Для оцінювання вогнезахисної здатності матеріалів для сталевих конструкцій застосовують методи випробувань, які наведені в стандартах EN 13381-4:2013 і EN 13381-8:2013. За результатами цих випробувань визначають дані про мінімальні товщини вогнезахисних матеріалів, які в подальшому використовують при проектуванні сталевих конструкцій. Ці випробування дуже трудомісткі і вимагають значних витрат на створення стандартизованих зразків і проведення випробувань. У той же час існують методи, в яких використовують зразки зменшених розмірів і іншої форми, ніж у стандартизованих зразків. Актуальним є питання про можливість застосування методів зі зменшеними зразками як альтернативу методам EN 13381-4:2013 і EN 13381-8:2013. У статті досліджувалася збіжність результатів оцінювання вогнезахисної здатності двох типів вогнезахисних матеріалів для сталевих конструкцій, отриманих при випробуваннях стандартизованих зразків і зразків зменшених розмірів. Встановлено, що значення мінімальної товщини реактивного вогнезахисного матеріалу, отримані за даними випробувань зразків зменшених розмірів, мають переважно більші величини, ніж при застосуванні стандартизованих зразків. Для пасивного вогнезахисного матеріалу мають місце переважно більші величини значення мінімальної товщини, отримані з використанням стандартизованих зразків. Різниця між значеннями мінімальної товщини реактивного вогнезахисного матеріалу, отриманими на зразках зменшених розмірів і стандартизованих зразках, досягає 79,0 %, а для пасивного вогнезахисного матеріалу – 62,5 %. Такі значення різниці свідчать про неможливість застосування зразків зменшених розмірів для оцінювання вогнезахисної здатності матеріалів для сталевих конструкцій для всіх діапазонів зведеної товщини сталевого профілю, критичної температури сталі і нормованої межі вогнестійкості конструкцій, наведених в EN 13381-4:2013 і EN 13381-8:2013

Ключові слова: вогнезахисна здатність, вогнезахисний матеріал, критична температура, межа вогнестійкості, сталева конструкція

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INFLUENCE OF TESTING SAMPLES' PARAMETERS ON THE RESULTS OF EVALUATING THE FIRE-PROTECTIVE CAPABILITY OF MATERIALS

S. Novak
PhD, Senior Researcher*
E-mail: novak.s.fire@gmail.com
V. Drizhd
PhD
Research and Production Enterprise "Spetsmaterialy"
Telmana str., 12, Borispol, Ukraine, 08304
E-mail: varvara.drizhd@gmail.com
O. Dobrostan
PhD*
E-mail: dob2009@ukr.net
L. Maladyka
PhD
Department of Fire and Prevention
National University of Civil Defence of Ukraine
Chernyshevska str., 94, Kharkiv, Ukraine, 61023
E-mail: l.maladyka@gmail.com
*Scientific Testing Center
Ukrainian Civil Protection Research Institute
Rybalska str., 18, Kyiv, Ukraine, 01011

1. Introduction

One of the main requirements for buildings and structures is to maintain the bearing capacity of building structures during a fire. It applies to steel structures widely used in construction, such as columns and beams. Fire resistance of these structures is insignificant due to the significant thermal conductivity of steel. Therefore, we have to use reactive and passive fire-protective materials to increase their bearing capacity [1, 2].

Reactive fire-protective materials are materials, which provide formation of a heat-insulating coating (swelling materials) under conditions of fire, and ablation materials.

Such materials provide fire protection of structures due to heat-insulating and endothermic effects. Passive fire-protective materials are materials, which do not change their physical state under heating and provide protection due to their physical and thermal properties. Passive fire-protective materials include materials, which contain water or substances that absorb heat and provide heat absorption under heating. Such materials may be coatings applied by the method of spraying, plasters, mats, panels and slabs.

It is necessary to perform tests according to EN 13381-4 [1] (for passive fire-protective materials) or EN 13381-8 [2] (for reactive fire-protective materials) to determine minimum values of the thickness of fire-protective materials, which are sufficient to stop rising of temperature of steel structures before the critical temperature of steel for the normal duration of a fire impact under the standard temperature mode. There is a valid DSTU B V.1.1-17 [3] in Ukraine. It corresponds to the European standards. Testing goes using standardized samples, such as steel columns (with a height of 1.0 m) and beams (with a length of 4.0 m and 1.0 m) of various profiles. It is necessary to place samples into a furnace (beams of 4.0 m in length under mechanical load, other samples without load) and subject them to fire exposure under the standard temperature mode and measure the temperature in certain places on their metal surface. It is necessary to correct the obtained experimental data in terms of the given temperature, taking into account parameters of ability of fire-protective material to cohesion and (or) ability to stay intact during a fire impact. It is possible to determine the mentioned parameters by comparison of temperature values on the loaded and unloaded beams. Based on the corrected data on temperature of samples, we can define a value of the minimum thickness of fire-protective material using one of the methods for assessment given in the above-mentioned standards. We can determine values for different values of reduced thickness of a steel profile, temperature of steel and duration of fire impact, which corresponds to the normalized threshold of fire resistance. The obtained values of the minimum thickness of fire-protective material characterize its fire-protective capacity. Application of methods with standardized samples is mandatory for determination of data on fire resistance of materials used in design of steel structures.

