Numerical and Analytical Study of the Distribution of Concentrated Pressure in the Wall of a Steel I-beam

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Abstract. The theory of the strength of load-bearing structural elements made of steel I-beams suggests that the nature of the stress distribution in the element is known, including from the action of concentrated pressure. A concentrated load is often applied at the level of the upper girdle of the beams, and causes local stresses in the wall. The walls of steel I-beams, due to their insignificant thickness, are sensitive to local pressure. That is why it is necessary to accurately determine the most stressed sections of the wall and the intensity of local stresses. In this paper, we consider a test model of a steel I-beam with a span of 9 m, to the upper girdle of which a concentrated load of 200 kN is applied. The local stresses in the wall are determined by analytical and numerical methods. The numerical calculation of the beam model was performed in the SCAD Office computing complex. The beam is modeled from volumetric isoparametric finite elements. The length of the beam wall is divided by two-sided stiffeners into nine compartments, with a step of 1000 mm. A comparative analysis of the nature of the distribution of local stresses in the wall of a steel beam obtained by analytical and numerical calculations is presented. Recommendations are given on taking into account local stresses in the beam wall from the action of a concentrated load when calculating strength.

1. Introduction
Concentrated forces are often applied to the upper girdle of steel I-beams for various purposes. Examples of elements of structures experiencing concentrated pressure [5] are crane beams, beams of supporting structures for equipment, roof beams and others. The upper girdle of the steel beam has a distributing effect and transfers concentrated pressure to the wall [15]. Since the walls of steel beams have a small thickness [10, 18], local stresses in them, especially near the places of application of concentrated forces, can reach large values. An inaccurate determination of the intensity and nature of the stress distribution can lead to a loss of strength or stability [3, 9, 16] by the thin wall of a steel beam. The standard methodology (SP 16.13330.2017) for determining the stresses in the beam wall from the action of concentrated loads was developed for calculating the rod schemes of double-bearing steel beams [17]. Modern computing programs provide the ability to simulate the load-bearing elements of steel structures in an explicit form, with minimal differences from the real structure [19]. The calculation apparatus of most computing complexes is the finite element method (FEM) [6, 20], which allows you to create a three-dimensional model of a building structure from volumetric finite
elements (FE). According to the results of calculating the computer model of the beam, it is possible to plot the pressure distribution in the wall and determine the stress values in each (FE) [12]. This study examined a test model of a beam with a span of 9 m, to the upper girdle of which a concentrated load of 200 kN is applied. A comparative analysis of the calculation results by analytical and numerical methods is presented.

2. Statement of the problem and assessment methodology
The distribution of concentrated pressure in the wall of a steel beam is considered on the example of a test model with a span of 9 m. A concentrated load of 200 kN was applied to the upper girdle of the beam. Further, the stress values in the wall are determined by numerical and analytical methods.

2.1. Calculation model of a steel beam for numerical research
The following thicknesses of the elements of the test model of the steel beam are specified: wall - 6 mm, flanges - 16 mm, support webs - 20 mm, web stiffener - 10 mm. Beam material - steel C355. The beam wall is divided into nine compartments with 10 mm thick double-sided web stiffeners installed in increments of 1000 mm ‘figure 1’. Each beam element is modeled from two rows of FE in thickness. The calculation by numerical method was performed in the SCAD Office software package [7]. Elements of the calculation model ‘figure 2’: wall, girdles, web stiffeners, support webs, are presented as eight-node isoparametric FEs, element type in the calculation program No. 36. The total number of volumetric FE elements of the beam model is 9032. Limitations on linear displacements are established along the axes of the bolts: articulated movable left support, articulated fixed right support. From the plane in the level of the upper girdle along the supporting webs, constraints are imposed, restricting linear displacements along the Y axis ‘figure 1’. The concentrated force $F = 200$ kN is set in the FE assembly [1], located on the longitudinal axis of the beam with reference to the left edge of 3445 mm.

