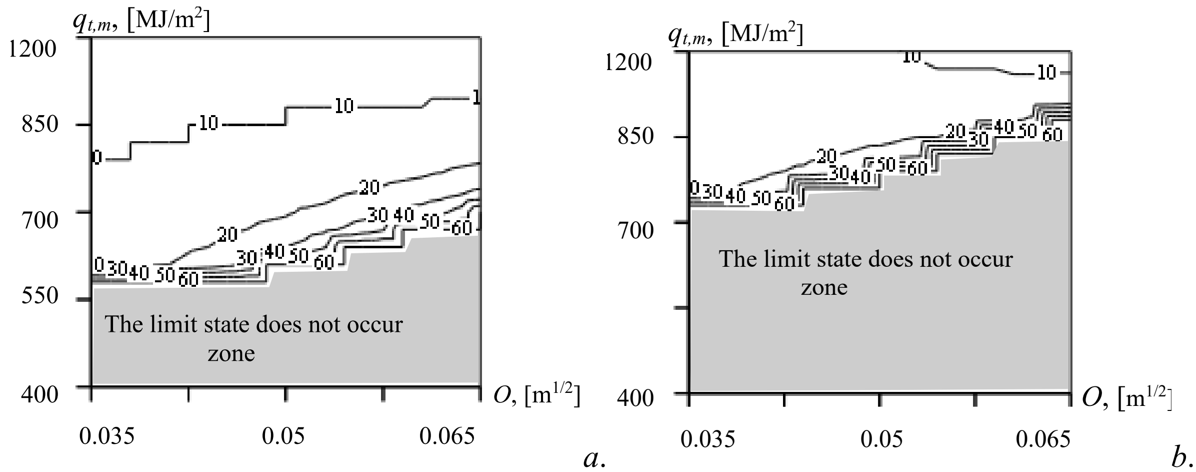

Fig. 5. Nomogram for determining the parameters of slit coefficients and fire load density in premises under fire to design fire-resistant steel building structures at A_m/V = 150 [m^{-1}]: a - θ_{cr} = 350 [°C]; b - θ_{cr} = 500 [°C].

Using nomograms, similar to the nomograms shown in fig. 5, it is possible to determine the actual limit of fire resistance of an element with a certain cross-section coefficient A_m/V which is calculated for critical temperature from the standard series, as shown in fig. 6.

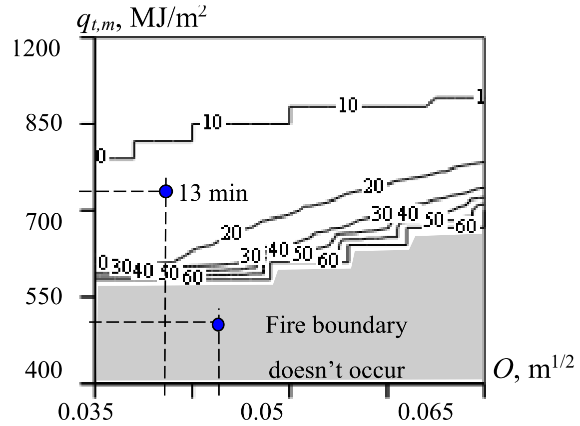

Fig. 6. A scheme for determining the limit of fire resistance of an element of steel building structure, according to the proposed nomograms.

In order to determine the actual limit of fire resistance by the nomographic method using the proposed nomograms, one can use the sequence of procedures given in fig. 7.

