Analysis of the Methods to Calculate the Equivalent Fire Duration

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ABSTRACT

Three methods for the calculation of equivalent fire duration were analyzed. These are the methods of the standards EN 1991-1-2, GOST R 12.3.047-2012 and the methods based on fire modeling by FDS 6. Various rooms and their structures (concrete, non-protected and fire-proofed steel), and fire sources were considered. It was found that the GOST R 12.3.047-2012 method gives higher values of equivalent fire duration in comparison with the EN 1991-1-2 and FDS 6 methods. Not only the equivalent fire duration, but also actual fire resistance limits were evaluated by FDS 6 taking into account the heating of structures. It was shown that FDS 6 can be successfully used in cases when the standards are not applicable or give overestimated results.

KEYWORDS: Fire modeling, fire resistance, equivalent fire duration.

INTRODUCTION

The concept of equivalent fire duration, t_{eq}, is now often used for calculation of the required fire resistance limits (see for example [1–9]). The equivalent fire duration is the duration of the standard fire that has the effect on a structure which is the same as that by the real fire. The equivalent fire duration for steel (both non-protected and fire-proofed) and concrete structures can be determined by applying the concept of a critical temperature for the heating of the steel structure or a steel armature. Numerous studies [1–9] are dedicated to the calculation of the equivalent fire duration. The GOST standard [7], created on the basis of investigations [1–6], proposes the value t_{eq} to be determined using the diagrams relating the equivalent fire duration to the duration of the real fire, t_r, the aperture factor, Π, of a room, and the type of the structure (concrete, fire-proofed or non-protected steel). The calculation of the t_{eq} value was performed in [8], and it was concluded that the proposed formula (including the standard formula [9]) does not satisfactorily agree with the experiments. Questions about the calculations of the required fire resistance limits were considered in [10]. It was noticed that two main concepts are possible: a) the required fire resistance limit is determined by taking into account the complete burning of all the fire load; b) it is accepted that structures should preserve their bearing capabilities for the time required for evacuation and rescue of occupants and the operation of fire brigades. The choice between these concepts should be made by the organization regulating the fire safety. The study in [10] realizes the first concept. The estimation of the equivalent fire duration includes calculations of the temperature of a gas mixture in a room with the fire, the room structure temperatures, and the change of the structure bearing capability; this is a rather complicated procedure. Another way is taking into account the fire load and the ventilation conditions. But this simpler way is not as exact as the first method. In [10] the calculations were performed according to the EN standard [9], which uses the second simple approach. Critical comments on the EN standard [9] were made.

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Various empirical and semi-empirical formulas for the calculation of the equivalent fire duration were applied in [11]. Most of these formulas assume that the value of t_{eq} does not depend on the structure type (concrete, steel, etc.). It was concluded that the methods for calculation of the equivalent fire duration can give results differing by 300%. The standard in [9] gives satisfactory results for fire-proofed structures, but for non-protected steel structures agreement with the experiment is much worse. The absence of a scientific foundation in the method in [9] is mentioned.

It follows from the brief analysis presented above that the EN standard method [9] is empirical, and the GOST standard method [7] is based on the integral fire model developed in [1]. At the same time, the computer code FDS can simulate the fire dynamics in a room with the heating of the room structures taken into account [12]. Therefore, this study aims to investigate the performance of FDS 6 in the calculation of the equivalent fire duration in a room made of concrete and non-protected steel structures, and to compare the FDS method with the two standard methods. Any other investigations of the FDS 6 computer code itself were beyond the scope of this study.

METHODOLOGY OF THE ANALYSIS

The equivalent fire duration was calculated using the computer code FDS 6 [12]. A typical office room with an area of $A_f = 210$ m^2 and a height of $H = 3.3$ m (volume $V = 693$ m^3) was considered. The room has vertical openings with a height of $h = 2$ m, while the width of these openings was varied in the calculations. The specific fire load was taken to be 511 MJ/m^2 according to the EN standard [9] and the fuel was assumed to be equivalent to wood. The properties of wood required for the calculations were taken from [13].

