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Враховуючи необхідність мінімізації масо-габаритних показників сталевих конструкцій, актуальним є питання про ефективність застосування для них комбінованої системи вогнезахисту. У статті досліджувався тепловий стан сталевих конструкцій з такою системою вогнезахисту в умовах вогневого впливу за стандартним температурним режимом згідно з ДСТУ Б В.1.1-4-98. У експериментальних зразках використовували сталеві пластини квадратної форми зі стороною 500 мм і товщиною 5 мм та 10 мм. Проведеним дослідженням встановлено особливості залежностей температури сталевих конструкцій з пасивним і реактивним вогнезахисними матеріалами двох торгових марок від тривалості вогневого впливу.*

Встановлено, що ці залежності для сталевих конструкцій з комбінованою, пасивною і реактивною системами вогнезахисту мають монотонно зростаючий характер. Максимальні значення тривалості вогневого впливу мають місце для експериментальних зразків, які мають товщину сталеві пластини 10 мм, для критичної температури сталі 600 °С. Вони становлять 111 хв, 101 хв, 55 хв відповідно для комбінованої, пасивної і реактивної систем вогнезахисту.

Встановлено, що для комбінованої системи вогнезахисту закономірним є підвищення тривалості досягнення критичної температури сталі порівняно до пасивної та реактивної систем вогнезахисту. Це обумовлене ефективним поєднанням фізико-хімічних властивостей пасивного і реактивного вогнезахисних матеріалів.

Для тривалості вогневого впливу до 79 хв значення тривалості досягнення критичної температури сталі для комбінованої системи вогнезахисту перевищує суму тривалостей її досягнення, які мають місце для пасивної і реактивної систем вогнезахисту. Це свідчить про ефективність комбінованої системи у цьому діапазоні тривалості вогневого впливу.

З підвищенням тривалості вогневого впливу має місце зниження ефективності комбінованої системи вогнезахисту.

Ключові слова: вогнезахисний матеріал, критична температура сталі, сталева конструкція, система вогнезахисту, вогневий вплив

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THERMAL STATE OF STEEL STRUCTURES WITH A COMBINED FIRE PROTECTION SYSTEM UNDER CONDITIONS OF FIRE EXPOSURE

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1. Introduction

According to EU Regulations No. 305/2011 [1], Technical regulations [2] and the state construction standards [3], one of the basic requirements for buildings is the preservation of the bearing capacity of structures during a fire within the specified period.

One of the ways to preserve this ability is to use fire protective materials applied for building structures of various

types (for example, walls, floors, beams, columns) made of concrete, steel, wood, etc.

The types of fire-retardant materials for building structures were established in the instructions for technical approval of fire retardant materials in Europe ETAG No. 018-1 [4], ETAG No. 018-2 [5], ETAG No. 018-3 [6], ETAG No. 018-4 [7].

In accordance with these guidelines for steel structures (columns and beams), passive and reactive fire retardant

materials are used. Passive fire-retardant materials (plates, plasters, etc.) do not change their physical state during heating and provide fire protection of structures due to their thermo-physical properties. Such materials are capable of ensuring the bearing capacity of steel structures within the period of fire exposure, which can reach the value of 240 minutes, which corresponds to the highest standardized class of fire resistance of these structures [8]. However, the magnitude of the thickness of passive fire-retardant materials on steel structures is significant and reaches tens of millimeters. At the same time, the thickness of the coating from reactive fire-retardant materials on steel structures does not exceed a few millimeters. These materials under conditions of thermal influence during a fire change their physical state, increase considerably in volume due to swelling and thus provide fire protection thanks to the heat-insulating effect and the course of endothermic reactions. However, reactive fire protective materials are able to provide the bearing capacity of steel structures for a limited period of fire exposure, which usually does not exceed 90 minutes.

The effective combination of physical and chemical properties of passive and reactive fire-retardant materials caused their application in building structures, in particular, in passages of engineering communications [9], a combined fire protection system – mineral wool slabs with a reactive fire-retardant swelling coating. This combined fire protection system can be used for steel structures and provide their bearing capacity for a long period of fire exposure at the fire protective thickness, the value of which is lower than for a passive fire protection system.

Given the widespread use of steel structures in buildings and the need to minimize their weight and dimensional indicators, the research aimed at further improvement and development of the technologies of fire protection systems of these structures should be considered relevant.

2. Literature review and problem statement

According to DSTU EN 13501-2 [8], steel columns and beams belong to bearing structures that do not perform any enclosing function during a fire and have normalized classes of fire resistance from R 15 to R 240. It is considered that these structures lose their bearing ability when the values of deformation rate (the rate of axial displacement of columns and rate of beams deflection) and of actual deformation (axial displacement of columns and deflection of beams) exceed the standard values. Evaluation of fire resistance of steel structures based on the loss of bearing capacity is carried out by testing using the methods given in EN 1365-3 [10] (for beams) and EN 1365-4 [11] (for columns), or by the computational methods established by the European Construction Code EN 1993-1-2. At the same time, there is a different approach, when reaching the critical temperature by a steel structure is considered to be a sign of the loss of bearing capacity. This is the temperature, at which the steel structure destruction is expected at a uniform temperature distribution in a structure for a given level of loading [12]. This approach was implemented in standards EN 13381-4 [13] and EN 13381-8 [14], which provides test methods to determine the impact of fire-retardant materials on the fire resistance of steel structures.

