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About optimal geometric parameters of a developed I-beam with a perforated web

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Abstract. For the first time, questions of optimization of geometric parameters of developed I-beam with a perforated web are considered with the use of the finite element method in PC ANSYS Mechanical. For the linear model of the material, strength and stiffness calculations are performed depending on the shape of the cut: the height of the I-beam development and the distance between the holes. For the I-beam with the highest height, the stability of the web was checked, the first two critical loads and forms of stability loss were obtained. The optimum degree of development is shown on the example of the 12-meter developed I-beam from the initial rolled I-beam with a height of 60 cm. The strength and rigidity of the beam is determined when the length of the distance between the holes is changed.

1 Status of the question

Developed I-beams with a perforated web in their design features occupy an intermediate position between a welded beam from rolled T-beams and Vierendeel trusses.

The exact method of their calculation is connected with certain difficulties, in view of the complicated configuration of the holes.

In TsNIISK together with VNIIMontazhspetsstroi [1] and at the experimental plant VNIIGAZA [2] in the 1970s, experimental studies of a series beam structures from developed I-beams with a perforated web made it possible to develop a calculation method based on the approximate calculation of Vierendeel trusses.

The purpose of the research was to assess the actual bearing capacity, deformability and the nature of the destruction of full beam structures from developed I-beams with a perforated web, working on transverse bending under the action of two concentrated loads located at a distance of 1 / 4-1 / 3 span from the supports.

The initial profile was the I-beams № 36, № 40 and № 50 in accordance with GOST 8239-59* from steel VSt.3ps.

The ratio of the height of the cross section of the perforated I-beam to the height of the original varied from 1.39 to 1.5.

The ratio of the height of the cross-section of the tested beams to the span was 1/12 - 1/18 and covered the characteristic range of bending beam structures.

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The transverse bending was provided by a system of links preventing the exit of the upper flange from the plane.

The entire sections of the web of the tested structures did not lose stability, including in places of application of concentrated loads, despite the absence of vertical ribs there.

The exhaustion of the load-carrying capacity of all tested structures occurred as a result of the appearance of yield in the extreme fibers of the T-section.

The appearance of relatively early yield in the sections of the web, where the holes begin to change their height, was of a local character and was practically no effect on the bearing capacity of the structure.

Taking into account the results of the tests, the calculation bearing strength of perforated I-beams working on transverse bending should be carried out in a weakened section opening at the maximum normal stresses arising in the T-sections and consisting of normal stresses from the bending moment *M* and normal stresses from the action of the moment *M* σ_Q of conditionally applied shear forces, i.e. $\sigma = \sigma_M + \sigma_Q \le R$, where *R* is the design resistance of steel to tension and compression.

The normal stresses from the bending moment in the cross sections near the holes are distributed linearly, in proportion to the distance from the longitudinal axis of the beam (Fig. 1).

at points 1, 4: $$\sigma_M = \pm\frac{M_{I-I}\cdot H}{2J_x}, \quad (1)$$

at points: 2, 3: $$\sigma_M = \pm\frac{M_{I-I}\cdot(H-h)}{J_x}, \quad (2)$$

where *H* – height of developed I-beam, cm;

h – height of the original I-beam, cm;

J_x – moment of inertia of the perforated beam in section *I-I* (net section) with respect to the axis x-x, cm^4;

M_{I-I} – bending moment in section *I-I*.

In the area of simultaneous action of the bending moment and the transverse force, the total transverse force in the sections along the hole is assumed to be distributed proportionally to the moments of inertia of the T-sections and concentrated in the cross section passing through the middle of the hole.

With a symmetrical section of the developed profile, the magnitude of the transverse force is distributed equally between the T-sections.

At a certain distance from the conventional point of application of the transverse force to the normal stresses from the bending moment in the sections along the apertures, stresses caused by the action of the applied lateral force are added.

Under these conditions, the maximum stresses from the transverse force arise in sections *I-I*, *III-III* (fig. 1) and for points 1-8 can be determined by the formulas:

at points: 1, 5, 4, 8: $$\sigma_Q = \pm\frac{Q_b}{2W_{\perp\max}}, \quad (3)$$

at points: 2, 6, 3, 7: $$\sigma_Q = \pm\frac{Q_b}{2W_{\perp\min}}, \quad (4)$$

where *b* – T-section length, cm;

Q – transverse force in section, N;

$W_{\perp\max}$, $W_{\perp\min}$ – the greatest and the least moments of resistance of a T-section of constant height, cm^3.