In the calculations according to the GOST standard [7], the key parameter is the fire duration t_f, which can be determined (in hours) by the formula:

$$t_f = \frac{\sum P_i Q^r_{ni}}{6258 A_V \sqrt{h}} \frac{n_{ev} \sum P_i}{\sum n_i P_i}, \tag{1}$$

where P_i is the amount of the fire load for the material type i, kg, Q^r_{ni} is the specific lowest heat of combustion of the i-th material, MJ/kg, A_v is the total area of the openings, m^2, h is the height of the openings, m, n_{ev} is the average burning rate of wood, kg/ (m^{2}min), n_i is the burning rate for the i-th material.

Another important parameter for calculation of the equivalent fire duration is the so-called aperture factor Π, determined by the formula:

$$\Pi = A_V h^{1/2} V^{2/3}. \tag{2}$$

Then the equivalent fire duration is determined by the diagrams [7] taking into account the values t_f, Π and the type of structure (concrete, fire-proofed or non-protected steel).

The equivalent fire duration t_{eq} according to the EN standard [9] is calculated (in min) by the formula:

$$t_{eq} = \left(q_{f,d} k_b w_f\right) k_c, \tag{3}$$

where $q_{f,d}$ is the effective specific fire load, MJ/m^2, k_b is a coefficient equal to 0.07 min·m^2·MJ^{-1}, k_c is a coefficient equal to 1.0 for concrete structures, w_f is a coefficient taking into account the ventilation conditions and determined by the formula:

$$W_f = (6/H)^{0.3}\frac{0.62+90(0.4-\alpha_V)^4}{1+b_V\alpha_h}, \tag{4}$$

$\alpha_v = A_v/A_F$ is the ratio of the area of the vertical openings A_v and the area of the room A_f, $\alpha_h = A_h/A_f$ is the ratio of the area of the horizontal openings to the area of the room A_f, $b_V = 12.5(1 + 10\ \alpha_V - \alpha_V^2)$ is a coefficient. We consider a room without horizontal openings, that is $\alpha_h = 0$.

The effective specific fire load $q_{f,\,d}$ is determined by the formula:

$$q_{f,d} = q_{f,k} m \delta_{q_1} \delta_{q_2} \delta_n, \tag{5}$$

where $q_{f,k}$ is a normative fire load accepted to be equal to 511 MJ/m^2 as for the office room, m is a coefficient of the completeness of combustion equal to 0.8, δ_{q1} is a coefficient taking into account the risk of a fire origin for various sizes of room, which was accepted to be equal to 1.5, δ_{q2} is a coefficient taking into account the risk of a fire origin depending on the type of room, which was accepted to be equal to 1.0, $\delta_n = \sum_{i=1}^{10} \delta_{ni}$ is a coefficient taking into account fire protection measures. The values δ_{ni} were determined on the basis of the EN standard [9] and are presented in Table 1.

Table 1. Values of the coefficients δ_{ni}

Coefficient	Objective	Value
δ_{n1}	Taking into account the availability of automatic fire extinguishing tools (this tool is absent)	1.0
δ_{n2}	Taking into account the availability of an external fire water supply (available)	0.87
δ_{n3}	Taking into account the availability of thermal fire detectors (available)	1.0
δ_{n4}	Taking into account the availability of smoke fire detectors (available)	0.73
δ_{n5}	Taking into account the availability of an automatic signal sending a fire alarm to a fire station (absent)	1.0
δ_{n6}	Taking into account the availability of the fire station related to the building considered (absent)	1.0
δ_{n7}	Taking into account the availability of the city fire station (available)	0.78
δ_{n8}	Taking into account the availability of safe ways for a fire team to access the room of the fire (available)	1.0
δ_{n9}	Taking into account the availability of an internal fire water supply (available)	1.0
δ_{n10}	Taking into account the availability of smoke ventilation (available)	1.0

The characteristics of wood as the fire load [13] are:

- net heat of combustion 13.8 MJ/m^2;
- mass burning rate 0.039 kg/(m^2·s);
- flame propagation velocity 0.05 m/s.