These test methods [13, 14] allow obtaining the data on the fireproof capacity of a fire protection system in a

form suitable for the direct introduction to the standards of construction design. According to these methods, a series of short unloaded steel structures (1.0 m long), protected by a fire protection system, are subjected to testing in the standard temperature mode. These tests are carried out in accordance with EN 13381-4 [13] for the systems without any reactive fire-retardant materials and according to EN 13381-8 [14] for the fire protection systems with reactive materials.

In addition, loaded and unloaded beams or columns are subjected to thermal influence in a similar manner in order to obtain information on the ability of a fire protection system to remain intact and the one that retains adhesion to a steel structure (gripping ability).

These tests concern fire retardant materials, when they are used on solid steel beams or I-beam profile columns (I or H), as well as hollow columns with the round or rectangular cross-section. During testing, the temperature of structures is measured in a number of points of a steel surface. To assess a fire protection system, only the data concerning the temperature of short steel structures are used. However, these data are adjusted to fit the gripping ability. The estimation of the properties of a fire protection system, which characterize the restriction of heat exposure, is performed based on the adjusted average temperature of steel for each short structure, using one of the evaluation procedures provided in the standard. As a result of this evaluation, a series of tables and graphical images are obtained, which relate to the time intervals of retaining fire resistance of 15 minutes, 30 minutes, 45 minutes etc. Each table or graphical image indicates the minimum thickness of the fire-retardant material required to ensure that the design (critical) temperatures of 350 °C, 400 °C, ..., 750 °C on the steel structures that have certain cross-section coefficients, will not be exceeded.

According to these methods of testing [13, 14], the properties of a number of fire protection systems for steel structures, which use passive or reactive fire retardant materials, were evaluated. The results of this assessment show that the use of reactive materials ensures retaining the fire resistance of steel structures during the period of fire exposure from 15 min to 90 minutes at the thickness of the applied layer of a coating from 0.2 mm to 2.2 mm [15, 16].

Passive fire-retardant materials enhance the fire resistance of steel structures up to 240 minutes [15, 17]. However, the values of their thickness are much higher than those for reactive fire-retardant materials and reach 70 mm.

The decrease in thickness of passive fire-retardant material, necessary for the normalized fire resistance of a steel structure, can be achieved by applying a layer from the reactive fire-retardant swelling material on its exposed (heated) surface. The swelling coatings are the thermo-reactive fire retardant materials consisting of four chemical components: an acid source, a carbon source, a nitrogen source and a foaming agent [18]. The swelling process that occurs during fire exposure causes the formation of bubbles in the coating, its foaming, and an increase in volume up to 100 times relative to its original thickness [19]. The forming structure is a porous layer of many parts with high insulating properties [20, 21].

It looks like a foamed substance and manifests itself as a heat barrier with low thermal conductivity [22, 23]. Because of this, it reduces the rate of penetration of high temperature into a steel structure [24, 25].

The typical rise in the temperature of steel structures, which are equipped with a fire-retardant swelling coating, undergoes three stages [26]. Among them, the stage of a significant decrease in the temperature increase rate during the formation of the swollen layer and the stage of increasing this rate due to the high temperature, weight loss, and a decrease in the thickness of the swollen layer.

It should be noted that the results provided in the above-mentioned works are not enough to substantiate the possibility of decreasing fire resistance by applying a reactive coating to the surface of passive material. These works are mainly related to the research into the behavior of fire-retardant reactive materials applied on the steel surface. The behavior of these materials at their location on the surface of passive fire-retardant material may be different. That is why there are reasons to believe that the uncertainty of the influence of fire protection parameters on fire resistance of steel structures, in which a combined fire protection system is applied, makes the research in this direction relevant.

3. The aim and objectives of the study

The purpose of our studies was to identify the peculiarities of the thermal state of steel structures with a combined fire protection system under conditions of fire exposure in the standard temperature mode, according to [27].

To achieve the aim, the following tasks were set:

- to determine the dependences of the temperature of steel structures with passive and reactive fire-retardant materials on the duration of fire exposure in the standard temperature mode;
- to establish the influence of the thickness of components of a combined system of fire protection on the thermal state of steel structures under conditions of fire exposure in the standard temperature mode;
- to estimate the deviation between the value of the duration of achieving the critical temperature of steel, obtained for a combined and other fire protection systems.

4. Fire retardant materials and methods for studying the thermal state of steel structures with a combined fire protection system

4.1. The studied fire-retardant materials and equipment used in the experiments

The study was carried out using the passive fire-retardant material – slag cotton plate “KNAUF” THERMATX Feinfresco of the density of 300 kg/m³ and thickness of 15 mm [28]. The reactive fire-retardant swelling material “Endotherm 250103” was also used. This material has a volumetric swelling rate of 39.90 cm³/g, determined by DSTU-N-P BV.1.1-29 [30], and coating density in the dry state 1240 kg/m³.

The research into the thermal state of protected steel structures under conditions of fire exposure was carried out

with the use of a fire furnace, shown in Fig. 1 [31]. The furnace has a depth of 850 mm, a width of 650 mm, and a height of 730 mm and provides a standard temperature mode according to [27]. The temperature in the furnace was measured and controlled with the use of thermocouples T1_{fu}–T5_{fu}. The experimental sample was mounted in a vertical slot of a furnace instead of shutter 4.

To carry out the study, eight experimental samples, divided into three groups, were produced. The parameters of these samples are shown in Table 1. In this table, the thickness of the reactive fire-retardant coating corresponds to the average value of the thickness of a fire-retardant coating in the dry state.

