Designing Fire Protection of Steel Corrugated Web Beams for Wastewater Treatment Plant

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Abstract. The paper describes effective constructive fire protection of steel corrugated beams by using large sheet and slab cladding. It introduces a scheme of fire-resistant steel beams with contact connection of elements of sheet and slab cladding to a steel bearing core. The study provides analytical equations of thickness of sheet and slab cladding with account of required fire resistance. The technical result of the new design solution includes increase of reliability of cladding elements fastening by means of fastening screws with a countersunk head and a pointed end, weight reduction of large size cladding materials and steel, reducing cross-sectional area of fire-resistant beams, increasing actual fire resistance of steel beams, reducing the risk of steel beam failure in the initial stage of fire and direct losses.

1. Introduction

Unprotected steel constructions of water supply facilities under fire conditions quickly lose their load-carrying capacity (after $5 \div 15$ min), collapse themselves and contribute to the collapse of other building structures, which leads to significant material losses.

2. Problem Description

There is a well-known construction of a steel fire-resistant I-beam. Its cladding is made in the form of two hollow ceramic stone shells, which is laid close-by to the web and the lower flange of the I-beam [1]. However, this design of an I-beam fire protection has a number of shortcomings: its cladding elements are made of heavy material which is ceramic stone with $1200 \div 1400$ kg/m3 density. It significantly increases the mass of fire protective cladding. Besides, internal voids ($25 \div 30\%$) in ceramic stone contributes to the quick warming up of the cladding to critical temperatures of steel I-beam heating and to $20 \div 25\%$ reduction of its fire resistance limit. What is more, modern construction industry does not produce cladding products in the form of shells made of ceramic stone, therefore, it is not either industrial or economically viable.

There is another well-known construction of a steel fire-resistant I-beam. It is a steel I-beam and fireproof cladding of large sheets and slabs installed with a gap. The gap between the fire protection cladding and the facets of the protected steel bearing bar of the beam is at least 25 *mm*; the structural support of the fire protection cladding is in the form of a frame made of steel longitudinal and transverse elements with 40 ÷ 75 *mm* height; and the fastening of the frame steel elements is done with 5 × 25 ÷ 5 × 45 thread-cutting screws [2]. This design of an I-beam fire protection also has numerous shortcomings: its frame consists of many separate elements which increases steel consumption for its production; cavities and gaps between the I-beam web, flanges and the slabs of protective cladding increase dimensions of the steel beam cross-section (its cross-section area increases by 40 ÷ 45%; the consumption of cladding materials increases by 30 ÷ 35%). Besides, this steel beam fire resistance limit is reduced by 25 ÷ 30%; fastening elements of large sheet and slab cladding reliability, the I-beam corrosion resistance and cladding maintainability are also considerably reduced.

The third well-known construction of a steel fire-resistant I-beam consists of a steel bearing bar, elements of the I-beam reinforcement and sheet cladding. The steel bearing bar is made in the form of an I-beam with reinforcement elements of steel rolled sections with screw-threaded holes. There are fastening screws with a countersunk head and threaded pointed end in the holes. Reinforcement elements are attached to the bottom of the compressed and stretched I-beam flanges with elements of sheet and slab fire protection cladding threaded by fastening screws. The cladding elements thickness is determined with account of the indicators of its materials diffusion, of the conditions of the I-beam heating and the normative limit of the bearing beam of fire resistance. I-beam reinforcement elements located at the bottom of the compressed and stretched I-beam flanges are made either in the form of two pairs of angle bars or in the form of a steel U-section. Slab fire protection cladding thickness is not less than the height of the steel U-section flanges [3-11]. This design of an I-beam fire protection also has numerous shortcomings: its frame consists of steel rolled sections which increases steel consumption for its production; steel rolled sections consumption, in its turn, leads to an over-consumption of steel (up to 10%). The fire protection cladding thickness is determined by the required fire control point of the I-beam lower flange. This solution requires considerable expense of effective cladding materials; therefore, the upper flange and the web of the I-beam have fire protection surplus stock. It all means this design of fire protection is neither progressive nor economically viable, as the consumption of steel and cladding as well as the cost of works on I-beam fire protection increases considerably.