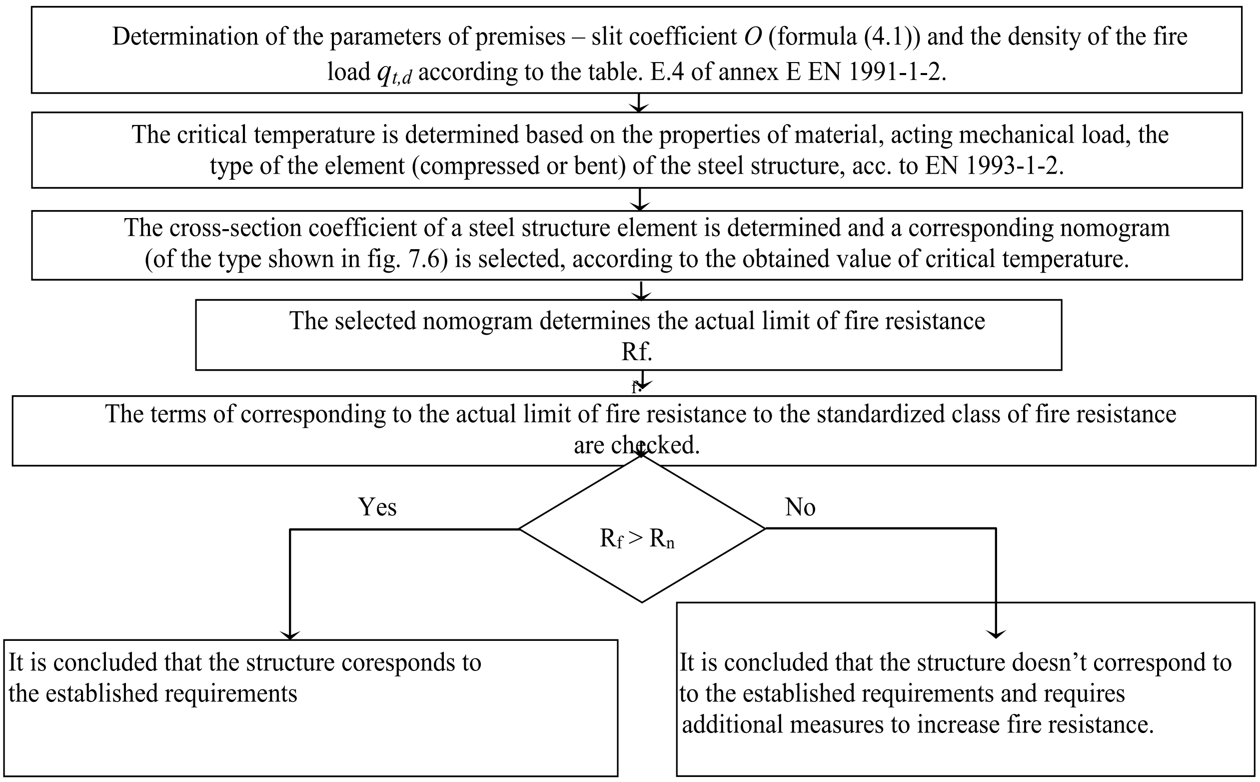

Fig. 7. Scheme for calculation a method on the asessment of fire resistance of the elements of steel structures by the nomographic method.

During a quick analysis on fire resistance it can be predicted that in most cases the maximum temperature is reached in less than 30 min and no longer rises. If the temperature does not rise to a critical value, then it can be substantiated that this structure element may correspond to any standard of fire resistance.

For this purpose, nomograms can be built for determining the coefficients of steel strength reduction and tensile modulus to use them later to determine the bearing capacity under the highest heating temperature of the structure. The fig. 8 shows an example of such nomograms for coefficients of tensile strength reduction, compressive strength, and tensile modulus of steel.