In group A, there were three experimental samples (A1–A3) with a combined fire protection system. Experimental samples A1, A2 represented a steel plate, to one side of which a slag cotton plate with the applied reactive fire-retardant coating was attached. Steel square plates with the side of 500 mm and a thickness of 5 mm (A1) or 10 mm (A2) were used.

The specified steel plate was not used in experimental sample A3

There were three experimental samples (B1–B3) with a passive fire protection system in group B. The experimental samples of this group differed from the samples of group A by the fact that there was no reactive fire-retardant coating on the surface of the slag cotton plate.

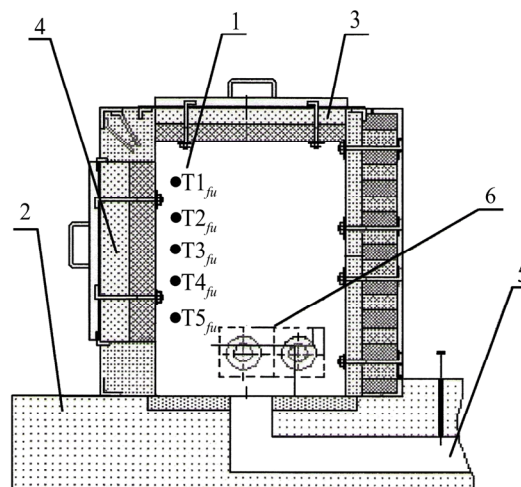


Fig. 1. General view of the fire furnace: 1 – fire chamber of furnace; 2 – concrete base; 3, 4 – furnace shutters; 5 – channel of combustion products release; 6 – burners; T1_{fu} – T5_{fu} – thermocouples in the furnace

Table 1

Parameters of the experimental samples

No.	Group	Fire protection system	Sample designation	Thickness of steel plate, mm	Thickness of passive fire protection material, mm	Thickness of reactive fire protection coating, mm
1	A	combined	A1	5	15	0.82
2	A	combined	A2	10	15	0.79
3	A	combined	A3	–	15	0.85
4	B	passive	B1	5	15	–
5	B	passive	B2	10	15	–
6	B	passive	B3	–	15	–
7	C	reactive	C1	5	–	0.78
8	C	reactive	C2	10	–	0.81

In group *C*, there were two experimental samples (*C1*, *C2*) with the reactive fire protection system. The slag cotton plate was not used in these samples. The reactive fire protection coating was applied to the surface of a steel plate on one side.

4.2. The procedure for determining the dependences of the temperature of steel structures on fire exposure duration

On the non-heated surface of the experimental samples, we mounted five thermocouples, one of which was located in the geometric center of this surface, and the rest – in the geometric centers of its separate quarters. The experimental samples from the non-heated surface were closed by the insulating plate, which consisted of two layers. The internal layer of the insulating plate, adjacent to the experimental sample, was made of ceramic cotton of the thickness of 20 mm, and the external layer – from the basalt plate of the thickness of 100 mm and density of 100 kg/m³.

The experimental sample, covered by the thermal insulation plate, was mounted in a vertical slit of the furnace. The furnace burners were turned on and the temperature in the furnace and on a non-heated surface of the experimental sample was measured and registered with the interval of 2 s. The temperature in the furnace was regulated so that the dependence of the average furnace temperature on the duration of the experiment should be consistent with the standard temperature mode according to [27]. The experiment was stopped after reaching the average temperature on the non-heated surface of the sample, determined by the readings of five thermocouples, of the value of 600 °C.

5. Results of studying the thermal state of steel structures under conditions of fire exposure

5.1. Dependences of the temperature of steel structures on the duration of fire exposure

The graphs of the measured values of the average temperature on the non-heated surface of the experimental samples (hereinafter – the temperature of experimental samples) of group *A* (with a combined fire protection system) are shown in Fig. 2. For all the samples of this group, the dependence of their temperature on the duration of fire exposure in the standard temperature mode has a monotonously growing character. The temperature increase rate is the highest for sample *A3* (without the steel plate), the lowest – for sample *A2* (with the steel plate of the thickness of 10 mm). The temperature value of 600 °C for these samples is reached at the 34th and 111th minutes, respectively. For sample *A1* (with a steel plate of the thickness of 5 mm), this temperature is reached at the 85th minute.

The results of measuring the thickness of the swollen layer of the fire protection coating after cooling the experimental samples to room temperature revealed that the maximum value of this layer is 18.2 mm, 16.9 mm, and 34.5 mm, respectively, for samples *A1*, *A2*, and *A3*.

The graphs of changing the temperature of the experimental samples of group *B* (with the passive fire protection system) are shown in Fig. 3. For all the samples of this group,

the nature of their temperature dependence on the duration of fire exposure under the standard temperature mode is the same as for the sample of group *A*. Sample *B3* (without a steel plate) has the highest temperature increase rate and sample *A2* (with the steel plate of the thickness of 10 mm) has the lowest rate. The temperature of 600 °C for these samples is achieved on the 16th and on the 101st minute, respectively. For sample *B1* (with a steel plate of the thickness of 5 mm), this temperature is achieved at the 69th minute.