Figure 1. The design scheme of the beam model.

Figure 2. Beam cross section diagram.
2.2. Analytical assessment method

To determine the stress values and the conditional length of the stress distribution section in the wall from the concentrated load, the standard methodology SP 16.13330.2017 was applied. The specified technique takes into account the bending stiffness of the upper girdle of the steel beam, namely, the influence of the geometric characteristics of the section of the flange on the stress distribution in the wall [4]. Local stresses are determined by the expression:

\[ \sigma_{loc} = \frac{F}{l_{ef}t_w}, \]  

(1)

where \( F \) – magnitude of concentrated force; \( t_w \) – wall thickness; \( l_{ef} \) – the conditional length of the voltage distribution, determined by the expression:

\[ l_{ef} = \psi \frac{I_f}{\sqrt{t_w}}, \]  

(2)

where \( \psi \) – coefficient adopted for welded and rolled beams under the action of concentrated pressure 3.25; \( t_w \) – wall thickness; \( I_f \) – moment of inertia of the section of the upper flange:

\[ I_f = \frac{b_f t_f^3}{12}, \]  

(3)

where \( b_f \) – flange width; \( t_f \) – flange thickness.

Next, we verify the convergence of the analytical methodology and the results of the numerical calculation of the beam model performed in the SCAD Office computer complex.

3. Analysis of the results of numerical and analytical calculations

The general view of the diagram of local stresses in the bulk FE model of the beam has an oval outline ‘figure 3’. According to the results of the numerical calculation of the beam, it can be noted that in a compartment with an applied concentrated load in the final elements of the wall, local stresses reach maximum values between the upper and the next row of CE of the wall in the vicinity of the force application unit ‘figure 4’. Further, local stresses are transmitted along the FE rows with a gradual attenuation ‘figure 4’. The length of the section transmitting concentrated pressure from the flange to the wall is 135 mm; the width is equal to the wall thickness \( t_w = 6 \) mm. The value of local compressive stresses in the upper row of the CE of the wall is -148.3 MPa ‘figure 5’.

![Figure 3. General view of the calculated model of bulk FE.](image-url)
Figure 4. Diagram of the distribution of local stresses in the wall inside the compartment.

Figure 5. Diagram of the distribution of local stresses in the FE of the upper row of the wall.

An analytical calculation using formulas (1), (2) yields the values of the local stress and the conditional length of the local pressure distribution section [11]. The diagram of the distribution of local stresses has a parabolic outline ‘figure 6’. The distance between the zero points of the local stress diagram ‘figure 6’ is taken as the conditional length of the stress distribution. The local compressive stress obtained by expression (1) was -390 MPa, and the calculated conditional length of the stress distribution portion $l_{ef} = 85.5$ mm ‘figure 6’ was found by expression (2).

Figure 6. The diagram of the distribution of local stresses, with the analytical method of calculation.
4. Conclusions
The performed numerical and analytical study allows us to draw the following conclusions:

4.1. The shape of the diagram of the distribution of local stresses in the wall in the numerical calculation has an oval shape and extends below the midline of the beam with a gradual attenuation of intensity. In the analytical method, the generally accepted form of local stresses has a parabolic shape.

4.2. The analytical calculation method [8] shows a higher intensity of compressive stresses in the wall than the results of numerical calculation [2].

4.3. The length of the distribution of local stresses in the wall, at the point of contact with the flange, obtained by the analytical method is less than that found by numerical calculation of the FE model of the beam.

4.4. The use of volumetric FE models of steel load-bearing beams allows one to obtain a more accurate distribution of local stresses and, therefore, to assign thinner walls [13, 14, 21] that satisfy the conditions of strength and stability. With appropriate justification, it is recommended to use three-dimensional FE models of load-bearing elements of structures for higher theoretical accuracy of calculations, especially in conditions of complex loading of the structure.

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