There are methods, which imply using of samples of shapes and sizes, which are different from the standardized samples, for assessment of fire resistance of materials for steel structures in addition to the test methods [1, 2]. In particular, authors of paper [4] apply method with the use of square steel plates with a side of 500 mm and thickness of 5 mm. Researchers covered plate surface, which was exposed to heat, with fire-protective material with a layer of thermal insulation from their unheated side. According to the method from works [5, 6], researchers used plates with thickness of 10 mm in addition to the steel plates specified above. There were square steel plates with a side of 200 mm and thickness of 5 mm in addition to steel plates with a side of 500 mm and thickness of 5 mm, in methods in papers [7, 8].

Methods with samples of shapes and sizes, which differ from standardized samples (hereinafter – "samples of reduced sizes"), are not suitable for determination of data on fire resistance of materials used in design of steel structures.

These methods do not imply mechanical loading on samples. Their implementation requires much lower material costs than for the methods with standardized samples. Therefore, the question of introduction of methods with samples of reduced size is expedient as an alternative to the methods [1, 2] for determination of data on fire-resistance of materials used in design of steel structures.

We can substantiate possibility of such implementation based on the analysis of data on convergence of results of assessment of the fire-protective capacity of materials. We can obtain the data by methods with the use of standardized samples and samples of reduced sizes. Therefore, we can consider studies aimed at further improvement and development of methods for assessment of the fire-protective capacity of materials for load-bearing steel structures as expedient ones. In particular, the study of an influence of sample parameters for tests (their shape and size) on results of assessment of the fire-protective capacity of materials for steel structures is also expedient.

2. Literature review and problem statement

Studies on fire resistance of steel structures found that loss of bearing capacity of steel structures (collapse of a structure or appearance of boundary deformations) occurs at the initial stage of a developed fire in the absence of fire-protective materials [9]. The paper presented data on fire resistance of unprotected steel beams obtained by the calculation method and during tests. However, we should note that the paper did not provide data on fire resistance of steel structures with fire-protective materials. Authors of paper [10] determined fire resistance of steel structures protected by reactive coatings according to the experimental studies. Authors of a work [11] presented the results of experimental studies on an influence of external coating on efficiency of reactive fire-protective materials for steel structures. They carried out the above-mentioned experimental studies of fire-protective materials using standardized samples. Unfortunately, these works did not presented the results of research on data on fire resistance of materials for samples of different shape and size. Paper [12] presented data on behavior of steel columns with partial damage to fire protection under a fire impact. The data gave possibility to predict fire resistance of steel structures under conditions of a real fire. There were no data on a thermal state of protected steel structures under fire conditions by the standard temperature mode in the paper. Work [13] provided the procedure and results of calculation of fire resistance of steel structures with reactive fire-protective material using the condition for the constant value of its coefficient of thermal conductivity. We can use the results of the studies to assess fire-protective capacity of materials for steel structures. However, the presented procedure is not suitable for determination of a thermal state of protected steel structures of various shapes and sizes. Authors of work [14] provided data on convergence of experimental data on duration of a fire impact to reaching the critical temperature of steel for standardized samples and samples of reduced sizes. These data are for the "Endotherm 400202" [15] reactive fire-protective material, which swells under a heat impact under fire conditions, and for the "Endotherm 210104" passive fire-protective material (plates) [16]. The results obtained in work [14] showed the satisfactory convergence of experimental data on duration of a fire impact to reaching the critical temperature of steel for standardized samples [1, 2] and samples of reduced sizes [5]. This makes possible to use samples of reduced sizes to assess a thermal state of protected steel structures under standard temperature mode instead of standardized samples. The above-mentioned gives possibility to reduce material costs for creation of samples and to carry out an assessment of a thermal state of protected steel structures. However, the results presented in work [14] are insufficient for substantiation of possibility of using of samples of reduced size for assessment of the fire-protective capacity of materials.

Therefore, we have reasons to believe that lack of certainty in the question about an influence of a shape and size of samples for tests of protected steel structures (hereinafter – test parameters of samples) on results of assessment of the fire-protective capacity of materials necessitates the study in this direction.