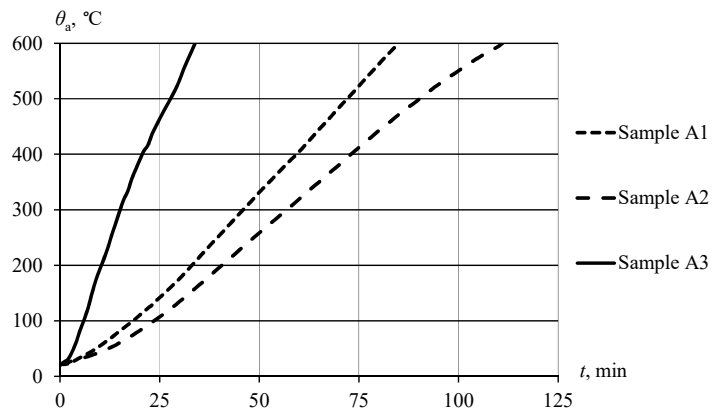


Fig. 2. Dependences of the temperature of the experimental samples of groups *A* (with a combined fire protection system) on the fire exposure duration in the standard temperature mode

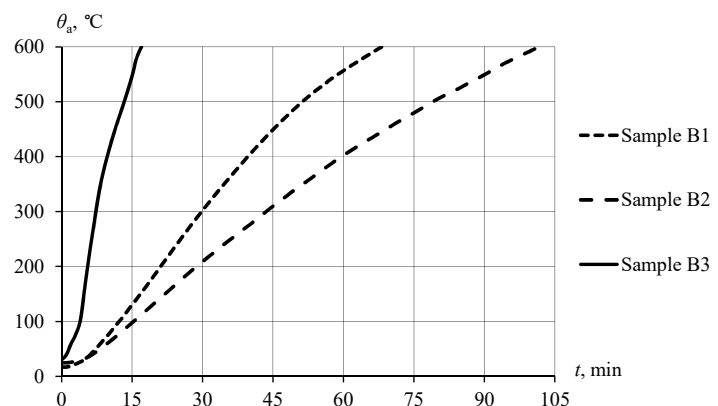


Fig. 3. Dependences of the temperature of the experimental samples of group *B* (with the passive fire protection system) on the duration of fire exposure under the standard temperature mode

For the experimental samples of group *C* (with the reactive fire protection system), the diagrams of the temperature change are shown in Fig. 4. For these samples, there is a typical increase in the temperature of steel structures, covered with the reactive fire-retardant swelling material [26]. At the first stage, where the samples' temperature is below 200 °C, the rate of an increase in their temperature is high. This is due to the fact that the thermo-physical and chemical properties of the reactive fire-retardant material at this stage do not undergo significant changes. Due to this and because of relatively high values of thermal conductivity coefficient and density of the reactive material, as well as the existence of a thin layer of fire-retardant coating, there is a significant increase in temperature of the experimental samples at this stage. The temperature of 200 °C for samples *C1* and *C2* is achieved at the 4th and the 7th minutes, respectively. At the second stage, at which the sample temperature has the values from 200 °C to 350 °C, the coating undergoes full

swelling with the formation of a thick layer with low density and a carbonized fire-retardant layer that has low thermal conductivity. The rate of an increase in temperature of the experimental samples at this stage is moderate compared to the first stage. The temperature of 350 °C for samples C1 and C2 is achieved at the 10th and 24th minutes, respectively. In the third stage, when the temperature of the samples is higher than 350 °C, the thermal conductivity of the coating increases due to high temperature, weight loss, and a decrease in thickness. The rate of temperature increase in the experimental samples at this stage is noticeably increased in comparison with the second stage. The temperature of 600 °C for samples C1 and C2 is achieved at the 23rd and 55th minutes, respectively.

According to the results of measuring the thickness of the swollen layer of the fire-retardant coating after cooling the experimental samples to room temperature, it was determined that the maximum value of this layer is 18.0 mm and 17.1 mm, respectively, for samples C1 and C2.

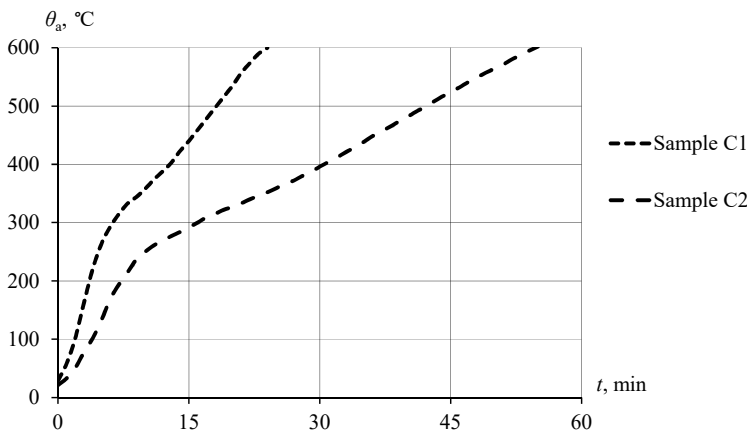


Fig. 4. Dependences of the temperature of experimental samples of group C (with the reactive fire protection system) on the duration of fire exposure in the standard temperature mode (samples 8, 9) (C1, C2)

According to the temperature data, the value of the fire exposure duration in the standard temperature mode, when different magnitudes of the design (critical) temperature of steel (hereinafter – the duration of achieving the critical temperature of steel) is achieved, were determined. The values of this duration are shown in Table 2.

Table 2

The values of achievement of the critical temperature of steel

Critical temperature of steel θ_{cr} , °C	350	400	450	500	550	600
Sample	Values of duration of achievement of critical temperature of steel t_{cr} , min					
A1	52	59	65	72	79	85
A2	65	73	81	90	99	111
A3	18	21	24	28	31	34
B1	35	40	45	52	59	69
B2	51	59	68	78	89	101
B3	8	9	11	13	15	16
C1	9	12	15	18	20	23
C2	24	30	36	42	48	55

The data shown in Table 2 were used during the analysis of the results of measuring the temperature of the experimental samples and constructing dependences and making calculations, which are presented below.