The thickness of the concrete structures was assumed to be 20 cm, and the thickness of the protective layer was set at 5 cm. The properties of concrete were as follows [1]: density $\rho = 2250$ kg/m^3, thermal conductivity $\lambda = 0.84\text{-}4\cdot10^{-4}\cdot t$, W/(m·K) ($t$ is temperature, ^{o}C), specific heat capacity $C = 0.71+8.4\cdot10^{-4}\cdot t$, kJ/(kg·K), surface emissivity $\varepsilon = 0.63$. Locations of temperature sensors and the openings are shown in Fig. 1.

Non-protected steel structures (beams and columns) were also considered. The beam cross-section was a hollow square 0.15 x 0.15 m with a wall thickness of 0.015 m. According to [1], the reduced thickness of the beam was 0.0135 m. The columns had a square 0.21 x 0.21 m cross-section (the reduced thickness is 0.07 m [1]).

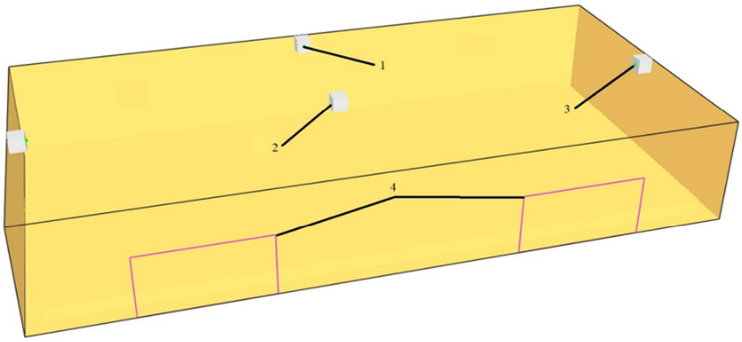

Fig. 1. Diagram of the room with the temperature sensors: 1 – wall (near ceiling); 2 – ceiling; 3 – column (near ceiling); 4 – openings.

The following properties of steel were used [1]: density $\rho = 7800$ kg/m^3, thermal conductivity $\lambda = 48\text{-}3.65\cdot10^{-2}\cdot t$, W/(m·K), specific heat capacity $C = 0.44 + 4.8\cdot10^{-3}\cdot t$, kJ/(kg·K), surface emissivity $\varepsilon = 0.74$. The fire source was in a square cavity with a surface area of $F = 2.7$ m^2 located in the center of the room. The fuel was 247 kg of diesel oil. The mass burning rate of the diesel oil was set at 0.04 kg/(m^2·s) [14]. The temperatures of the beams and the columns were detected near the ceiling of the room above the fire source.

RESULTS AND DISCUSSION

Concrete structures

FDS 6 was validated by predicting the heating of the room structures in the standard fire. The simulation results were compared with the data provided by Ref. [1], in which the conductive and radiative heat fluxes from the hot gas to the room structures at the standard fire are provided. These heat fluxes were used to calculate the temperatures of the room structures. The results shown in Fig. 2 indicate that a satisfactory agreement was obtained.

In Fig. 3, the predicted temperature growth at the distances of 5 and 10 cm from the heated surface is presented for the standard fire. These results were then used to evaluate the equivalent fire duration for the real fires simulated with the FDS 6 code.

FDS 6 simulations were performed for the values of $\Pi = 0.1$, 0.17 and 0.26 m$^{0.5}$, which are typical for office rooms. The simulation results for the heated surface temperature for $\Pi = 0.26$ m$^{0.5}$ are presented in Fig. 4. These temperatures have a maximum in the initial part of the fire. Then the temperatures increase slowly during the subsequent stage of the fire. The maximum is caused by the consumption of the initial oxygen with the subsequent air supply from the openings. The temperature curves show that, even for $\Pi = 0.26$ m$^{0.5}$, the fire is ventilation-controlled. The surface temperatures at the sensor locations are rather close to each other because the sensors are both situated in the upper part of the room. The temperature of the column is relatively low in comparison with the wall and the beams, and this is caused by the location of the column in the part of the room where the ventilation is weak.