3. The aim and objectives of the study

The objective of this study is determination of the convergence of results of assessment of the fire-protective capacity of materials for steel structures by methods using standardized samples and samples of reduced sizes.

We set the following tasks to achieve the objective:

– assessment of the fire-protective capacity of reactive materials and passive materials for steel structures according to test data on standardized samples and samples of reduced sizes;

– assessment of convergence between values of the minimum thickness of fire-protective materials obtained from data on tests of standardized samples and samples of reduced sizes.

4. Methods to study the influence of parameters of test samples on results of assessment of fire-protective capacity of materials

We used the "Endotherm 400202" reactive fire-protective material [15] and the "Endotherm 210104" passive fire-protective material [16] (hereinafter – reactive fire-protective material and passive fire-protective material, respectively) as study materials to resolve the tasks.

We used the method given in papers [4–6] to assess the fire-protective capacity of materials on samples of reduced sizes. The method consists in the experimental determination of non-stationary heating of fire-protective material under a fire impact by the standard temperature mode. We used square steel plates with a side of 500 mm and thickness of 5 mm and 10 mm as samples.

We determined values of time required to reach the critical temperature of steel in the range from 350 °C to 600 °C (with a step of 50 °C) on these plates by the results of measurements of temperature of steel plates for each sample. We approximated the data on this time using the numerical linear regression equation, which establishes the relationship between time required to reach the critical temperature of steel, thickness of fire-protective material and thickness of a steel plate. We calculated the value of $d_{p,cul}$ minimum thickness of fire-protective material by a formula (1) for different values of the normalized fire resistance threshold, the critical temperature of steel and the reduced thickness of a steel profile.

$$d_{p,cul} = \frac{t_{cr} - a_0 - a_3\theta_{cr} - a_6\theta_{cr}\dfrac{V}{A_m} - a_7\dfrac{V}{A_m}}{a_1 + a_4\theta_{cr} + a_2\dfrac{V}{A_m} + a_5\theta_{cr}\dfrac{V}{A_m}}, \quad (1)$$

where $d_{p,cul}$ is the value of the minimum thickness of fire-protective material obtained by the tests carried out on samples of reduced sizes, mm; t_{cr} is the normalized threshold of fire resistance of a steel structure, min; θ_{cr} is the critical temperature of steel, °C; V/A_m is the reduced thickness of a steel profile, mm; a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7 are the constants (regression coefficients).

We carried out the assessment of the fire-protective capacity of reactive and passive fire-protective materials on standardized samples according to the method given in DSTU B V.1.1-17 [3]. We applied the reactive fire-protective material to the surface of steel profiles. We also created a box-type fire protection system of a rectangular cross-section using the passive fire-protective material. We exposed standardized samples (steel columns and flanged beams) to fire according to the standard temperature mode. Two of four beams were under mechanical load. We measured temperature of columns and beams for each sample and determined values of the time required to reach the critical temperature of steel in the range from 350 °C to 750 °C (with a step of 50 °C). We corrected the data related to the time, taking into account parameters of ability of the fire-protective material to coherence and (or) ability to remain intact during a fire impact. We determined these parameters by comparison of values of the time required to reach the critical temperature of steel on loaded and unloaded beams.

We determined the value of d_p minimum thickness of the fire-protective material according to the corrected data by the method of numerical linear regression using the formula, which was analogous to formula (1). We calculated the thickness values for the same values of a normalized fire resistance threshold, critical temperature of steel and reduced thickness of a steel profile used in the assessment of the fire-protective capacity based on experimental data obtained on samples of reduced sizes.

Paper [14] gave parameters of standardized samples and samples of reduced sizes and the results of determination of values of the time required to reach the critical temperature of steel for reactive and passive fire-protective materials on these samples.

We calculated $\delta_{d,cul}$ deviations (differences) between values of the minimum thickness obtained by the tests performed on samples of reduced sizes and the values of the minimum thickness obtained by the tests performed on standardized samples according to formula (2). We performed calculations for values of the normalized threshold of fire resistance from 30 minutes to 90 minutes – for the reactive fire-protective material, and from 45 minutes to 240 minutes – for the passive fire-protective material. We changed the value of the critical temperature of steel from 350 °C to 650 °C for the reactive fire-protective material, and from 350 °C to 750 °C for the passive fire-protective material. The range of values for the reduced thickness of a steel profile was from 2.9 mm to 14.3 mm for the reactive fire-protective material, and from 4.0 mm to 20.0 mm for the passive fire-protective material.