3. New Technological Solution

This paper puts forward a new technical solution which improves the design of a steel beam with corrugated web fire protection, increases durability and operational reliability of steel beams with corrugated web, as well as improves fire-technical and economic indicators of beam structures and saves resources in the production of steel beams with corrugated web fire protection.

Technological results of this study are as follows: the improvement of the design of a steel beam with corrugated web fire protection; increase of industrial production efficiency of fire-resistant cladding; increase of fire resistance limit of steel beams, reduction of risk of beam failure in the initial stage of fire, increase of corrugated web beams load-carrying capacity; weight reduction of thermal protective cladding materials and steel; increase of labor productivity in the course of construction works on steel beams fire resistance; steel beams increased stability; increase of reliability and corrosion resistance of welded I -beams; increase of maintainability of fire protection cladding; future possibilities of using new progressive design solutions of steel beams with corrugated web in building construction; cost reduction of structural fire protection of steel beams; retention of load-carrying capacity of fire resistant steel beams for the time of people evacuation from the building during a fire; increase of the actual fire resistance limit of steel beams; increase of efficiency of steel beams girders thermal protection.

The specified technological result can be obtained while using the new technical solution and observing certain conditions. The main peculiarity of third well-known construction of a steel fire-

resistant I-beam consisting of a steel bearing bar with elements of the I-beam reinforcement (which are angle bars or U-sections attached to the bottom of the compressed and stretched I-beam flanges of sheet and slab fire protection cladding) *is* that its steel bearing bar is a welded I-beam with corrugated web, and its fire protection cladding is made of gypsum sheets and mineral-cotton slabs. There are thermal protective girders of mineral-cotton slabs attached to welded I-beam flanges ends; the stretched I-beam flange is protected by composite cladding of large size gypsum sheets and mineral-cotton slabs at its lower bound. There is composite cladding of mineral-cotton slabs with assigned thickness and a layer of concrete-perlite mortar at lateral sides of the I-beam corrugated web. Provided that the duration of resistance of each composite element of the welded I-beam is r_{us}, *min*, their resistance to thermo-force action without taking into account its fire protection, can be determined by the following analytical equation (1):

$$r_{us} = 6 \cdot \left[\frac{A_s}{P_0} + 18,33 \cdot \sqrt{1 - J_{\sigma s}} - 0,5 \right]$$

(1)

where $J_{\sigma s}$ is the intensity of force stresses in the welded I-beam composite element $(0.1 \div 1.0)$; A_s is the steel surface area of the welded I-beam cross-section, mm^2; P_0 is the perimeter of heating of the welded I-beam composite element, mm;

The required degree of the welded I-beam composite element fire protection C_{req}, sm − is determined by the following logarithmic equation (2):

$$C_{mp} = \ln \left[\frac{R_{uн} - r_{us}}{48 \cdot \left(1 - J_{\sigma s} \right)^3} \right]$$

(2)

where R_{in} is the required limit of the beam fire resistance, min; r_{us} is the duration of the welded I-beam composite element resistance to high temperature exposure without its fire protection, min;

the required thickness of the welded I-beam thermal protective girders δ_{on}, mm is determined by the indicative equation (3):

$$\delta_{on} = \frac{C_{mp} \cdot D_{вm}^{0,8}}{1,43 \cdot m_0}$$

(3)

where D_{req} is the required degree of fire protection welded I-beams flanges, sm; D_c is the indicator of thermal diffusion of protective girders, mm^2/min; m_0 − is the indicator of heating conditions of the control point of any welded I-beam flange $(0.5 \div 1.0)$;

The required thickness of the composite cladding of the I-beam corrugated web − δ_{cc}, mm − is defined by the equation (4):

$$\delta_{occ} = 1,4 \cdot C_{mp} \cdot D_{вm}^{0,8}$$

(4)

where C_{req} is the required degree of welded I-beam corrugated web fire protection, sm; D_{vt} is the indicator of thermo-diffusion of the corrugated composite cladding, mm^2/min;