Predicted temperatures dependencies at the depth of 5 cm for various values of Π are presented in

Figs. 5–7. The curves have maxima, and their locations (at approximately 4500 s) do not coincide with the time instant when the fire ceases at 3400 s (see Fig. 4). This is due to the heat transfer from the heated surfaces to the inner part of the structure.

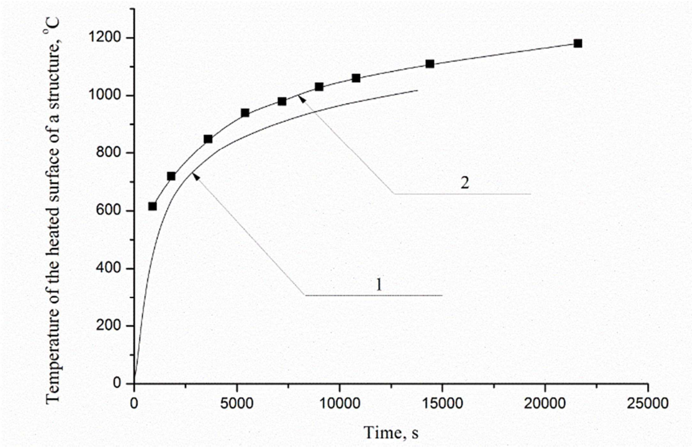

Fig. 2. Dependence of the temperature of the heated surface of the plane concrete structure on time in the standard fire. 1 – FDS 6 code; 2 – data [1].

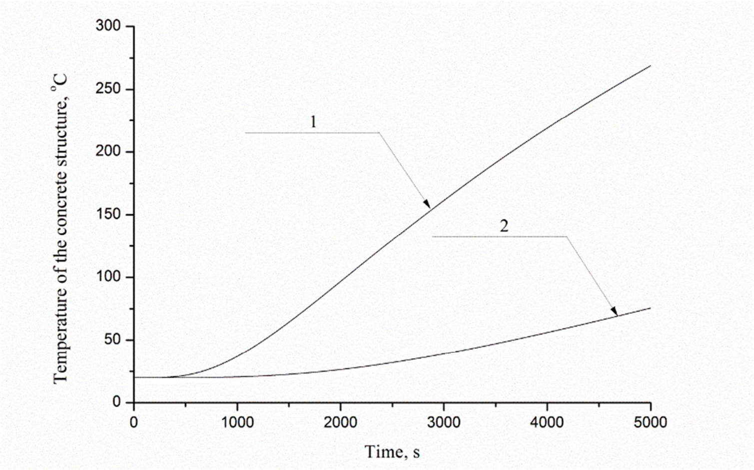

Fig. 3. Results of calculations of the heating of the structures by the standard fire at various depths from the heated surface. 1 – 5 cm; 2 – 10 cm.

The results of the structure temperature calculations (Figs. 5–7) and the data for the standard fire can be used to evaluate the equivalent fire duration. Consider a room with the concrete structures covered by the 5 cm thick protecting layer and determine the time instant at which the maximum temperature occurring in the real fire is equal to that in the standard fire. The 5 cm thickness value for the protected layer was chosen as an example, and this method can be applied for any thickness.

The equivalent fire duration evaluated by FDS 6 are presented in Table 2. Calculation results obtained according to the GOST and EN standards [7, 9] are also shown for comparison.

Table 2 shows that the values of t_{eq} predicted by FDS 6 and by the EN method [9] in most cases are comparable. The largest deviations are found for high values of Π ($\Pi = 0.26$ m$^{0.5}$). With the increase of Π from 0.10 to 0.26 $m^{0.5}$, the value of t_{eq} obtained with FDS 6 increases, and this is caused by the enhanced ventilation conditions and by the increased thermal impact of the fire on the structures (in this case, the fire is ventilation-controlled). At the same time, the values of t_{eq} calculated by the EN standard method [9] decrease as the value of Π increases, and the reason of this is not clear. The results obtained by the GOST method [7] differ substantially from those obtained by FDS 6 and the EN method [9]. The reasons for such deviations are not clear, too.