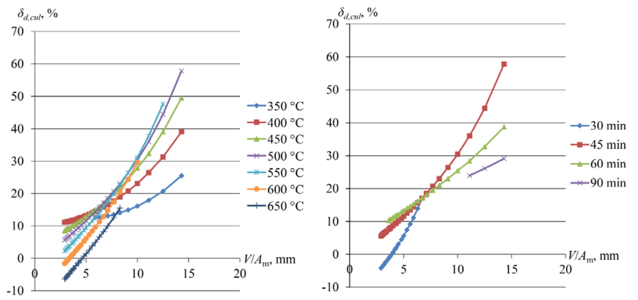
$$\delta_{d,cul} = 100 \cdot (d_{p,cul} - d_p) / d_p, \quad (2)$$

where $d_{p,cul}$ is the value of the minimum thickness of fire-protective material obtained by the tests carried out on samples of reduced sizes, mm; d_p is the value of the minimum thickness of fire-protective material obtained by the tests carried out on standardized samples, mm.

5. Results of studying the influence of parameters of samples for tests on the results of the assessment of the fire-protective capacity of materials

We found that the investigated fire-protective materials provide different ranges of the normalized threshold of fire resistance of steel structures. It makes up from 30 minutes to 90 minutes for the reactive fire-protective material and from 45 minutes to 240 minutes for the passive fire-protective material. Values of the minimum thickness of fire-protective materials depend on the value of reduced thickness of a steel profile, critical temperature of steel and a normalized threshold of fire resistance of a steel structure. These values vary from 0.37 mm to 2.07 mm for the reactive fire-protective materials, and from 13.0 mm to 63.8 mm for the passive fire-protective materials.

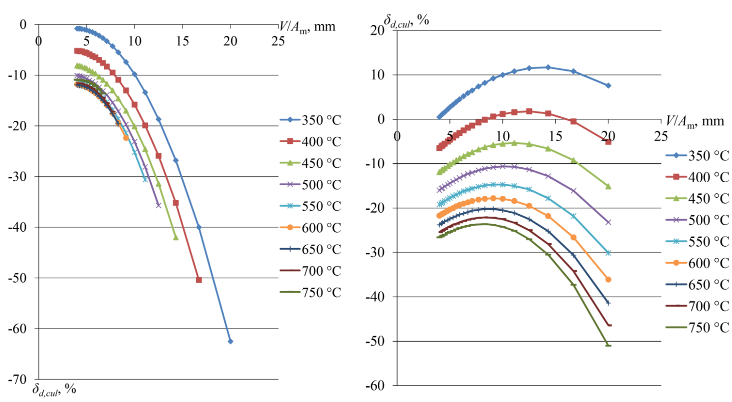
The dependence of $\delta_{d,cul}$ deviation on the reduced thickness of a steel profile for the reactive fire-protective material is monotonic in nature. $\delta_{d,cul}$ deviation increases significantly with an increase in the reduced thickness. Its value depends on the value of the critical temperature of steel and the normalized fire resistance threshold (Fig. 1).



a *b*

Fig. 1. Dependence of $\delta_{d,cul}$ deviation on V/A_m reduced thickness defined for the reactive fire-protective material: *a* – for the normalized threshold of fire resistance of 45 minutes and different values of θ_{cr} critical temperature of steel (°C); *b* – for the critical temperature of steel of 500 °C and different values of t_{cr} normalized fire resistance threshold (min)

$\delta_{d,cul}$ deviation decreases with an increase in the reduced thickness for the passive fire-protective material at values of the normalized fire resistance threshold of 45 minutes and 60 minutes (Fig. 2, *a*). Most of these dependencies have an extremum for other values of the normalized fire resistance threshold (Fig. 2, *b*). $\delta_{d,cul}$ deviation increases with an increase in the reduced thickness from the minimum value to some value. Further increase of the reduced thickness leads to a decrease in $\delta_{d,cul}$ deviation. The value of this deviation for the passive fire-protective material, as well as for the reactive fire-protective material, depends on the value of the critical temperature of steel and the normalized threshold of fire resistance.



a *b*

Fig. 2. Dependence of $\delta_{d,cul}$ deviation on V/A_m reduced thickness defined for the passive fire-protective material: *a* – for the normalized fire resistance threshold of 60 minutes and different values of θ_{cr} critical temperature (°C); *b* – for the normalized threshold of fire resistance of 150 minutes and different values of θ_{cr} critical temperature (°C)

Tables 1, 2 present the values of $\delta_{d,cul}$ deviation summed up for the whole range of the normalized fire resistance threshold for reactive and passive fire-protective materials. We determined the arithmetical average value of $\delta_{d,cul,avg}$ deviations and the average square F_d deviation given in these tables by the following formulas:

$$\delta_{d,cul,avg}=\sum_{j=1}^{m}(\delta_{d,cul\ j})\cdot m^{-1}, \qquad (3)$$

$$F_d=\left[\sum_{j=1}^{m}(\delta_{d,cul\ j})^2\right]^{0,5}\cdot m^{-0,5}, \qquad (4)$$

where m is the number of $\delta_{d,cul}$ deviations.

