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Chapter 6: Building Materials

Chapter 7: Materials and Technologies for Preventing of Technogenic Emergencies

Investigation of the Limit of Fire Resistance of a Steel Beam at Loss of Integrity of a Fire-Resistant Lining

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Abstract. In this article, to solve the main problems, we determined the temperature regime of heating the steel beam, which took into account the fact of loss of integrity of the fire-retardant lining due to the thermal effects of fire. When calculating the temperature, the time of exposure to the standard temperature of the fire and the value of the heating temperature of the steel beam with mineral wool lining at which the latter loses its integrity was determined. Taking into account the geometrical parameters of the cross section of the studied I-beam, according to the finite-element scheme, the steel beam was divided into four elements of SHELL type with five points of integration in thickness in the Belichko-Tsai formulation. After the calculation, the corresponding results were obtained in the form of graphs of changes in the maximum deflection of the beam and the rate of increase of the maximum deflection depending on the time of exposure to the standard temperature of the fire. The critical values of the occurrence of the limit of fire resistance according to the graph of maximum deflection and the graph of the rate of increase of deflection were determined. The difference between the indicators shows that the time of the limit state of loss of bearing capacity is 70 min less, if not taking into account the loss of fire-retardant capacity of mineral wool fire-protection due to loss of integrity.

Introduction

Steel structures are widely used in construction, but the high thermal conductivity of the metal is a significant disadvantage that affects the fire safety of such structures. Ensuring the safety of building structures made of metal remains relevant for a long time. To solve this, there are a number of ways to ensure fire safety by increasing the fire resistance of steel structures. Among such methods, the issues of facing metal structures with non-combustible materials are widely studied, and their effectiveness is proved by experimental tests, modeling of heat transfer processes taking into account stress-strain states and mathematical calculations. However, the study of different types of linings, taking into account their advantages and high efficiency of increasing the fire resistance of steel structures, not taking into account the loss of integrity of the fire protection lining and its impact on thermal conductivity and normalized time of fire resistance. Mineral wool boards are a promising non-combustible material that is widely used for thermal insulation of buildings. Given the advantages of mineral wool materials, promising and relevant is the issue of increasing the limit of fire resistance of steel structures used as a fire-retardant cladding of mineral wool coating.

Analysis of Recent Achievements and Publications

A large number of works are devoted to the study of the limits of fire resistance of steel. In most cases, steel structures are considered as a material that must be protected from fire.

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A large number of works are devoted to the study of the limits of fire resistance of steel. In most cases, steel structures are considered as a material that must be protected from fire.

In the article [1] the processes of integrity loss of fire-retardant cladding from mineral wool of a steel I-beam are considered. The relation between fire-retardant cladding integrity and its thermal insulating ability was studied. It is shown that the fire-retardant cladding loses its integrity under the thermal influence of fire long before the onset of the limit state of loss of fire resistance in terms of bearing capacity. The conditions under which fire-retardant cladding loses its integrity and fire-retardant ability are investigated. The data obtained in the work [1] were the prerequisites for this study.

In the work [2] the influence of fire temperature regimes, obtained by the proposed mathematical models, on the mechanical characteristics of metal structures was researched. However, it was not taken into account that metal structures can be protected by special means.

In the work [3] the results of processing of steel elements of protection by the swollen coverings are shown. The experiments were performed in the laboratory of the National Fire Service of Italy. Testing of steel structures with mineral wool protection was not performed.

In the work [4], studies have shown the effectiveness of fire-retardant compositions intended for fire-retardant steel structures, but along with the advantages there are significant disadvantages due to the manufacture of appropriate fire-retardant compositions and complexity in the application process. The study of fire resistance of steel structures protected by mineral wool was not performed.

Purpose

The purpose of this work is to calculate and establish the dependences of the detachment time of the fire-retardant cladding and the limit of fire resistance on the design parameters of steel beams with fire-retardant protection based on mineral wool cladding. For this purpose it is necessary to establish the parameters influencing change of limit of fire resistance and to establish their dependence on change of a temperature mode and integrity of a fire-retardant mineral wool covering.

To describe the algorithm and perform calculations that allow to study the influence of structural parameters of steel beams with mineral wool fire protection on their limit of fire resistance.

To carry out calculations and establish the dependences of the peeling time of the fire-retardant cladding and the limits of fire resistance on the design parameters of steel beams with fire protection.