5. 2. Influence of the thickness of components a combined fire protection system on the thermal state of steel structures

The influence of the thickness of steel plate d_a (hereinafter – the thickness of a steel structure) with a combined fire protection system on the duration of achievement of the critical temperature of steel is shown in Fig. 5. The dependence of this duration on the thickness of a steel structure has a monotonously growing character. The duration increase rate is greater for smaller values of thickness d_a . At the increase in thickness from 0 to 10 mm, the highest increase in duration, which is 77 minutes, occurs for the critical temperature value of 600 °C, the lowest (47 min) – for a temperature of 350 °C. In this case, the relative increase in duration (reduced to magnitude t_{cr} , determined for thickness d_a , which is 10 mm) is the same for all values of the critical temperature of steel and makes up 71 %.

Dependence of the duration of achievement of the critical temperature of steel on the thickness of a steel structure with the passive fire protection system (Fig. 6) has the same monotonously growing character as for the combined system. At the increase in thickness from 0 to 10 mm, the highest increase in duration, which is 85 minutes, occurs for the critical temperature of 600 °C, the lowest (43 min) – for the temperature of 350 °C. In this case, the relative increase in duration is also the same for all values of the critical temperature of steel and makes up 84 %.

The influence of the thickness of a steel structure with a reactive fire protection system on the duration of achieving the critical temperature of steel is shown in Fig. 7.

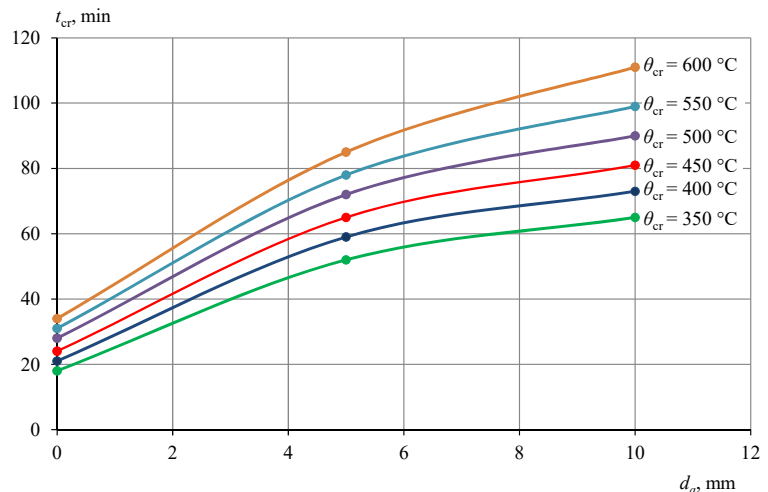


Fig. 5. Dependence of duration of achievement of the critical temperature of steel on the thickness of a steel structure with a combined fire protection system (Table 1, group A)

In Fig. 7, the magnitudes of duration t_{cr} for thickness $d_a=0$ correspond to the time intervals, in which according to the standard temperature mode according to [18], the corresponding values of the critical temperature of steel θ_c

are achieved. Thus, the magnitudes of duration t_{cr} are 1 min, 2 min, 2 min, 3 min, 4 min, and 5 min respectively for such values of critical temperature θ_{cr} : 350 °C, 400 °C, 450 °C, 500 °C, 550 °C, and 600 °C.

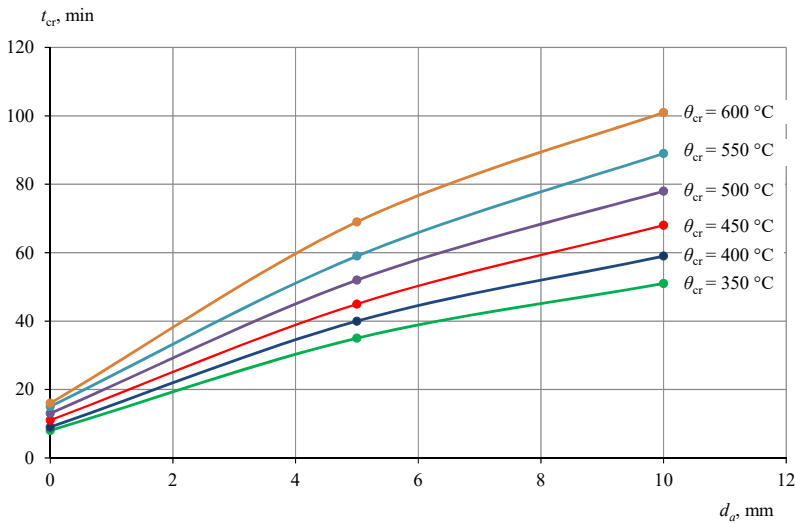


Fig. 6. Dependence of the duration of achieving the critical steel temperature on the thickness of a steel structure with a passive fire protection system (Table 1, group B)