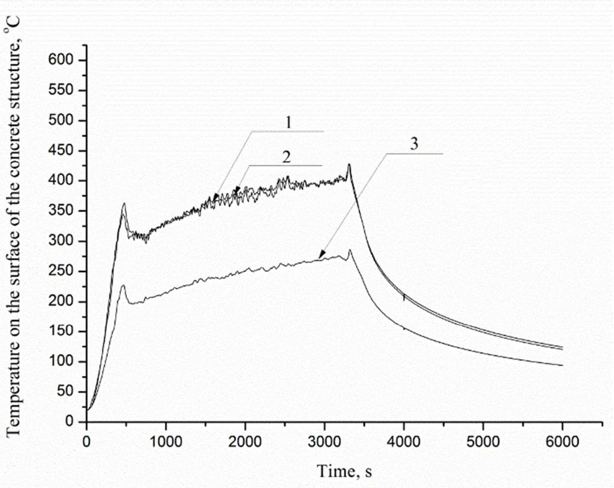

Fig. 4. Results of calculations on the heated surface of the concrete structures for $\Pi = 0.26\ m^{0.5}$.
1 – ceiling; 2 – wall; 3 – column.

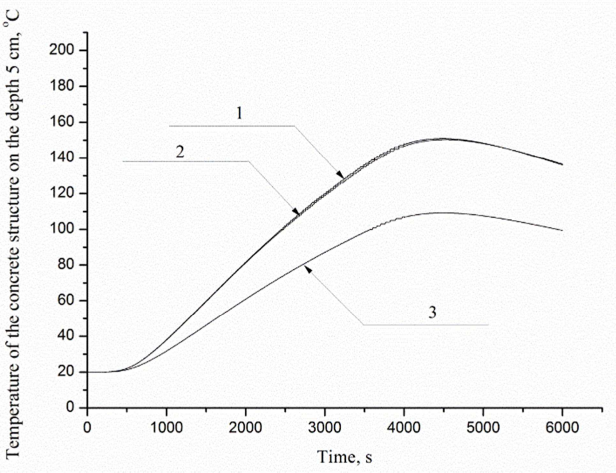

Fig. 5. Results of calculations of the temperatures of the concrete structures at depth 5 cm for $\Pi=0.26\ m^{0.5}$.
1 – ceiling; 2 – wall; 3 – column.

Calculations of the thermal fluxes absorbed by the structures for various Π values were carried out. The absorbed thermal flux is determined as the difference between the incident thermal fluxes and those emitted by radiation. The typical dependence of the absorbed thermal flux on time is presented in Fig. 8. It can be seen that the absorbed thermal flux has a maximum at the initial stage of the fire, when the structures are not hot enough to emit sufficient radiative power. Then the dependence of the density of the absorbed thermal flux varies rather weakly (quasi-stationary value) up to the end of the burning, after which this heat flux becomes negative. This means that the hot structure emits more thermal energy than it absorbs. The typical values of the absorbed heat flux during the fire are quite close to those measured experimentally [1]. It was found that the higher the Π value is, the higher is the absorbed heat flux.

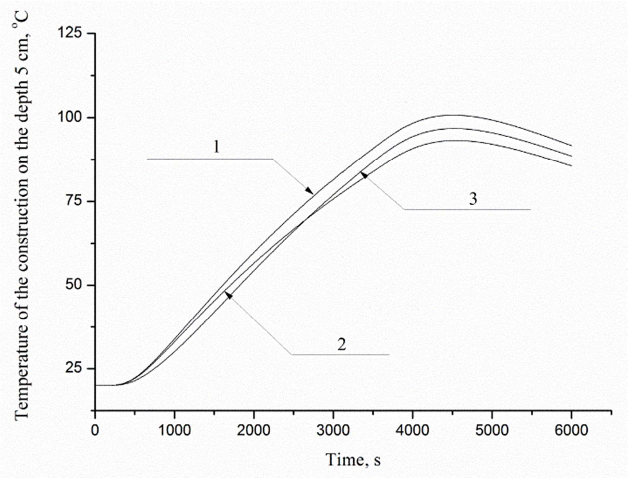

Fig. 6. Results of calculations of the temperatures of the concrete structures at depth 5 cm for $\Pi=0.17\ m^{0.5}$.
1 – ceiling; 2 – wall; 3 – column.