The indicator of heating conditions m_0, of the control point of any welded I-beam flange at two-way heat supply is determined by the power equation (5):

$$m_0 = 0,5 \cdot \left(a_y / a_x \right)^{0,5}$$

(5)

where a_x and a_y − the depth of the control point of any girder of the flange along x and y axis, mm − is determined according to analytical equations (6) and (7):

$$a_x = \delta_x + \left(\delta_x \cdot \frac{b}{2} \right)^{0,5\, b/H^{0,25}} \tag{6}$$

$$a_y = \delta_y \tag{7}$$

where δ_x and δ_y is the thickness of complex cladding of the welded I-beam stretched flange along the axes of coordinates x and y, mm; b is the flange width of the welded I-beam, mm; H is the height of the steel I-beam cross-with protective cladding, mm; and the indicator of heating conditions of the control point of the welded I-beam corrugated web at symmetrical two-way heat supply $m_{0,cw} = 0,5$;

The height of the thermo-protected girder of the welded I-beam flanges – h_p, mm – is accepted from the condition (8):

$$h_з \geq 6 \cdot \delta_s \tag{8}$$

where δ_s is the flange thickness of the welded I-beam, mm;

The design degree of the welded I-beam flanges fire protection – C, sm – is defined by the analytical equation (9):

$$C = \frac{1,4 \cdot m_0 \cdot \delta_{on}}{D_{вm}^{0,8}} \tag{9}$$

where m_0 is the indicator of the control point (0.5 ÷ 1.0) heating conditions; δ_{od} is the design thickness of the flanges protective girder, mm; D_{vt} is the diffusion indicator of the complex cladding material of a stretched flange, mm^2/min;

The design limit of fire resistance of the welded I-beam composite element is F_{ur}, min. On the loss of its load bearing capacity in the conditions of fire, it is determined by the analytical equation (10):

$$F_{ur} = 48 \cdot \left(1 - J_{\sigma s} \right)^3 \cdot e^C + r_{us} \tag{10}$$

where $J_{\sigma s}$ is the intensity of power stresses in cross-section of the welded I-beam composite element (0.1 ÷ 1.0); C is the design degree of the welded I-beam fire protection, sm; r_{us} is the duration of the welded I-beam composite element resistance to thermal effects without its fire protection, min.

Figures1, 2, 3 illustrate the construction of a protected steel beam with a corrugated web: the longitudinal section A-A (Fig. 1), the view from above Б-Б (Fig. 2), the cross-section B-B (Fig. 3). The figures show the following elements: 1 – stretched flange; 2 – compressed flange; 3 – corrugated web; 4 – protective girder of the flange; 5 – composite cladding of corrugated web; 6 – complex cladding of the stretched flange; 7 – control points of the stretched flange; 8 – the control point of the corrugated web; 9 – floor of the building; b and h – the width and the height of the welded I-beam cross-section, mm; d and h_w – the corrugated web thickness and height, mm; d_s the welded I-beam flange thickness, mm; g_0 is the force loading, kH/ml.

The project solution suggests using steel beams with corrugated web while under reconstruction. Fire-technical characteristics of the structure and its bearing beams: fire resistance level – I (first); constructive fire-resistance class – CO (fire-proof); number of floors – 6; normative limit of the bearing beam fire resistance $R_{in} = 120\ min$ (see Table 21, RF Federal Law № 123-2016); steel bearing core is the welded I-beam, the web height is $h_w = 750\ mm$, the welded I-beam height $h = 790\ mm$; flange width $b = 300\ mm$, the thickness of the corrugated web $d = 2\ mm$; flange thickness $\delta_s = 20\ mm$; one welded I-beam flange cross-section area $A_{sn} = 60\ sm^2$.