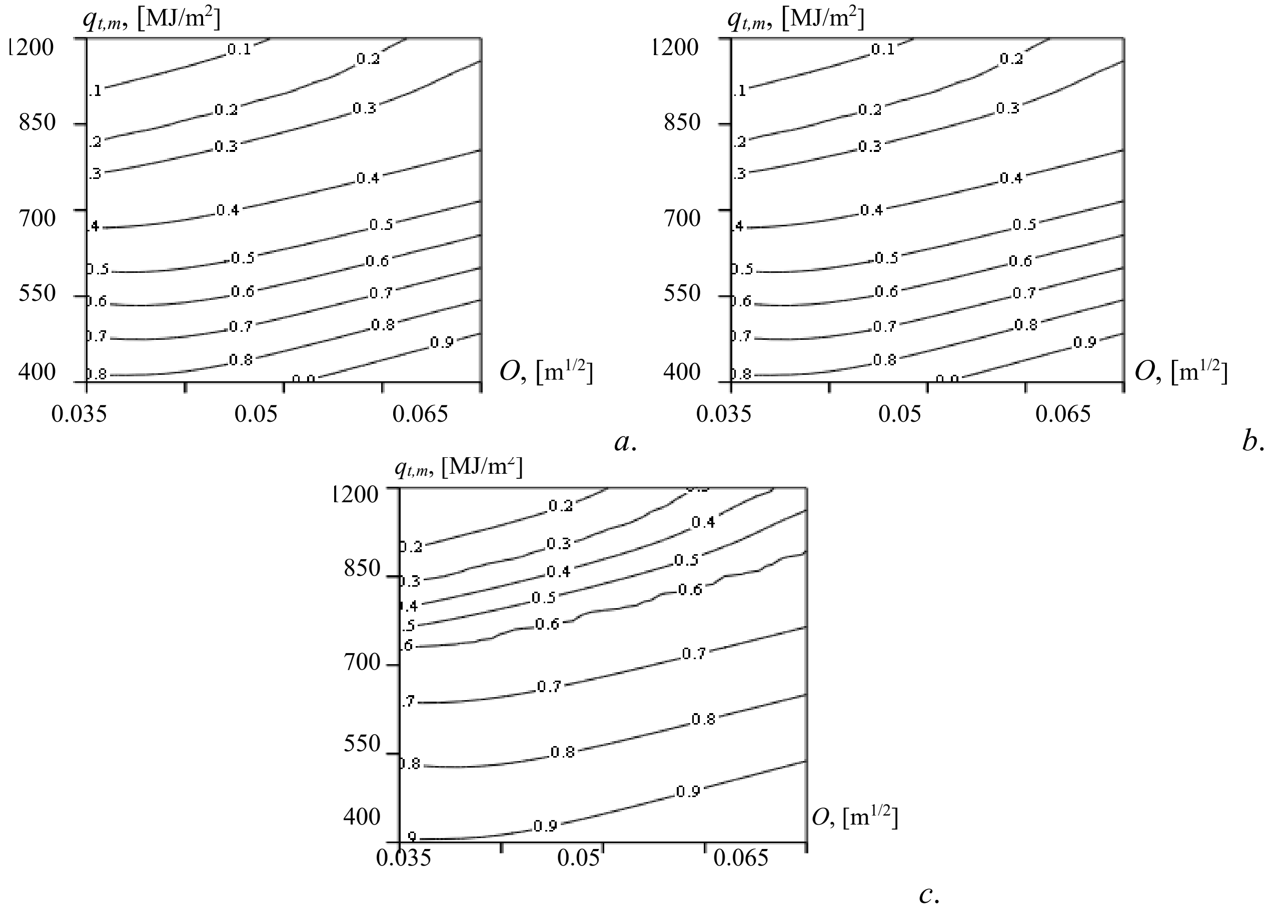

Fig. 8. Nomogram for determining the coefficients of tensile strength (a) reduction, compressive strength (*b*) reduction and tensile modulus (*c*) reduction to design fire-resistant steel building structures at A_m/V = 150 [m^{-1}].

The given diagrams allow determining coefficients of reduction that are used to determine the residual bearing capacity of elements of steel structures by the methods recommended by the standard [1].

Similar diagrams can be built to determine the boundary strains of the structures. Three types of I-beams with cross-sections corresponding to [9] were selected for the construction of such diagrams. The parameters of these sections are given in tab. 2.

Table 2. Geometric characteristics of I-beams.

I-beam profile according to DSTU 8768:2018	Geometric characteristics of cross-sections	
	Cross-section coefficient A_m/V, [m^{-1}]	Resistance moment, W_x, [m^3]
Profile № 55	157.842	$2000 \cdot 10^{-6}$
Profile № 40	123.246	$947 \cdot 10^{-6}$
Profile № 27a	93.684	$407 \cdot 10^{-6}$

Using the data in tab. 2, we can determine the boundary moment using the formula [1]:

$$M_{c,Rd} = M_{pl,Rd} = \frac{W_{pl} f_y}{\gamma_{M0}}. \qquad (5)$$

where W_{pl} – is the resistance moment of the beam cross section;

γ_{M0} – coefficient of reliability of the relevant properties of the material in case of fire (according to EN 1993-1-2: 2012 [1] it is to be assumed equal to 1.0).

In result of necessary calculations, there were constructed corresponding surfaces of the values of the beam boundary moments with the corresponding cross sections, depending on the slit coefficients and the fire load density. The constructed surfaces are shown in fig. 9.

Fig. 9 shows that the obtained data can be used to build nomograms to determine the corresponding beam boundary moment.