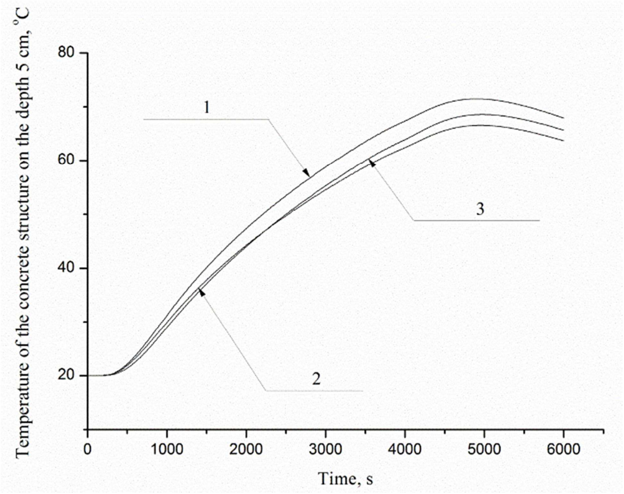

Fig. 7. Results of calculations of the temperatures of the concrete structures at depth 5 cm for $\Pi=0.1\ m^{0.5}$.
1 – ceiling; 2 – wall; 3 – column.

Table 2. Calculated equivalent fire duration for concrete structures

Type of structure	Π, m$^{0.5}$	Equivalent fire duration t_{eq}, min		
		FDS 6	GOST R 12.3.047-2012	EN 1991-1-2-2009
Beams	0.10	47	69	62
	0.17	76	93	54
	0.26	162	90	45
Walls	0.10	47	240	62
	0.17	76	204	54
	0.26	162	192	45
Columns	0.10	47	180	62
	0.17	76	138	54
	0.26	84	126	45

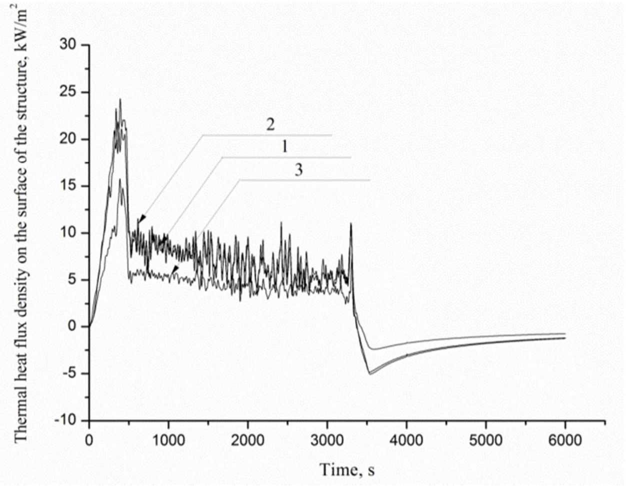

Fig. 8. Typical dependence of the thermal flux absorbed by the concrete structures on time. 1 – ceiling; 2 – wall; 3 – column.

STEEL STRUCTURES

Simulation results for heating of the steel structures exposed to the standard fire are presented in Fig. 9. It can be seen that the heating of the beams initially proceeds faster than that of the column because the beam has a lower reduced thickness. After a longer time, the temperatures of these structures become equal, but their temperatures are significantly lower than those of the concrete structure surfaces (compare Figs. 2 and 9). This is due to the higher thermal conductivity of steel compared with that of concrete.