A pair of bent U-sections with dimensions of $h_1 \times b_1 \times \delta_1 = 120 \times 60 \times 4\ mm$ are taken as the thermo-protective girder of the stretched flange; another pair of bent U-sections with dimensions of $h_2 \times b_2 \times \delta_2 = 60 \times 60 \times 4\ mm$ are taken as the thermo-protective girder of the compressed flange. A mineral-cotton
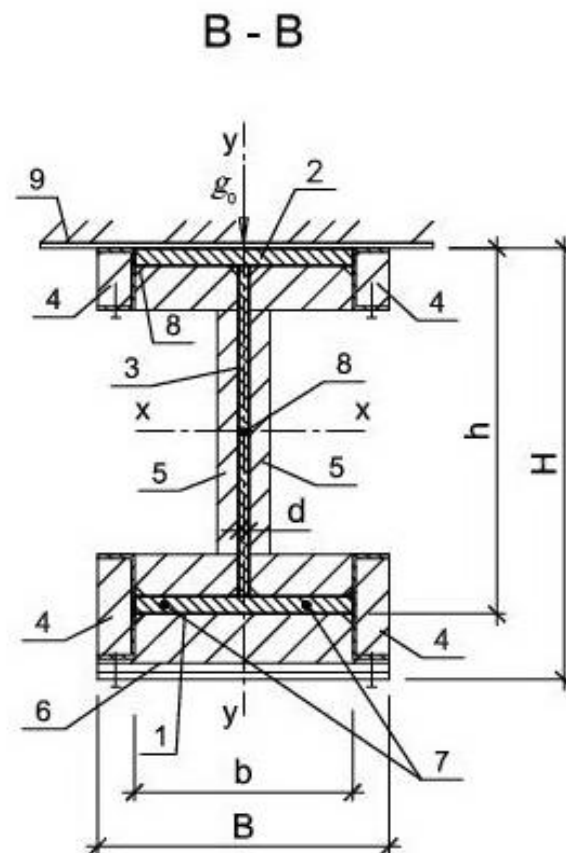
slab P-100 with 60 *mm* thickness together with a layer of concrete-perlite mortar are used as thermo-protected composite cladding of the corrugated web.
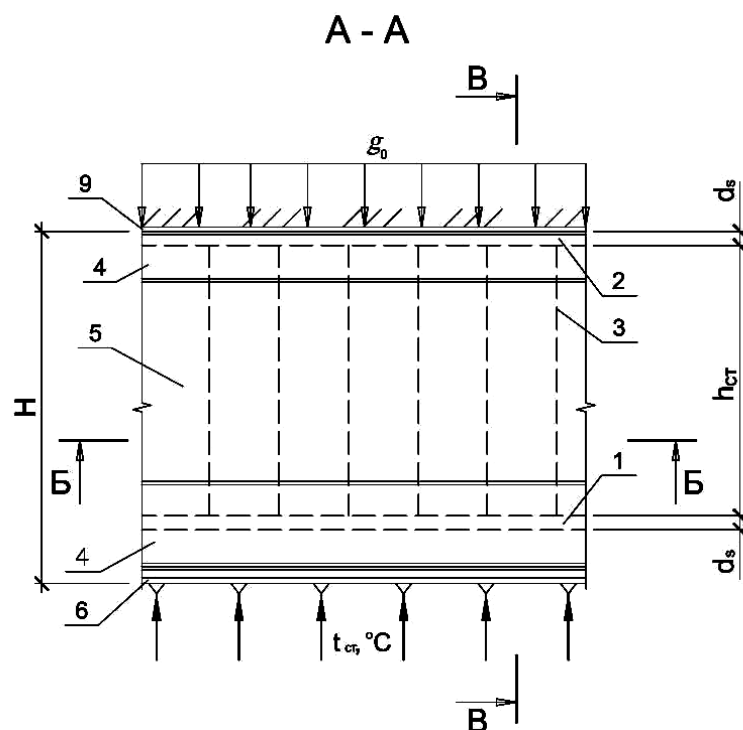
Figure 1. The construction of a protected steel beam with a corrugated web: longitudinal section.
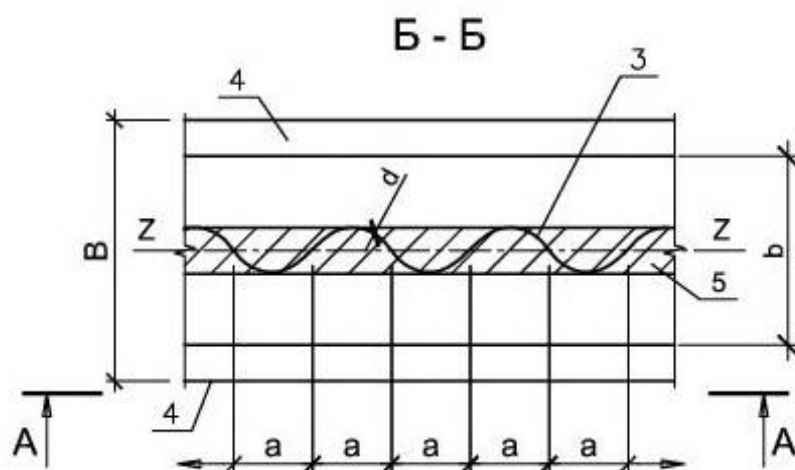
Figure 2. The construction of a protected steel beam with a corrugated web: view from above