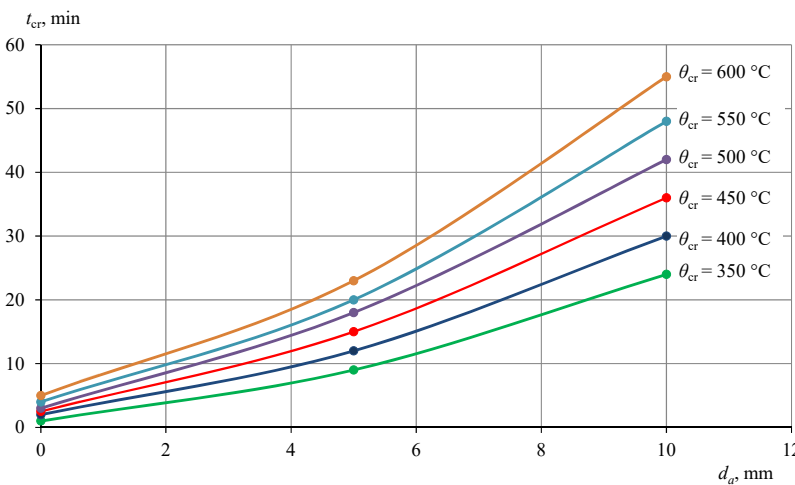


Fig. 7. Dependence of duration of achievement of the critical temperature of steel on the thickness of a steel structure with a reactive fire protection system (Table 1, group C)

Analysis of Fig. 7 reveals that for steel structures with the reactive fire protection system as well as for other systems, the dependence of the duration of the achievement of the critical temperature of steel has a monotonously growing character.

However, for a reactive system, unlike other fire protection systems, the rate of an increase in the duration is higher for higher values of thickness d_a . At an increase in thickness d_a from 0 to 10 mm, the greatest increase in duration, which is 50 minutes, takes place for the value of the critical temperature of 600 °C, the lowest (23 min) – for a temperature of 350 °C. In this case, the magnitude of a relative increase in duration has an insignificant dependence on the critical temperature of steel and decreases from 96 % (at 350 °C) to 91 % (at a temperature of 600 °C).

5.3. Estimation of deviation between the durations of achievement of critical temperature, obtained for various fire protection systems

According to formula (1), we calculated the deviation (difference) $\delta t_{cr,AB}$ between the values of duration of achievements of the critical temperature of steel, obtained for steel structures with a combined and a passive fire protection system. The calculations were carried out for the values of critical temperature from 350 °C to 600 °C (with the pitch of 50 °C) and thickness d_a , which makes up 0, 5 mm and 10 mm. For example, when calculating $\delta t_{cr,AB}$ for the critical temperature of 500 °C and thickness d_a , which makes up 5 mm, values $t_{cr,A}$ and $t_{cr,B}$ make up, respectively, 72 min (Tables 1, 2, sample A1, fig. 8, group A) and 52 min (Tables 1, 2, sample B1, Fig. 8, group B). The calculation results are presented in Table 3.

$$\delta t_{cr,AB} = 100(t_{cr,A} - t_{cr,B}) / t_{cr,A}, \quad (1)$$

where $t_{cr,A}$ is the duration of achievement of a certain critical temperature of steel, determined for the experimental sample of group A (with a combined fire protection system), which has a certain thickness of a steel plate d_a , min; $t_{cr,B}$ is the duration of achievement of the critical temperature of steel that is the same as for the experimental sample of group B (with the passive fire protection system), min.

Analysis of the data given in Table 3 reveals that deviation $\delta t_{cr,AB}$ with an increase in the thickness of a steel structure significantly decreases. For example, for the critical temperature of 600 °C with an increase in thickness from 0 to 10 mm, this decrease is 83 %. An increase in this deviation is caused by an increase in the critical temperature of steel (Fig. 9). For example, for the thickness of 5 mm and the critical temperature of 600 °C, deviation $\delta t_{cr,AB}$ has the value that is 39 % less than for the critical temperature of 350 °C.

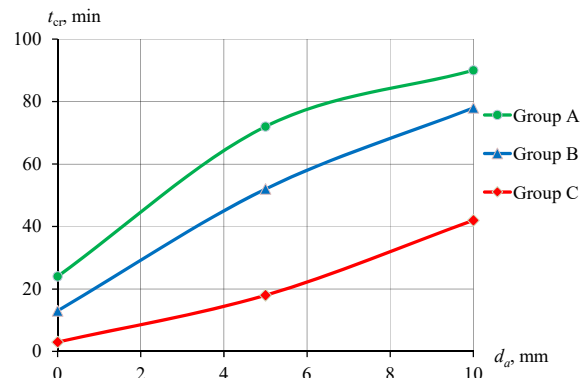


Fig. 8. Dependence of the duration of achievement of the critical temperature of steel, which is 500 °C on the thickness of a steel structure with various fire protection systems

Table 3

The values of indicators of deviation of the duration of achieving the critical temperature of steel

Critical temperature of steel $\theta_{cr}, ^\circ\text{C}$	350	400	450	500	550	600	
Deviation indicator	Values of deviation indicator						
Thickness $d_a,$ mm							
$\delta t_{cr,AB}, \%$	0	56	57	54	54	52	53
$\delta t_{cr,AB}, \%$	5	33	32	31	28	24	19
$\delta t_{cr,AB}, \%$	10	22	20	16	13	11	9
$\delta t_{cr,AB}, \%$	0	50	48	46	43	39	38
$\delta t_{cr,AB}, \%$	5	15	12	8	3	0	-4
$\delta t_{cr,AB}, \%$	10	-15	-22	-28	-30	-33	-41

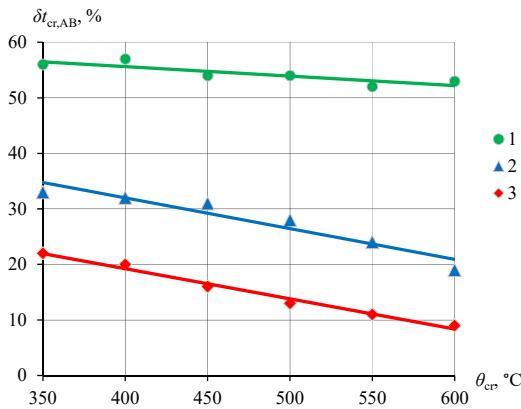


Fig. 9. Dependence of deviation $\delta t_{cr,AB}$ on the critical temperature of steel for different values of thickness of a steel structure: 1 – $d_a=0$; 2 – $d_a=5$ mm; 3 – $d_a=10$ mm

This dependence of deviation $\delta t_{cr,AB}$ on the critical temperature of steel, and the thickness of a steel structure can be explained by a decrease in thermal insulation efficiency of the reactive fire retardant coating after completion of the stage, where the coating undergoes complete swelling.