Consideration on methods and results

When calculating the temperature of the fire, the fact of loss of integrity of the fire-retardant cladding due to the thermal effects of the fire must be taken into account. This can be achieved by applying the formula to increase the temperature $\Delta\theta_{a,t}$ for a period of time Δt, which has this form [5]:

$$\Delta\theta_{a,t} = \frac{\lambda_P A_P}{V d_P c_a \rho_a} \cdot \frac{\left(\theta_{g,t} - \theta_{a,t}\right)}{\left(1+\varphi/3\right)} \cdot \Delta t - \left(e^{\varphi/10} - 1\right) \cdot \Delta\theta_{g,t} \quad (\Delta\theta_{a,t} \geq 0 \text{ when } \Delta\theta_{g,t} > 0), \tag{1}$$

here $\phi = \frac{c_P \rho_P}{c_a \rho_a} \cdot d_P A_P / V$,

where A_P / V – the cross-sectional coefficient of a steel beam with a fire protection system based on mineral wool; c_a – temperature dependence of specific heat of steel, (J/(kg·°C)) (tabular data); c_P = 1000 – specific heat capacity of mineral wool fire-retardant lining, which is not temperature-dependent (J/(kg · K)); d_P – the thickness of the mineral wool plate of the fire protection system (m); Δt = 30 – time interval (c); $\theta_{a,t}$ – the current value of the steel temperature at a certain point in time

t (°C); $\theta_{g,t}$ – the temperature of the gaseous medium in the room with the fire at the time t (°C); $\Delta\theta_{g,t}$ – increase in the current temperature of the gaseous medium in the room with the fire for a period equal to a step in time Δt (°C); λ_P – temperature dependence of the thermal conductivity of mineral wool cladding of the fire protection system (W/(m·°C)); ρ_a = 7850 – density of steel, (kg/m^3); ρ_P = 200 – density of mineral wool facing of fire protection system (kg/m^3).

According to the data [1], formula (1) is applied until the moment when the mineral wool lining of the fire protection system retains its integrity, ie until the time of 44.5 min under the influence of the standard temperature of the fire and at the heating temperature of the steel beam 425 °C. After that, it is assumed that the mineral wool lining loses its integrity and the following formula should be used, which determines the temperature rise $\Delta\theta_{a,t}$ for a period of time Δt [5]:

$$\Delta\theta_{a,t} = k_{sh} \cdot \frac{A_m}{V c_a \rho_a} \cdot \dot{h}_{\text{net}} \Delta t \,, \tag{2}$$

where k_{sh} – adjustment factor that takes into account the effect of the shading effect of the beam by other structures;

$\dot{h}_{\text{net}}$ – the estimated value of the total specific heat flux, W/m^2.

The total specific heat flux is determined by the expression [5]:

$$\dot{h}_{\text{net}} = \dot{h}_{\text{net},c} + \dot{h}_{\text{net},r} \,, \tag{3}$$

where $\dot{h}_{\text{net},c}$ – total specific heat flux of convective heat transfer; $\dot{h}_{\text{net},r}$ – total specific heat flux of radiant heat transfer. Total specific heat flux of convective heat transfer, W·m^{-2}, calculated by expression [5]:

$$\dot{h}_{\text{net},c} = \alpha_c \cdot (\theta_g - \theta_m), \tag{4}$$

where α_c = 25 – heat transfer coefficient during convective heat transfer, W·m^{-2}·K^{-1};

θ_g – ambient gas temperature in case of fire near the beam, °C;

θ_m – the temperature of the heating surface of the steel beam, °C.

Total heat flux during radiant heat transfer, W·m^{-2}, which is calculated by this expression [6]:

$$\dot{h}_{\text{net},r} = \mathrm{F} \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot ((\theta_g + 273)^4 - (\theta_m + 273)^4), \tag{5}$$

where F = 1 – the form factor of irradiation of a steel beam;

ε_m – the degree of blackness of the surface of the steel beam;

ε_f = 1 – the degree of blackness of the radiation of the gas environment of the fire;

σ = 5,67 · 10^{-8} W·m^{-2}·K^{-4} – constant of Stefan - Boltzmann.

With this approach, the calculation of expression (2) occurs at an initial temperature, which is equal to the temperature calculated at the time of loss of the integrity of the fireproof mineral welding by the formula (1).

Using this approach, the corresponding calculations were carried out, as a result of which a mode of heating of a steel beam with mineralwater lining was built, provided its loss of integrity by 44.5 seconds at heating temperature of the steel beam 472 °C according to the calculations given in [1]. The resulting temperature mode is submitted to fig. 1.