Table 1

Values of $\delta_{d,cul}$ deviations for the reactive fire-protective material defined for the range of the normalized fire resistance threshold from 30 minutes to 90 minutes

θ_{cr} critical temperature of steel, °C	350	400	450	500	550	600	650
$\delta_{d,cul,min}$ minimal value, %	11.7	7.6	2.5	–4.2	–13.4	–27.1	–6.4
$\delta_{d,cul,max}$ maximal value, %	79.0	56.9	49.5	57.8	47.6	44.9	45.4
Difference ($\delta_{d,cul,\max}-\delta_{d,cul,\min}$), %	67.3	49.3	47	62	61.0	72.0	51.8
$\delta_{d,cul,avg}$ average value, %	19.2	16.9	15.8	13.3	10.3	9.7	10.8
Quantity of m_{pos} positive values, %	100	100	100	87.7	80.0	83.8	79.7
F_d value, %	23.1	19.3	18.5	17.7	17.3	18.2	16.2

It follows from Table 1 that $\delta_{d,cul,\min}$ minimum value is from –27.1 % to 11.7 % for the reactive fire-protective material and the range of normalized fire resistance threshold from 30 minutes to 90 minutes. $\delta_{d,cul,\max}$ maximum value varies from 44.9 % to 79.0 %. The difference ($\delta_{d,cul,\max}-\delta_{d,cul,\min}$) is from 47.0 % to 72.0 %. $\delta_{d,cul,avg}$ average value ranges from 9.7 % (at 600 °C) to 19.2 % (at 350 °C).

Values of the mentioned parameters ($\delta_{d,cul,\min}$, $\delta_{d,cul,\max}$, $\delta_{d,cul,\text{avg}}$) decrease with an increase in the critical temperature of steel (Fig. 3, *a*). The average deviation of F_d exceeds $\delta_{d,cul,avg}$ average value by a value from 2.4 % (at 400 °C) to 8.5 % (at 600 °C). m_{pos} number of positive values of $\delta_{d,cul}$ deviation makes up 100 % in the range of the critical temperature of steel from 350 °C to 450 °C. m_{pos} number decreases to 79.7 % with an increase in the critical temperature (Fig. 4). We should note that the non-monotonic nature of some of dependencies shown in Fig. 3 and 4 has connection with the fact that we used restrictions of the minimum and maximum calculated values of d_p thickness of fire-protective material given in DSTU B V.1.1-17 [3] for determination of d_p thickness of fire-protective material. Because of this, we did not use the obtained values, which exceeded the limit values of thickness.

Table 2

Values of $\delta_{d,cul}$ deviation for the passive fire-protective material defined for the range of the normalized fire resistance threshold from 45 minutes to 240 minutes

θ_{cr} critical temperature of steel, °C	350	400	450	500	550	600	650	700	750
$\delta_{d,cul,min}$ minimal value, %	−62.5	−50.4	−48.9	−58.3	−45.1	−50.2	−56.4	−46.4	−51.0
$\delta_{d,cul,max}$ maximal value, %	28.2	14.7	4.4	−3.1	−7.7	−7.3	−6.3	−5.0	−3.3
Difference ($\delta_{d,cul,\max}$ − $\delta_{d,cul,\min}$), %	90.7	65.1	53.3	55.2	37.4	42.9	50.1	41.4	47.7
$\delta_{d,cul,avg}$ average value, %	1.5	−4.7	−9.7	−13.6	−16.4	−18.6	−20.8	−22.5	−24.1
Quantity of m_{pos} positive values, %	65.5	22.1	4.9	0	0	0	0	0	0
F_d value, %	12.5	10.1	12.1	15.1	17.2	19.4	21.8	23.3	25.1