Figure 3. The construction of a protected steel beam with a corrugated web: cross-section.

Construction works on the steel beam with corrugated web thermo-protection include the following stages. Firstly, the surfaces of the welded I-beam composite elements are prepared. Then reinforcement elements of the welded I-beam are connected to the welded I-beam flanges with intermittent splined joints $l_s \geq 50$ *mm* long spaced at intervals of $S_1 \leq 80 \cdot r_{min}$ in a stretched flange and $S_2 \leq 80 \cdot r_{min}$ in a compressed flange. Here r_{min} is the radius of gyration of an angle bar or of a U-section, *cm*. The next steps are the anti-corrosion layer coating; selection of materials for fire protective cladding; calculation of thickness of complex cladding elements; production of slabs of the composite corrugated web composite cladding – 5 and the stretched flange composite cladding – 6. It follows by U-sections or reinforcement angle bars installation on the welded I-beam flange flat ends; installation of complex cladding elements of the stretched flange – 6 and fastening them with screws; corrugated web surface and welded I-beam flanges coating with a glue layer – 3 and gluing mineral-cotton slabs for the corrugated web to them – 3; complex cladding of the stretched flange – 6; coating of the surface of the corrugated web complex cladding – 5 and of the slab fire protective cladding for the stretched and compressed flanges with fiberglass (if necessary).

4. Conclusions
The research yielded the following conclusions:
1. The new technical solution refers to the area of buildings and structures fire safety and can be used while manufacturing of fire-resistant steel beams with corrugated web, in particular.
2. The technological result of the proposed technical solution is the steel beam with corrugated web fire protection design improvement; increase of industrial production of fire-proof cladding and its fastening; increase of load bearing capacity of steel beams with corrugated

web; cladding and steel materials weight reduction; increase in labour productivity while constructing fire protection.

3. This technological result can be achieved because the welded I-beam has a corrugated web, the flat ends of the welded I-beam with corrugated web flanges are protected with a thermo-protective girder of mineral-cotton slabs; and their edges heated at fire are protected by mineral-cotton slabs and large gypsum plasterboards with complex cladding, Besides, the welded I-beam flanges are have thermo-protective girders along their flat ends; the thickness of the beam with the corrugated web and its thermo-protective girder is determined by calculation; the height of the thermo-protective girder of the stretched flange is accepted according to the condition $h_{pr} = 6 \cdot \delta_s$, where d_s is the thickness of the stretched shelf, *mm*. The corrugated web of the welded I-beam is covered by a thermo-protective mineral-cotton layer with a thickness determined by calculation and with a cement-perlite mortar layer with a thickness that depends on the required fire resistance limit of the beam with a corrugated web.

5. References

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