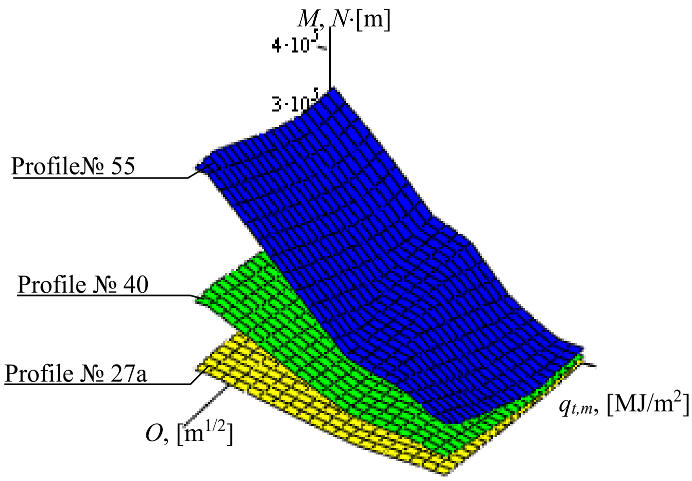

Fig. 9. Surface values of boundary moments of beams with corresponding cross-sections depending on the slit coefficient and fire load density for different section profiles of I-beams according to [9].

Fig. 10 shows the diagrams for determining the boundary moments of the corresponding steel beams.

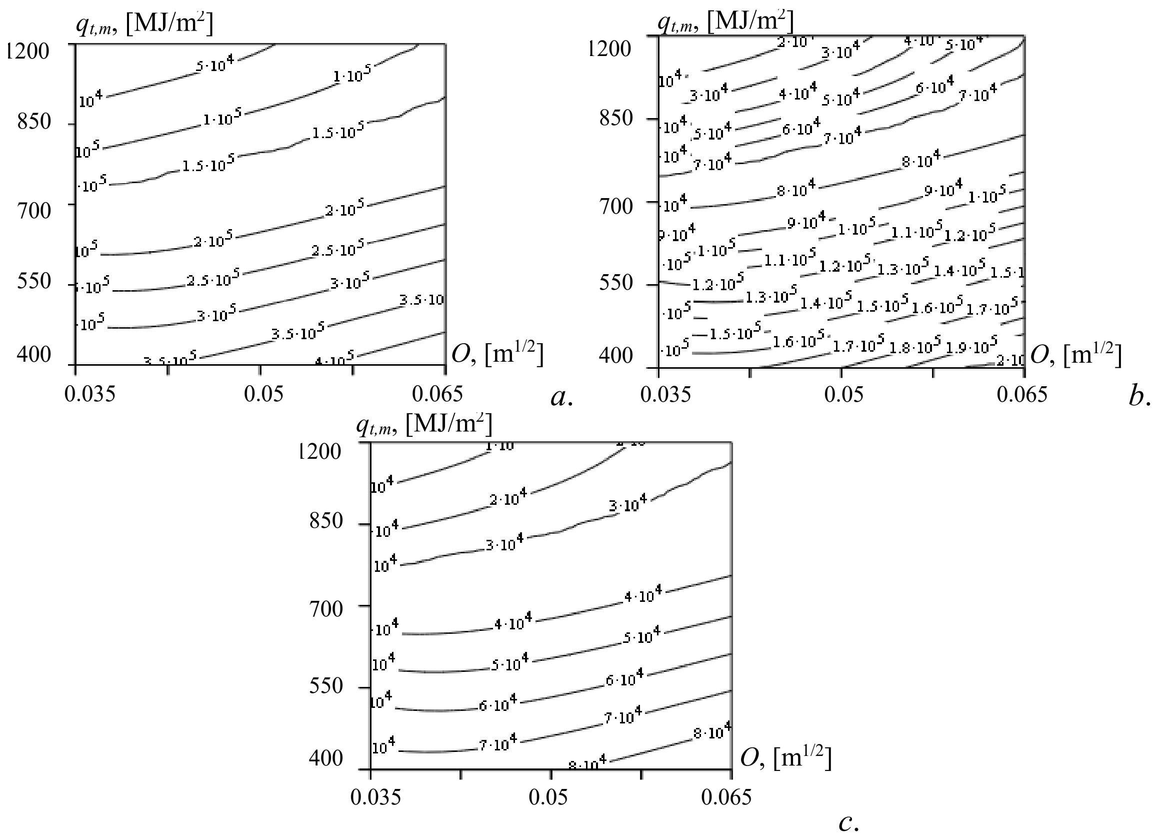

Fig. 10. The nomogram for determining the coefficients of boundary moments of beams for various profiles of cross sections of I-beams, according to [9]: a – profile №55, b – profile №40, c – profile №40.