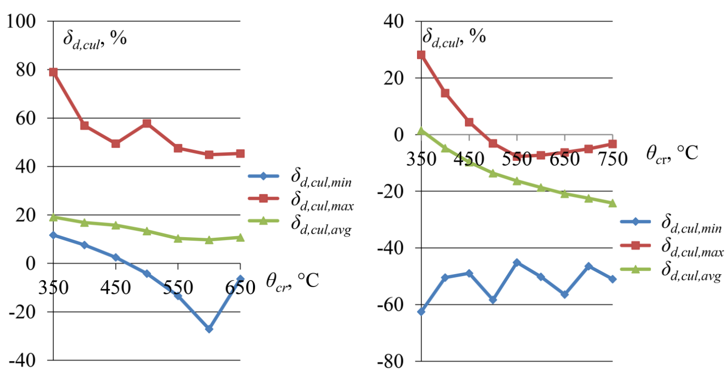


Fig. 3. Dependences of $\delta_{d,cul,\min}$ minimum value, $\delta_{d,cul,\max}$ maximum value and $\delta_{d,cul,\text{avg}}$ average value on the critical temperature of steel: *a* — for the reactive fire-protective material; *b* — for the passive fire-protective material

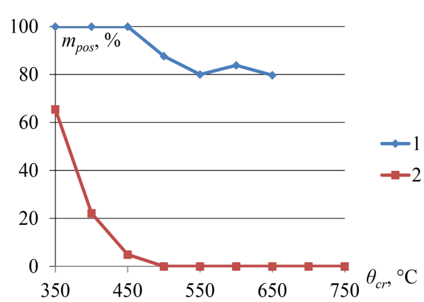


Fig. 4. Dependence of m_{pos} positive values of $\delta_{d,cul}$ deviation on the critical temperature of steel: 1 — for the reactive fire-protective material; 2 — for the passive fire-protective material

$\delta_{d,cul,min}$ minimum value is from −62.5 % to −45.1 % for the passive fire-protective material and the range of the normalized fire resistance threshold from 45 minutes to 240 minutes (Table 2, Fig. 3, *b*). $\delta_{d,cul,\max}$ maximum value varies from −3.1 % to 28.2 %. The difference ($\delta_{d,cul,\max}$− $\delta_{d,cul,\min}$) is from 37.4 % to 90.7 %. $\delta_{d,cul,\text{avg}}$ average value makes up from −24.1 % (at 750 °C) to 1.5 % (at 350 °C).

There is no dependence on the critical temperature for $\delta_{d,cul,min}$ value ($\delta_{d,cul,min}$ values are in the range defined above with an average value of −51 %). $\delta_{d,cul,\max}$ value decreases with an increase in the critical temperature of steel to 550 °C, and then it increases. $\delta_{d,cul,\text{avg}}$ value decreases with an increase in the critical temperature. Values of the average square deviation of F_d exceed (by modulus) $\delta_{d,cul,\text{avg}}$ values by (0.8...1.5) % in the range of the critical temperature of steel from 500 °C to 750 °C. If the value of the critical temperature of steel is smaller, the difference is greater. It has a maximum value of 11.0 % (at 350 °C). The number of m_{pos} positive values of $\delta_{d,cul}$ decreases from 65.5 % to zero deviation in the critical temperature range from 350 °C to 500 °C. This number does not change with further increase in the critical temperature (Fig. 4).

The analysis of the calculated data shows that $\delta_{d,cul}$ deviation (difference) between values of minimum thickness obtained from test data on samples of reduced sizes and standardized samples for the reactive fire-protective material are positive values mainly. The deviation has negative values mainly for the passive fire-protective material (Tables 1, 2, Fig. 4).

We can explain the above as follows. The average values of the time required to reach the critical temperature of steel for samples of smaller sizes are smaller than for standardized unloaded samples for the reactive fire-protective material [14]. The possible reason is a higher fire protection efficiency when applying the reactive fire-protective material to the surface of a doubletree structure than to the surface of a plate. The difference between the average values of $\delta_{t,cul,\text{avg}}$ time required to reach the critical temperature of steel determined from the test data obtained using samples of reduced sizes and standardized unloaded samples, ranges from −1.1 % to −12.5 %, depending on the critical temperature of steel [14]. After correction of the experimental data for standardized samples, taking into account parameters of ability of fire protective material to coherence and (or) ability to remain intact under a fire impact, the difference between average values of $\delta_{t,cul,mod,\text{avg}}$ time required to reach the critical temperature of steel determined according to the tests data obtained using of samples of reduced sizes and standardized samples, ranges from −1.1 % to −9.8 %. There is non-essential difference in $\delta_{t,cul,\text{avg}}$ and $\delta_{t,cul,mod,\text{avg}}$ values, because there was no significant damage to the fire protection material in the profiled fire protection system with the reactive fire-protective material due to deformation of standardized loaded samples (beams) under a fire impact. Therefore, the difference between an increase in the temperature of standardized loaded and unloaded samples was insignificant and $\delta_{t,mod,avg}$ average difference between the time required to reach the critical temperature of steel on standardized unloaded and loaded samples with the reactive fire-protective material do not exceed 3.9 % (Fig. 5).