It is not difficult to verify that the maximum total normal stresses $\sigma = \sigma_M + \sigma_Q$ arise at points 2, 3, 5, 8, and their values can be determined by the following formulas:

at points 2 и 3: $$\sigma = \pm\left(\frac{M_{I-I}\cdot(H-h)}{J_x} + \frac{Q_{II-II}\cdot b}{2W_{\perp\min}}\right) \quad (5)$$

at points 5 и 8: $$\sigma = \pm\left(\frac{M_{III-III}\cdot H}{2J_x} + \frac{Q_{II-II}\cdot b}{2W_{\perp\max}}\right) \quad (6)$$

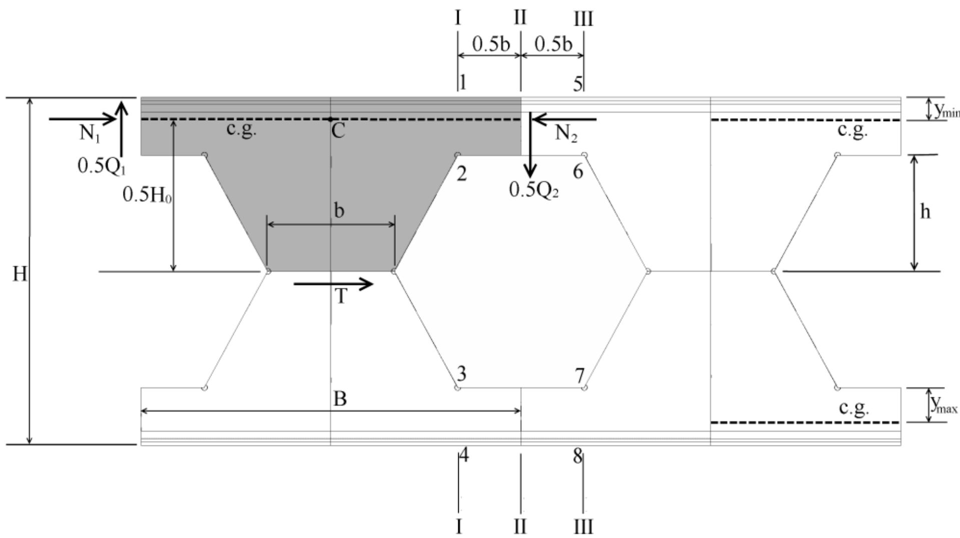


Fig. 1. Geometric parameters and the scheme of application of internal forces in the developed I-beam.

Thus, the strength of bent elements from perforated I-beams should be checked by formulas (5) and (6), and the values of normal stresses at points 2 and 3 should not exceed $\sigma \le mR$, at points 5 and 8 $\sigma \le R$, where $m = 1,2$ – the coefficient of conditions work, taking into account the local nature of the extreme stresses in the corners of the holes at points 2 and 3.

The magnitude of the tangential stresses in the weld region can be determined by taking into account the assumptions made for the normal stresses.

For this purpose, cut out a part of the beam, shown in Fig. 1, and apply the forces acting on it.

Forces N_1 и N_2 – the components of the bending moment are applied along the center of gravity of the T-section; $0.5Q_1$ и $0.5Q_2$ – values of the conditionally applied lateral force with symmetrical sections; T – shear force in the web.

Having the sum of the moments of forces relative to the point C, the shearing force T and the magnitude of the shearing stresses acting in the weld seam are determined from the equilibrium condition of the cut beam part:

$$\tau = \frac{QB}{H_0 t_w l_w}, \quad (7)$$

where $Q = \frac{Q_1 - Q_2}{2}$ – transverse force, N;

B – step of holes in a perforated beam, cm.

H_0 – distance between centers of gravity of T-sections, cm;

t_w – web thickness, cm;

$l_w = b - 2$ – the length of the welded joint, taking into account bad welding at the ends, cm.

The overall stability of perforated beams, as well as the stability of the web, is recommended to be checked in accordance with the requirements of SNiP for bending beams with entire web.

Particular attention should be paid to checking the stability of the web in the area of support and large concentrated loads.

The deformability of the bent perforated I-beam should be determined taking into account the effect of lateral force.

The total deflection f is assumed to consist of a deflection f_M from the action of the bending moment, defined as for a beam with entire web, and a deflection f_Q, caused by the action of shear forces.

$$b : f = f_M + f_Q$$

The values f_M и f_Q, are determined from the general formulas for the resistance of materials.

For bending beam structures with a ratio $\frac{H}{L} \le \frac{1}{15}$ value of deflection from the action of the transverse force f_Q can be taken approximately equal to 6% of the deflection caused by the action of the bending moment: $f_Q = 0{,}06 f_M$

The basic calculation provisions were taken as a basis for the writing of Chapter 19 of SNiP II-23-81 *.