Table 3 shows the calculation results for the equivalent fire duration. The fire source is the cavity of the area of F = 2.7 m^2 with diesel oil. We neglect the time of flame propagation over the fuel surface because this time is much shorter than the fire duration. The equivalent fire duration was calculated as the duration of the standard fire which is required to warm the steel structures up to the maximum temperatures obtained for a real fire as evaluated with FDS 6. Calculated values of t_{eq}

obtained by the standard methods [7, 9] are also presented. Because the GOST standard [7] gives the results for steel structures only for a local fire, the choice of the necessary input data was made only for the parameter $H/\sqrt{F}$ = 2.0, for which the GOST standard [7] contains appropriate data for both vertical and horizontal structures.

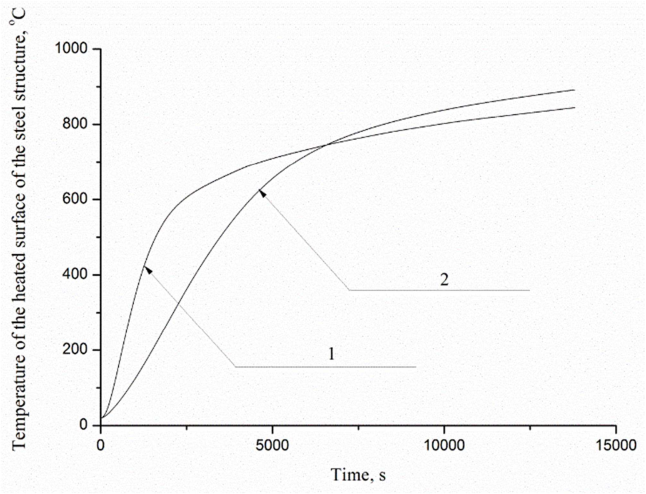

Fig. 9. Dependence of the temperature of the heated surface of the steel structures on time. 1 – beam; 2 – column.

Table 3. Calculated equivalent fire duration and actual fire resistance for steel structures

Type of structure	Π, $m^{0.5}$	Equivalent fire duration t_{eq}, min			Actual fire resistance t_a, min	
		FDS 6	GOST Standard [7]	EN Standard [9]	400	500
Beams	0.1	37	50	62	8	12
	0.17	22	50	54	22	[a]
	0.26	28	50	45	11	18
Columns	0.1	25	8	62	[a]	[a]
	0.17	20	8	54	[a]	[a]
	0.26	35	8	45	[a]	[a]

[a] Maximum temperature of the structure after burning out the entire fire load does not reach the critical temperature (400 or 500ºC)

There is no clear difference between the values of t_{eq} for horizontal (50 min) and vertical (8 min) structures calculated according to the GOST standard [7]. It should also be mentioned that the calculations with FDS 6 give substantially lower values of t_{eq} than those obtained by the EN standard method [9]. The steel structures, unlike the concrete structures, are warmed up to the critical temperatures (500ºC according to [1] or 400ºC with an appropriate reliability) in a quite short time, which can be determined as the actual fire resistance limit t_a of the structure in relation to a given fire. The value of t_a characterizes the time interval during which the structure maintains its bearing capacity for the given fire with the entire fire load burned out. In this case, the column is not heated up to the temperature of 400ºC during the burning of the fire load, and it is not reasonable to evaluate the actual fire resistance limit. At the same time, the beam can be heated up to 400ºC within 8 min (12 min for the temperature 500ºC) at $\Pi = 0.1$ m$^{0.5}$. Thus, FDS 6 makes it possible to not only evaluate the equivalent fire duration, but also the actual fire resistance limit.

CONCLUSIONS

In this study, the equivalent fire duration is evaluated for concrete and non-protected steel structures using FDS 6 and the standard methods GOST R 12.3.047-2012 and EN 1991-1-2-2009. It was found that the calculations according to GOST R 12.3.047-2012 give higher values of the equivalent fire duration than those obtained by FDS 6 and by EN 1991-1-2-2009 standard.

It is necessary to determine not only the required but also the actual fire resistance limits, which can be performed using FDS 6.

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