Under further fire exposure, the thermal conductivity of the coating increases due to high temperature, weight loss, and decreased thickness. Fig. 10 shows the dependence of deviation $\delta t_{cr,AB}$ on duration $t_{cr,A}$, which was constructed according to the data of Tables 2, 3. From this graph it follows that deviation $\delta t_{cr,AB}$ significantly decreases at an increase in duration $t_{cr,A}$. At an increase in $t_{cr,A}$ by five times (from 20 min to 100 min), deviation $\delta t_{cr,AB}$ decreases by 5.2 times (from 57 % to 11 %).

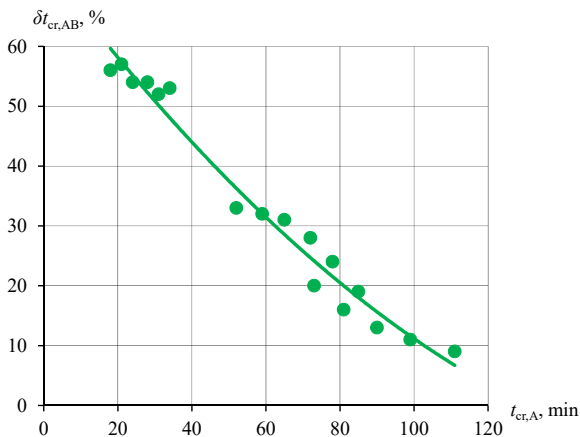


Fig. 10. Dependence of deviation $\delta t_{cr,AB}$ on duration $t_{cr,A}$

Table 3 also shows the data, determined from formula (2), regarding the deviation (difference) between the values of duration $t_{cr,A}$, obtained for the experimental samples of group A, and the values of duration $t_{cr,B}$ and $t_{cr,C}$, obtained for the samples of groups B and C.

For example, when calculating $\delta t_{cr,ABC}$ for the critical temperature of 500 °C and thickness d_a , which is 5 mm, values $t_{cr,A}$, $t_{cr,B}$ and $t_{cr,C}$ make up, respectively, 72 min (Table 1, 2, sample A1, Fig. 8, group A), 52 min (Table 1, 2, sample B1, Fig. 8, group B) and 18 min (Tables 1, 2, sample C1, Fig. 8, group C). Dependence of deviation $\delta t_{cr,ABC}$ on the critical temperature of steel is shown in Fig. 11.

$$\delta t_{cr,ABC} = 100 \left(t_{cr,A} - (t_{cr,B} + t_{cr,C}) \right) / t_{cr,A} \quad (2)$$

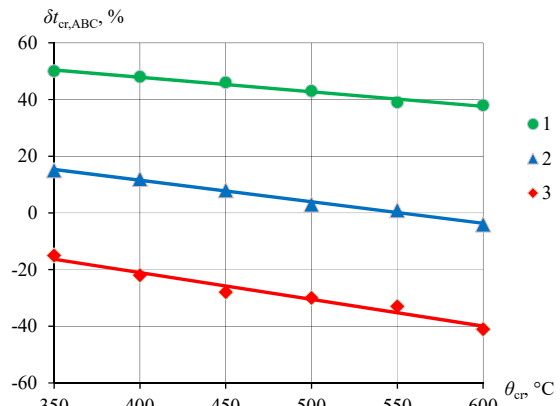


Fig. 11. Dependence of deviation $\delta t_{cr,ABC}$ on critical temperature of steel: 1 – $d_a=0$; 2 – $d_a=5$ mm; 3 – $d_a=10$ mm

It follows from the data shown in Table 3 and in Fig. 11 that deviation $\delta t_{cr,ABC}$ has positive magnitudes for the experimental samples, in which a steel plate was not used, and for the samples with a steel plate of the thickness of 5 mm. The exception is the value of deviation for the critical temperature of 600 °C and the samples with a steel plate having a thickness of 5 mm. The maximum duration of fire exposure, at which deviation $\delta t_{cr,ABC}$ has positive magnitudes, is 79 min (Table 2, sample A1, $\theta_{cr}=550$ °C).

For the experimental samples with a steel plate of the thickness of 10 mm, deviation $\delta t_{cr,ABC}$ has negative values. The existence of positive values of deviation $\delta t_{cr,ABC}$ means that under certain conditions, the value of the duration of achievement of the critical temperature for a combined fire protection system exceeds the sum of durations that occur for passive and reactive systems.

The existence of negative magnitudes of deviation $\delta t_{cr,ABC}$ for the thickness of 5 mm and 10 mm is explained by the fact that component $(t_{cr,B} + t_{cr,C})$ in formula (2) due to the significant magnitudes of duration $t_{cr,C}$ has the value that exceeds duration $t_{cr,A}$.

6. Discussion of results of studying the thermal state of steel structures with a combined fire protection system

As it follows from the obtained results (Table 3, Fig. 9, 10), when applying a combined fire protection system for steel structures, an increase in the duration of the achievement of the critical temperature of steel compared to passive and reactive fire protection systems is natural.