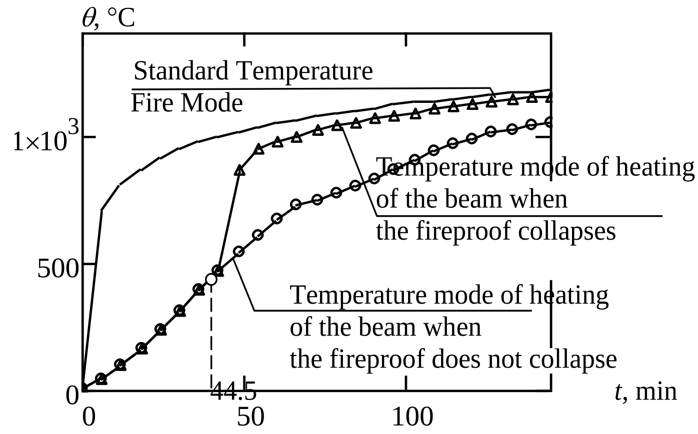

Fig. 1. Temperature mode of heating of a steel beam with mineralwater fire-retardant lining under conditions of influence of the standard temperature regime of fire without taking into account and taking into account the loss of integrity with fireproof mineralwater lining.

Analyzing the graph filed on fig. 1, you can notice that starting with 45 s the temperature of the steel beam is noticeably increased and practically 5 minutes approaching the temperature curve of the standard temperature regime of the fire. The resulting regime can be used to calculate the bearing capacity of the steel beam under conditions that understand the loss of fireproof capacity with mineralwater lining as a result of violation of its integrity.

To determine the boundaries of the steel steering stability, provided that the fireproof lining loses its fire protection capacity as a result of loss of its integrity, the calculation provisions were used in [1]. In this case, there is no need to simulate the existing fire protection lining, since the temperature mode of heating of the steel beam is determined.

To simulate the stress-strain state (SSS) in a steel beam with a fire-retardant lining of mineral wool, which at the appropriate time loses its fire-retardant ability due to loss of integrity, the geometric parameters of the cross section given in [1] were used. The length of the beam as in the previous case is 6 m. The peculiarity of this finite element model is that the steel beam was divided into four nodes of the SHELL type with five points of integration in thickness in the Belichko-Tsai formulation [7]. Steel beam material is an elastic-plastic material that allows to take into account temperature deformations [7].

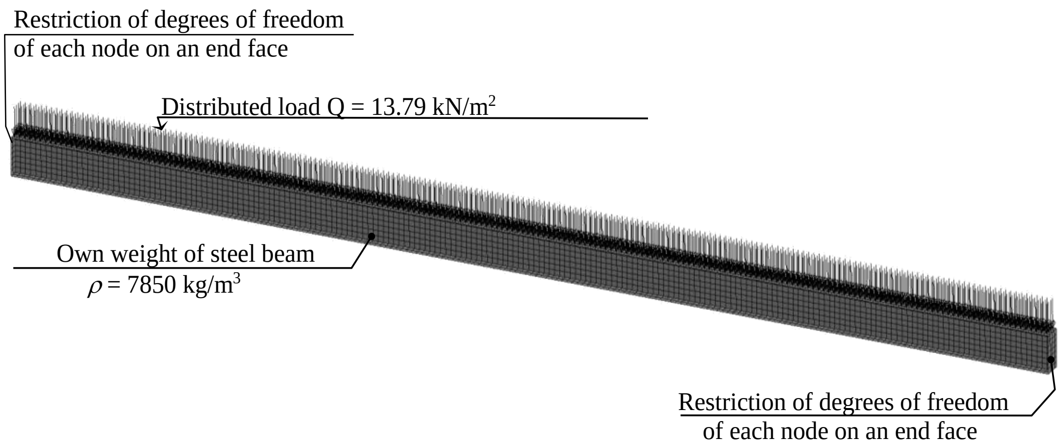

Fig. 2. Scheme of application of mechanical load to the steel beam and fastening conditions.

Before applying the temperature load, the steel beam is loaded sequentially with its own weight and the active distributed load, which must act during the entire time interval of the calculation, which is 17.5 s. The time factor here also has a conditional value, which is respectively converted into real time of the fire effect of the standard temperature of the fire 150 min.

In the scheme of application of loads of a steel beam with fire-retardant facing from mineral wool which is resulted in Fig. 2 the type and direction of the applied load and the conditions of fixing the ends of the beam are shown.

The magnitude of the distributed load is taken by the load factor $\mu = 0.2$.