$\delta_{d,cul}$ deviations for the reactive fire-protective material have positive values mainly, because the average values of the time required to reach the critical temperature of steel are less for samples of reduced sizes than the values of this time for standardized samples obtained after correction of experimental data.

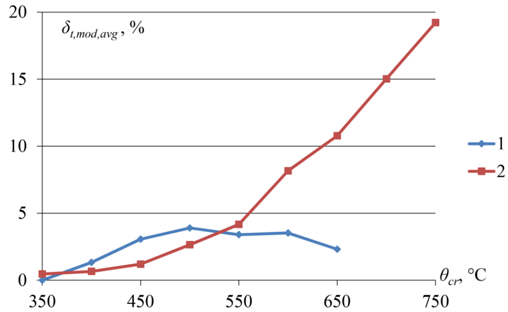


Fig. 5. Dependence of $\delta_{t,mod,\text{avg}}$ value on the critical temperature of steel: 1 – for the reactive fire-protective material; 2 – for the passive fire-protective material

For the passive fire-protective material, the difference between $\delta_{t,cul,\text{avg}}$ average values of the time required to reach the critical temperature of steel determined by tests on samples of reduced sizes and standardized non-loaded samples has a negative value (–0.5 % to –5.5 %) for the range of critical temperature of steel from 350 °C to 400 °C. The difference has a positive value (up to 10.2 %) for larger values of the critical temperature of steel [14].

After correction of the experimental data obtained for the standardized samples, the difference between $\delta_{t,cul,mod,\text{avg}}$ average time values is –5.2 % for the critical temperature of steel of 350 °C, and from 0.2 % to 28.2 % in the critical temperature range from 400 °C to 750 °C.

The difference between $\delta_{t,cul,\text{avg}}$ and $\delta_{t,cul,mod,\text{avg}}$ values is significant because there was a significant damage to the fire-protective material (Fig. 6) of the box-type fire protection system with the passive fire-protective material used in standardized samples after reaching the temperature of sample values (450–550) °C due to deformation of loaded samples (beams).


Fig. 6. Physical appearance of a loaded beam with the passive fire-protective material after the test

Damage to the passive fire-protective material during deformation of a beam causes a difference between increases in the temperature of standardized loaded and unloaded samples. The difference is significant. $\delta_{t,mod,\text{avg}}$ average difference between the time required to reach the critical temperature of steel on standardized unloaded and loaded samples with passive fire-protective material reaches 19.2 % (Fig. 5). $\delta_{d,cul}$ deviations for the passive fire-protective material have negative values mainly, because the average values of the time required to reaching the critical temperature of steel are larger for the samples of reduced sizes than the values of this time for standardized samples obtained after correction of the experimental data.

6. Discussion of results of studying the influence of sample parameters for testing on the results of assessment of the fire-protective capacity of materials

As follows from the results obtained (Table 1, Fig. 1, 3, *a*, 4), we get predominantly higher values of the minimum thickness of the reactive material in the assessment of the fire-protective capacity using samples of reduced sizes, than when using standardized samples. The number of these values makes up 90.2 %. The difference between values of the minimum thickness of the reactive fire-protective material obtained on samples of reduced sizes and standardized samples depends on reduced thickness, critical temperature of steel and a normalized fire resistance threshold. The difference increases from –27.1 % to 79.0 % with an increase in the reduced thickness from 2.9 mm to 14.3 mm. The average difference value decreases from 19.2 % to 10.8 % with an increase in the critical temperature from 350 °C to 650 °C. The average value of the difference increases from 2.8 % to 25.9 % with an increase in the normalized threshold of fire resistance from 30 minutes to 90 minutes.

We obtain predominantly smaller values of the minimum thickness of material for the passive fire-protective material (Table 2, Fig. 2, 3, *b*, 4), than for the use of standardized specimens. The number of these values is 89.7 %. For this material, the difference between values of the minimum thickness obtained on samples of reduced sizes and standardized samples increases (by modulus) (Fig. 2, *a*) from –0.8 % to –62.5 % at values of the normalized threshold of fire resistance of 45 minutes and 60 minutes with an increase in the reduced thickness from 4.0 mm to 20.0 mm. Most of these dependencies have an extremum (Fig. 2, *b*) for other values of the normalized fire resistance threshold. The average value of the difference increases from 1.5 % to –24.1 % with an increase in the critical temperature from 350 °C to 750 °C. The average value of the difference increases from –9.0 % to –15.9 % with an increase in the normalized threshold of fire resistance from 45 minutes to 90 minutes. Further increase in the threshold of fire resistance to 240 minutes leads to a decrease in the difference to –8.7 %.