To compare the obtained results with the results obtained using the standard fire regime approach, the corresponding calculations were made as shown in fig. 11.

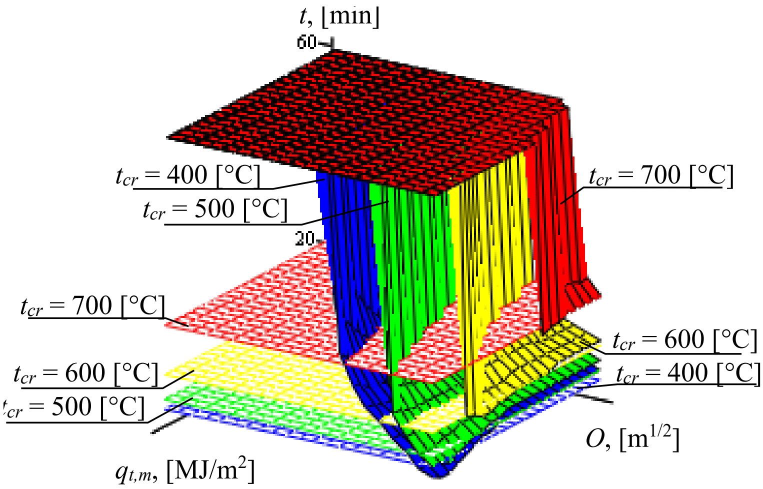

Fig. 11. Time distribution for reaching the boundary state of bearing capacity loss depending on the slit coefficient and fire load density for various critical temperatures in the steel element with a cross-section coefficient A_m/V = 70 [m^{-1}], as well as the corresponding time values for reaching the boundary state of the bearing capacity loss using the standard temperature regime of fire (horizontal area).

Analyzing the data shown in fig. 11, it can be observed that in almost all the area of the possible values of the opening coefficients and fire load density, the time of reaching the boundary state of the loss of load-bearing capacity is much greater for the temperature regimes determined by the proposed mathematical models than the values obtained using the standard temperature regime of fire.

However, there is also a small area when the occurrence time of loss of load-bearing capacity exceeds the values obtained using the standard temperature regime of fire. It should also be noted that the time of reaching the boundary state of the loss of load-bearing capacity when using the proposed mathematical method to determine the regimes of fire according to the parameters of the premises is on average 3.5 times higher than the values obtained by the standard temperature regime.

The time value of reaching the boundary state of the loss of load-bearing capacity when using mathematical method to determine the regimes of fire, according to the parameters of the premises, is less than the values obtained with the standard temperature regime of fire when the coefficient of openings is bigger than 0.061 and the fire load density is bigger than 1096 [MJ / m^2].

Summary

There was researched the thermal influence of the fire temperature regimes, obtained by the proposed mathematical models, on the mechanical characteristics of metal structures. As a result, the identified regularities of the influence of the parameters of the premises with the fires were shown in condition of decrease of slit coefficients and increase of the fire load density the actual limit of fire resistance begins to decrease. Additionally, at the values of fire load density less than 600 [MJ / m^2], there is an area where the occurrence of boundary state is not observed. Basing on the obtained regularities there were built the nomograms for determination of the limit of fire resistance for steel structures at standard values of critical temperature were constructed, the regularities were obtained and a corresponding method was developed.

The time of reaching the boundary state of the loss of load-bearing capacity, when using the proposed mathematical method to determine the regime of fire according to the parameters of the premises is on average 3.5 times higher than the values obtained by the standard temperature regime. The time value of reaching the boundary state of the loss of load-bearing capacity when using mathematical method for determining the regimes of fire in the parameters of the premises is less than the values obtained at the standard temperature regime of fire when the coefficient of openings is bigger than 0.061 and the fire load density is bigger than 1096 [MJ / m^2].

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