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Statement of the problem. In order to calculate the strength of the supporting beam, it is important to accurately determine the stress-strain state in the support node. There is a need to consider the possibility of transferring part of the bending moment from the middle of the span to the support node. A reduction in the bending moment in the span will allow the indicators of material consumption to be increased.

Results. In the SCAD Office software models of volumetric finite elements of two working beams with a span of 9 m each were calculated. The stress-strain of the elements of the support nodes was determined, the bending moment from partial pinching was calculated. A decrease in the value of the bending moment in the middle of the span was observed. The efforts in bolted connections are obtained. Recommendations on the structural reinforcement of the support node are presented.

Conclusions. The results of numerical calculations indicate a partial pinching of the beams in the support node, which leads to the appearance of a concentration of tensile stresses on the supporting sections of the beam wall and reduces stresses in the middle of the span. There is a possibility of reducing the cross section of the beam. Significant tensile forces in the bolts of the extreme upper row were revealed. There is a need for structural reinforcement of the support node.

Keywords: I-beam steel beam, node of the beam, computer model of the steel beam, stress-strain state of the beam, work power of the support node, partial pinching in the node.

Introduction. The constructive solution for the transmission of the support reaction through the support rib is employed in the form of a hinged unit for securing steel beams. This solution is used for steel floor beams, girders, crane beams and other load-bearing elements. If there are several bearing elements along the coordination axis, the supporting ribs are fastened together by bolts in several rows in the lower third of the height of the supporting rib of the

beam. But in the case of dense filling of the mounting gap between the supporting ribs of steel beams, in the bearing unit, apart from the transverse force, a bending moment is caused by partial pinching [15].

Extra stresses can cause a drop in the strength and stability of the bearing beam in the support node. Fiber where the conditions of strength and stability must be checked in compliance with the method of SP 16.13330.2017 "SNIIP II-23-81 * "Steel Structures", can also be located differently from what is indicated in idealized bar design schemes [11, 12, 20]. Partial pinching can reduce span bending moment. It will become possible to designate a more economical cross-section. Thus, it is important to study the stress-strain (SS) of the beam support node with partial pinching. Analytical and experimental investigation on the study of support joints of split steel beams was extensively performed by Soviet scientists and engineers. But it is only in the last decades that the possibilities have emerged for studying the power operation of load-bearing elements by means of numerical methods [16—18]. This is due to the development of computing systems whose computing apparatus is the finite element method (FEM) [3, 4, 9, 23], and the growing computing capacity of digital technology. But it can be noted that the dimension of the problems being addressed has increased as well [1]. In this research, the *SCAD Office* computer complex was employed for identifying the stress-strain of the beam structures [6, 14]. The FE model of two beams was designed based on volumetric isoparametric eight-node finite elements (FE) with a span of 9 m each. Three-dimensional modeling of steel beams allows enables one to calculate the stress-strain of all FE included in the supporting structures more accurately.

1. Parameters of the investigated beams. For the ongoing research, two test steel beams were adopted with a reinforced concrete floor installed on the upper belt. A payload is applied to the beams. The major layout parameters of the beams are assigned: span $L = 9$ m of each beam, step $B = 6$ m, material — steel C255. The joining of the beams to the head of the columns is articulated, the thickness of the monolithic reinforced concrete floor slab is 200 mm. Two combinations are considered: with symmetrical and asymmetrical loadings. The calculated load was applied according to Fig. 1, with an intensity of 4.55 kN/m^2 — for a permanent load, 2.4 kN/m^2 — for a temporary load. In terms of linear intensity for a step of 6 m: 27.3 kN/m from a constant load and 14.4 kN/m from a temporary load, respectively.

According to the results of the calculation of the bar scheme, the cross-section of a steel beam made of sheet steel C255 was pre-selected (Fig. 2). FE-models of beams are out-of-plane at the level of the upper chord every 3 m. Double-sided stiffeners are 10 mm in thickness and installed with a step of 1000 mm. The support reaction is transmitted through the

support ribs 20 mm in thickness. At the nodes of the ends of the ribs, links are installed that limit vertical linear displacements. The width of the supporting ribs and stiffeners is assigned to the width of the chords (shelves). The beam interface is comprised of three horizontal rows of M20 bolts with a pitch of 75 mm in height (two bolts in each row). The installation gap of 20 mm is filled with steel gaskets. The bolts and mounting spacers are modeled by means of one-way two-node ties [5, 7, 10]: the bolts operate in tension and disengage during compression, while the mounting spacers operate in compression and disengage during stretching (Fig. 3).