The load is applied sequentially. To exclude the influence of oscillatory dynamic effects when applying loads for the accepted time of the process at the stage of applying its own weight, the calculation was performed using dynamic relaxation according to the computational algorithm of Papadrakakis [7]. Other processes were calculated with an included option of global damping with a factor 0,16.

After the calculation, the corresponding results shown in fig. 3 in the form of graphs of changes in the maximum deflection of the beam and the rate of increase of the maximum deflection depending on the time of exposure to the standard temperature of the fire were received.

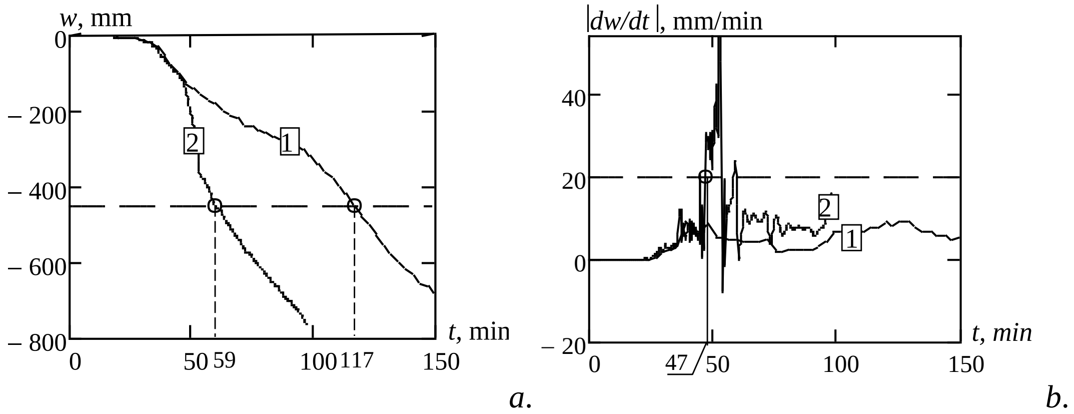

Fig. 3. Graphs of change of the maximum deflection of a beam (*a*) and the rate of increase of the maximum deflection (*b*) depending on the time of exposure to the standard temperature of the fire: 1 – for a beam with mineral wool fire protection which does not lose the integrity; 2 for beams with mineral wool fire protection, which loses its integrity and fire protection ability.

The critical values of the maximum deflection and the rate of increase of the deflection are determined by the formulas described in [1] and equal to the values calculated for the previous case, because the geometric parameters of the beam have not changed.

In the graphs shown in Fig. 4 it is seen that the limit of fire resistance occurs at 59 min on the schedule of maximum deflection and at 47 min on the schedule of increase in maximum speed. It can be seen that the time of the limit state of loss of bearing capacity is 70 min less, in case that the loss of fire-retardant capacity of mineral wool fire-protection due to loss of integrity is not taken into account. This emphasizes the importance of taking into account the fact of possible loss of integrity of any fire-retardant cladding, including mineral wool. In addition, when the integrity of the fire-retardant cladding is lost, there is a risk of shock thermal impact on the steel beam, as evidenced by the graph of the rate of increase of the maximum deflection of the steel beam with the loss of fire-retardant capacity of mineral wool cladding..

In order to study the influence of the structural parameters of steel beams with mineral wool fire protection on the limit of fire resistance, calculations were performed, including the procedures that make up the following sequence.

1. For a beam with certain design parameters the temperature mode of heating of a beam at influence of a standard temperature mode of a fire according to the formula is defined (1).

2. Using the mathematical apparatus and mathematical descriptions of the properties of materials described in [1], the time of influence of the standard temperature of the fire is calculated, at which the flame retardant mineral wool cladding detaches from the beam.

3. Using formulas (1) - (5), a new temperature regime of heating the steel beam is constructed taking into account the moment of time at which the flame retardant mineral wool cladding detaches from the beam similar to the one shown in Fig. 1.

4. Using the mathematical apparatus and mathematical descriptions of the properties of the materials contained in [1], the limit of fire resistance is calculated, as shown in fig. 3.

After calculation by this method, the results were obtained in the form of dependence of the detachment time of fire-retardant cladding and the limit of fire resistance on the structural parameters of steel beams with fire-retardant mineral wool cladding: beam cross-sectional coefficient, load level and thickness of mineral wool cladding. The obtained graphs are shown in fig. 4.