This is due to the effective combination of physical and chemical properties of passive and reactive fire-retardant materials.

Passive fire-retardant material ensures fire protection of a steel structure due to its thermo-physical properties, while reactive fire-retardant material does it due to the heat-insulating effect and the course of endothermic reactions [13, 14].

It should be noted that the existence of the reactive fire-retardant material on the surface of a slag cotton plate leads to a significant increase in the duration of achievement of the critical temperature at the stage when the reactive coating undergoes swelling. This is due to the formation at this stage of a thick layer with low density and a carbonized fire-retardant layer having low thermal conductivity.

At the subsequent increase in the duration of fire exposure, the thermal conductivity of a coating increases due to the high temperature, weight loss, and a decrease in thickness, which leads to a decrease in the effectiveness of reactive material.

In this sense, the most interesting is the interpretation of the results of determining deviations $\delta t_{cr,AB}$, $\delta t_{cr,ABC}$, shown in Fig. 10, 11, which proves the fact of decreasing the effectiveness of the reactive fire retardant material with an increase in the duration of fire exposure.

This indicates the existence of the value of fire exposure duration, above which the application of reactive fire-retardant material to the surface of the slag cotton plate does not lead to an increase in the duration of achievement of the critical temperature of steel. In addition, the existence of positive values of deviation $\delta t_{cr,ABC}$ for the range of fire exposure duration, which is from 0 to 79 minutes, indicates the effectiveness of the combined fire protection system in this range.

The obtained data on the duration of achievement of the critical temperature of steel, obtained for steel structures with various fire protection systems, make it possible to assert the following:

- for a combined fire protection system, the duration of achievement of the critical temperature of steel significantly depends on the thickness of a steel structure, and this dependence has a monotonously growing character;
- the effectiveness of a combined fire protection system is the highest for small values of thickness of a steel structure. At an increase in the duration of fire exposure, its efficiency decreases. For a certain duration of fire exposure, the application on the surface of passive fire-retardant material of the layer of the reactive coating does not make sense, because this application does not lead to an increase in the duration of the critical temperature of steel.

Such conclusions can be considered appropriate from the practical point of view because they make it possible to have a reasonable approach to determining the values of the thickness of components of a combined fire protection system.

From the theoretical point of view, they make it possible to argue about the certainty of the mechanism of combined fire protection, which is a definite advantage of this study. However, we can't but note that the results of this study were obtained for a combined fire protection system, which includes passive and reactive fire materials of only two trademarks [28, 29]. In addition, the maximum value of the duration of achievement of the critical temperature of steel, determined for this fire protection system, which is 111 minutes, is significantly lower than the fire exposure duration for the highest standardized class of fire resistance steel structures R 240 [8].

The results of determining deviation $\delta t_{cr,AB}$ (Fig. 10) do not indicate completely the unambiguous influence of dura-

tion $t_{cr,A}$ on the magnitude of this deviation for a combined fire protection system.

The influence for a combined fire protection system, in which the thickness of the layer from passive material exceeds 15 mm and duration of $t_{cr,A}$ reaches 240 minutes is ambiguous. Such uncertainty imposes certain restrictions on the use of the obtained results, which may be interpreted as the shortcomings of this study. The inability to withdraw the specified restrictions within this study generates a potentially interesting direction for further research. They may, in particular, be oriented towards the detection of dependences between the duration of achievement of the critical temperature of steel, fire retardant thickness, and the thickness of a steel structure for combined fire protection systems, suitable to ensure fire resistance within 240 minutes.

Such detection will make it possible to determine the optimum parameters of combined fire protection systems for steel structures that are acceptable to ensure their bearing ability for a wide range of fire exposure duration in the standard temperature mode.

7. Conclusions

1. The conducted research established the peculiarities of temperature dependences of steel structures with passive and reactive fire retardant materials of two brands on the fire exposure duration in the standard temperature mode. It was established that these dependences for steel structures with combined, passive, and reactive fire protection systems have a monotonously increasing character. The maximum values of fire exposure duration are for the experimental samples that have the thickness of a steel plate of 10 mm, for a critical temperature of steel of 600 °C. They are 111 minutes, 101 minutes, 55 minutes, respectively, for the combined, passive, and reactive fire protection systems.

For the experimental samples with the reactive fire protection system, there is a typical increase of their temperature, which is related to a change of thermo-physical and chemical properties of the reactive swelling fire-retardant material under conditions of fire exposure in the standard temperature mode.

2. It was established that the dependences of the duration of achievement of the critical temperature of steel on the thickness of a steel structure with the combined, passive, and reactive fire protection systems have a monotonously increasing character. At an increase in the thickness of a steel structure from 0 to 10 mm, the relative increase in the duration of achievement of critical temperature is the same for all values of this temperature and is 71 %, 84 % and 93 %, respectively, for the combined, passive, and reactive systems.

3. It was established that for a combined fire protection system, an increase in the duration of achievement of the critical temperature of steel compared to passive and reactive fire protection systems is natural, which is due to the effective combination of physical and chemical properties of passive and reactive fire-retardant material. For the fire exposure duration up to 79 min, the value of the duration of achievement of the critical temperature of steel for a combined fire protection system exceeds the sum of the duration of its achievement, which takes place for passive and reactive fire protection systems. This indicates the effectiveness of the combined system in this range of duration of fire exposure. At an increase in the duration of fire exposure, the efficiency of this fire protection system decreases.

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