Fig. 1. Design scheme for steel beams

Fig. 2. Transverse section of the steel beam

Fig. 3. General view of the support node of the FE-beam model

The volumetric model was designed in the environment of the *SCAD Office* software using the following type of finite element (FE) [3, 4, 9]: type 36 eight-node, isoparametric FE. The FE-model of two beams has the following computational dimension: 27636 nodes, 18126 elements, 82.768 degrees of freedom. The wall is divided in height into eight rows of FE, shelves and supporting ribs are divided into ten rows of FE in width. Each steel beam element is

modeled using two rows of volumetric FE in thickness. In this case, the following dimensions of isoparametric eight-node FE were employed: wall — $75 \times 75 \times 3$ mm, shelf overhangs — $40 \times 75 \times 8$ mm, support ribs — $40 \times 75 \times 10$ mm, stiffeners — $37 \times 75 \times 5$ mm. Connections in the form of constraints on linear displacements are set so that the fixing conditions correspond to the constructive solution of the junction of the elements: with hinged-fixed and hinged-movable supports [2, 8].

2. Methodology for identifying the VAT for the core design scheme. Diagrams of normal and tangential stresses were designed in the section coinciding with the geometric centers of the second vertical row of the FE of the I-beam model wall, with a tie from the edge of the supporting edge of the beam $x = 132.5$ mm, as it is in this row in the junction of the beams that FE have the highest concentration stress.

For a bar design scheme, the stress values are identified using the known expressions [2]:

$$\tau = \frac{Q_z S_x}{I_x t_w}, \quad (1)$$

$$\sigma = M_y y / I_x, \quad (2)$$

where Q_z , M_y are the values of the shear force and bending moment in the corresponding section; S_x is the static moment of the cut-off part of the section relative to the $x - x$ axis; I_x is the moment of inertia of the total section relative to the $x - x$ axis; t_w is the wall thickness of the I-beam; y is the coordinate measured from the $x - x$ axis to the considered fiber of the cross section.

As for loading the hinged beam with a uniformly distributed load q along the entire length, the values of internal forces are identified based on the following relationships:

$$Q_z = q(L - 2x) / 2, \quad (3)$$

$$M_y = qx(L - x) / 2, \quad (4)$$

where q is the value of the intensity of the uniformly distributed design load; Q_z , M_y are the values of shear force and bending moment for a cross section at a distance x ; x is the coordinate for identifying internal efforts; L is the beam span.

3. Analysis of the numerical and analytical results of the study. Below are the results of calculating volumetric models of beams in the form of fields of distribution of normal and tangential stresses (Fig. 4, 5, 6). Fig. 7 shows the horizontal displacements on the support sections.

Free rotation of the supporting part of the beam starts from the top row of bolted connections. In the section of the section, below the axis of the upper row of bolts, there is a partial pinching of the beam with the transfer of a part of the bending moment. Let us look into how the stresses in the FE located in the second vertical row of the beam support compartment change for combina-

tions of load cases № 1, № 2 of the model (Fig. 8a, b) and a combination of load cases № 1 for the bar scheme (Fig. 8c).

Fig. 4. General view of the mosaic of normal stresses σ (combination of load cases № 1)

Fig. 5. Mosaic of the normal stresses σ at the support node (combination of load cases № 1)

Fig. 6. Mosaic of the shear stresses τ at the support node (load combination № 1)

Fig. 7. Mosaic of the distribution of horizontal displacements in mm (combination of load cases № 1)

The stress diagrams indicate (Fig. 8, 9) that the values and nature of the stress-strain of the I-beam in the reference section of the FE model and the bar scheme differ significantly. Moreover, the case of a symmetrical load (combination of load cases № 1) is more dangerous and shows the maximum values of normal and shear stresses. It is assumed that this is caused by the partial compatibility of the operation of the supporting ribs of adjacent beams. The support section of the right, less loaded, beam unloads the support section of the left, more loaded, beam. If the values are inserted into the strength condition (44) SP 16.13330.2017 with the simultaneous action of a bending moment and a shear force for steel S255 at the most stressed point A according to Fig. 9a, b, we get:

$$\frac{0.87}{R_y \gamma_c} \sqrt{\sigma_x^2 + 3\tau_{xy}^2} \leq 1, \quad (5)$$

$$1.21 > 1, \quad (6)$$

where R_y is the design steel resistance to yield strength; γ_c is the operating condition factor; σ_x is the normal stress; τ_{xy} is the tangential stress.