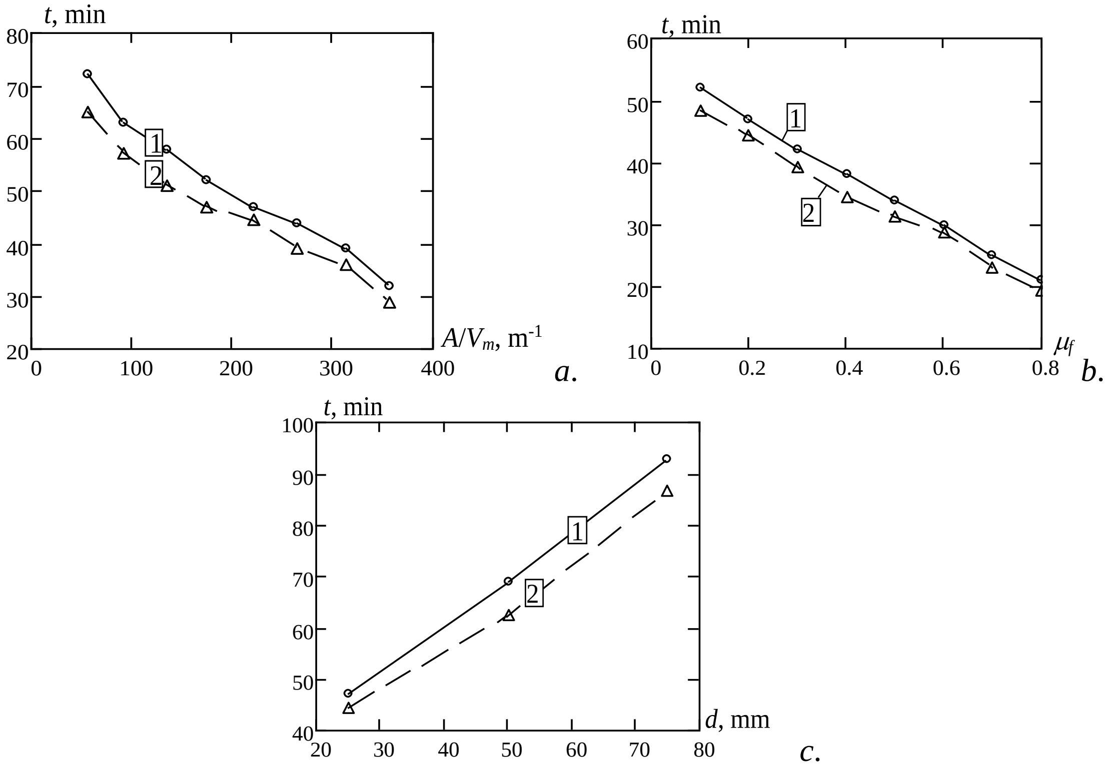

Fig. 4. Graphs of dependence of the limit of fire resistance of steel beam with fire-retardant mineral wool cladding (1) and the time of detachment of flame-retardant mineral wool cladding (2): *a* - on the value of the cross section of the beam; *b* – on the level of applied load; *c* – on the thickness of the fire-retardant mineral wool lining.

Analyzing these graphs, we can see that the limit of fire resistance has a correlation with the selected parameters and its dependence on them is close to linear. To do this, in the future a system of correction factors should be developed to reduce the value of the limit of fire resistance due to the sudden destruction of fire protection systems.

Summary

The limit of fire resistance comes at 59 minutes according to the schedule of maximum deflection and at 47 minutes according to the schedule of increase of maximum speed. It can be seen that the last time of onset of the limit state of load-bearing capacity is 70 min less, in case if the loss of fire-retardant capacity of mineral wool fire-retardant due to the loss of integrity is not taken into account. This emphasizes the importance of taking into account the fact of possible loss of integrity of any fire-retardant lining, including mineral wool. In addition, when the integrity of the fire-retardant cladding is lost, there is a risk of shock thermal impact on the steel beam, as evidenced by the graph of the rate of increase of the maximum deflection of the steel beam with the loss of fire-retardant capacity of mineral wool lining.

We described algorithm and performed calculations, which make it possible to study the influence of structural parameters of steel beams with mineral wool fire protection on their limit of fire resistance.

After calculation by this method, the results were obtained in the form of dependence of the detachment time of fire-retardant cladding and the limit of fire resistance on the structural parameters of steel beams with fire-retardant mineral wool cladding: beam cross-sectional coefficient, load level and thickness of mineral wool cladding. According to the calculations, the limit of fire resistance is correlated with the selected parameters and its dependence on them is close to linear.

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