Comparing the data obtained for reactive and passive fire-protective materials, we should note that there are rather large ranges of changes in the difference between values of minimum thickness obtained on samples of reduced sizes and standardized samples. The range is from –27.1 % to 79.0 % for the reactive material, and from –62.5 % to 28.2 % for the passive one.

It is not possible to consider such values of the difference acceptable for determination of the fire-protective capacity of materials for all ranges of reduced thickness, critical temperature and a normalized fire resistance threshold given in papers [1, 2].

However, we can consider the obtained data on the convergence of the results of the assessment of the fire-protective capacity of materials as expedient ones from a practical point of view, because they make possible to substantiate the use of samples of reduced size for research tests. It is possible to determine values of reduced thickness, critical temperature of steel and a normalized threshold of fire resistance with deviations of acceptable values by the obtained results. We can apply them to experimental tests. We can direct the study tests, for example, to determine the optimal composition of fire-protective materials or to determine the optimum values of thickness of fire-protective coating for standardized samples used in tests by the methods from papers [1, 2]. However, it is impossible to deny that we studied only one material among different types of reactive and passive fire-protective materials in the study. It is quite possible that the results will be different for fire-protective materials of these types of other brands. Such uncertainty imposes restrictions on application of the results on definition of convergence. We can interpret this fact as the disadvantage of the study. The impossibility to escape the mentioned restrictions in the framework of this study substantiates the direction for further research. The objective of further studies may be identification of features of assessment of the fire resistance of protected steel structures and the fire-protective capacity of their materials.

7. Conclusions

1. The study revealed features of the fire-protective capacity of reactive and passive materials for steel structures. We determined the fire-protective capacity by tests on standardized samples and samples of reduced sizes. The feature is the fact that the investigated fire-protective materials provide different ranges of the normalized fire resistance threshold of steel structures: from 30 minutes to 90 minutes for reactive fire-protective material and from 45 minutes to 240 minutes for passive fire-protective material. The values of reduced thickness of a steel profile, critical temperature of steel and a normalized threshold of fire resistance of a steel structure affect the value of the minimum thickness of fire-protective materials significantly.

An increase in the reduced thickness from 2.9 mm to 14.3 mm leads to a decrease in the minimum thickness from 1.460 mm to 0.427 mm for the reactive fire-protective material, in particular, for the critical temperature of steel of 500 °C and the normalized threshold of fire resistance of 45 minutes. For the same threshold of fire resistance and the reduced thickness of 5.9 mm, an increase in the critical temperature from 350 °C to 650 °C leads to a decrease in the minimum thickness from 2.059 mm to 0.564 mm. For the same value of the reduced thickness and the critical temperature of steel 500 °C, an increase in the normalized threshold of fire resistance from 30 minutes to 60 minutes leads to an increase in the minimum thickness increases from 0.445 mm to 1.679 mm.

For the passive fire-protective materials, in particular, for the critical temperature of steel 500 °C and the normalized threshold of fire resistance of 150 min, an increase in the reduced thickness from 4.0 mm to 20.0 mm leads to a decrease in the minimum thickness from 48.1 mm to 22.8 mm. For the same threshold of fire resistance and the reduced thickness of 5.9 mm, an increase in the critical temperature from 350 °C to 750 °C leads to a decrease in the minimum thickness from 49.7 mm to 34.6 mm. For the same value of the reduced thickness and the critical temperature of steel of 500 °C, an increase in the normalized threshold of fire resistance from 45 minutes to 210 minutes leads to an increase in the minimum thickness from 15.5 mm to 58.8 mm.

2. We established that values of the minimum thickness for the reactive fire-protective material obtained by tests on samples of reduced sizes are significantly larger than those with application of standardized samples. On the contrary, values of the minimum thickness obtained using standardized samples are significantly larger. The difference between values of the minimum thickness obtained on samples of reduced sizes and standardized samples reaches 79.0 % for the reactive fire-protective material, and it is 62.5 % for the passive fire-protective materials. The average values of this difference range from 9.7 % to 19.2 % (for the critical temperature of steel from 350 °C to 650 °C) – for the reactive fire-protective retardant material, and from 24.1 % to 1.5 % (for the critical temperature of steel from 350 °C to 750 °C) – for the passive fire-protective material.

Such differences in values indicate that application of samples of reduced size is impossible for the assessment of the fire-protective capacity of materials for steel structures for all ranges of reduced thickness, critical temperature and a normalized fire resistance threshold given in papers [1, 2]. We can use such samples for experimental tests with the mentioned parameters of narrower ranges than in papers [1, 2]. For example, we can use such samples for tests aimed at determination of the optimal composition of fire-protective materials or for determination of the optimum values of thickness of fire-protective coating for standardized samples used for tests by the methods from papers [1, 2].

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