The condition for checking the strength at point A is not satisfied. It is essential to make a beam wall on the support section from steel of strength class C355 or to increase the wall thickness in the support compartment by assigning a wall thickness of 8 mm. But partial pinching of the beam not only raises the stresses from the bending moment in the support section, but also reduces the magnitude of the moment in the span [13, 22].

Let us examine the nature of the distribution of the bending moment: for the FE models of two beams (previously described) with partial restraint, for the FE model of a single beam without partial restraint (horizontal ties are imposed for the right support at the nodes at the level of the lower flange) and the bar scheme of a statically definable beam. The values of

bending moments for FE-models were identified using the expression (2). The values of the normal stresses in the middle of the span were previously calculated in the *SCAD Office* software. From the difference in bending moments in the span for the case of two beams with partial restraint and the case of one beam without restraint, the component of the bending moment from the restraint of the support node was obtained. In the bar scheme, the bending moment is obtained according to the previously shown expression (4).

Fig. 8. Diagrams of normal stresses, MPa, for the second vertical row of FE:

- a) values of the normal stresses for load combination No. 1;
b) for a combination of load cases № 2; c) for the rod scheme of combination № 1

Fig. 9. Diagrams of shear stresses, MPa, for the second vertical row of FE:

- a) values of the shear stresses for load combination № 1;
b) for a combination of load cases № 2; c) for the rod scheme of combination № 1

Based on the diagrams of bending moments in Fig. 10, partial pinching relieves the beam in the middle of the span reducing the bending moment by 14.3 %.

Fig. 10. Diagrams of the bending moments M_y

Fig. 11 shows a diagram of the location of the bolts in the support rib prior to the calculations (Fig. 11, a) and following the analysis of the results of the numerical study (Fig. 11, b).

Fig. 11. Layout diagram of a bolted connection in a support node:

a) prior to the research; b) based on research results

The tensile forces in the M20 bolts are distributed unevenly over the horizontal rows: for the first row $N = 0$ kN, for the second (middle) row $N = 30$ kN in each bolt and for the uppermost

row, the tensile force in the bolt is $N = 268$ kN. Conventionally, it can be assumed that the rotation of the support node emerges around a line with zero bolt force (bottom row), and the forces in the second (middle) and extreme (upper) rows indicate a non-classical and non-triangular shape of the deformation diagram of the support rib during rotation. Most of the tensile force is applied to the top row of bolts. Two previously adopted M20 bolts of strength class 5.8 in the top row do not satisfy the condition of tensile strength. For the top row, it is essential to install 4 bolts M24 of strength class 8.8 or higher [19]. Each such bolt will have a maximum tensile force $N = 134$ kN.

Conclusions

1. As a result of the studies, pinching the beam was found to reduce the bending moment in the span by 14.3 %, the revealed redistribution of forces also decreases the deformation of the structure in the span. As the cross-section of double-support beams is selected based on two groups of limiting states precisely in the middle part of the span, a drop in the moment and deformations makes it possible to achieve an increase in material consumption indicators by selecting sections of steel I-beams with lower required geometric characteristics.
2. It has been established that beams with a gap tightly filled with mounting spacers and bolts tightened to the stop in the support section can be considered partially continuous mechanical systems. The properties of these systems call for further research to be carried out.
3. It has been proven that the moment from partial pinching in the support unit causes significant tensile stresses in the wall and reduces the load bearing capacity of the unit. The following constructive measures are set forth in order to strengthen the wall in the support compartment: increasing the wall thickness as well as the strength class of steel, welding the sheet for local reinforcement.
4. The above combination with asymmetric loading reduces the stress values in the elements of the support node.
5. The upper row of bolts in the support assembly was found to experience considerable tensile forces. Stretching can cause a loss of strength of the bolts if the section is taken for design reasons without considering the forces from partial pinching of the beam.
6. It has been confirmed that a complete analysis of the power operation of load-bearing steel beams is possible only if modern plate and / or three-dimensional FE models. The pivotal schematization of structural analysis does not enable one to completely identify the SS.
7. It is shown that the use of one-sided two-node connections in calculations in computer systems makes it possible to set the conditions for fixing a structure without explicitly modeling bolts and mounting gaskets.

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