All the calculation provisions above relate to engineering methods of calculation using obsolete regulatory documents created in the 1970s of the last century.

In 70-ies of the last century the author carried out experimental studies of the shape of the cut and bearing capacity of developed I-beams at the experimental plant VNIIGAZA, on the basis of which for the first time in the USSR the developed I-beams were used in the frame of the compressor station in Bukhara, and then in the frames of other compressor stations [2].

The normative method for calculating the developed I-beams with a perforated web, set out in SNiP II-23-81* [3] and without actualization, transferred to the "Updated" edition (SP 16.13330.2011) [4].

In this direction, a number of scientists were studied both by engineering methods [5-10] and using finite element modeling [11-16].

Currently on the basis works of the author on the improvement of building metal structures was research using the finite element method for the optimal cut of the I-beam. [17, 18]

2 Finite Element Simulation

Calculation of developed I-beams was carried out in PC ANSYS Mechanical.

In the programming language APDL, a program was written that implements the calculation of a set of constructive forms of developed I-beams with the ability to select and vary physical and geometric parameters, calculate and output the quantities of interest.

Finite elements of the *Solid186* type with a quadratic form function were used, which are much more accurate in the problems of calculating structures with thin wall than linear *Solid185*. [19, 20]

In static analysis to reduce the calculation time, the symmetry condition was used.

The results of calculation of developed I-beams with a perforated web made of the initial profile №60 (GOST 8239-89) with a length of 12 meters are given.

Beams have hinged supports at the ends and loaded with a uniformly distributed load.

The material was modeled as linearly elastic with a modulus of elasticity $E = 2.06 \cdot 10^5$ MPa, Poisson's ratio $v = 0.3$.

Steel class – *C245* (GOST 27772-2015) with resistance to bending with ultimate strength $R_u = 360$ MPa and yield strength $R_y = 240$ MPa.

To verify the calculated finite element model, an additional verification model with a smaller grid was built. The main results of the calculation on the basis of both models are presented in Table. 1, and the geometric model and fragments of finite-element models in Fig. 2.

To compare the results by different criteria, the maximum load was used. The maximum load was calculated using the following formulas:

$$F_{\max A} = \frac{R_u}{\sigma_{\max A}} q, \; F_{\max B} = \frac{R_y}{\sigma_{\max B}} q, \; F_{\max C} = \frac{L}{200 \cdot u_{\max}} q,$$

where $F_{\max A}$ – the maximum load at which the stress of Mises at the points at which the hole begins to change its height $\sigma_{\max A}$ does not exceed R_u;

where $F_{\max B}$ – the maximum load at which the stress of Mises in flange $\sigma_{\max B}$ does not exceed R_y;

where $F_{\max B}$ – the maximum load at which the deflection $u_{\max}$ does not exceed *1/200* of span L.

The results of the calculations are shown in fig. 3-5. For the developed I-beams with the highest height 108 cm, the stability of the web was checked (fig. 6).

Table 1. Comparison of finite element networks

Characteristics of the finite element grid	$\sigma_{\max A}$ **MPa**	$\sigma_{\max B}$ **MPa**	$u_{\max}$, **mm**
Calculated • 20 elements in height of I-beam between perforations • 8 elements along the cut line of the cut at the extreme perforations Total nodes – 275 595	58,21	4,76	0,847
Test • 30 elements in height of I-beam between perforations • 15 elements along the cut line of the cut at the extreme perforations Total nodes – 393 979	58,71	4,76	0,847

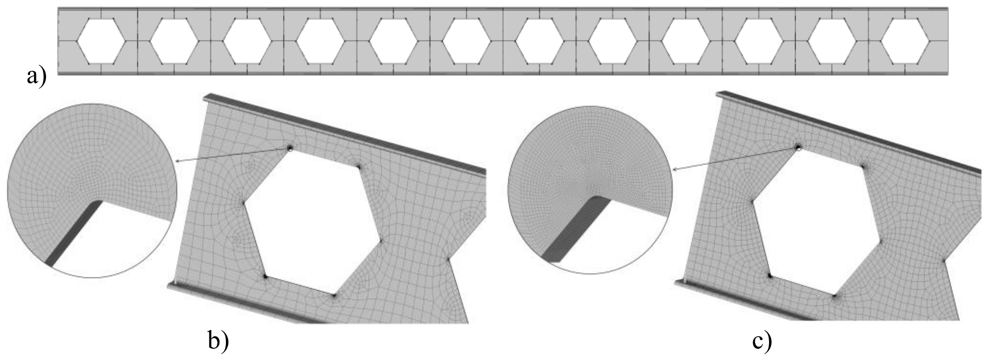
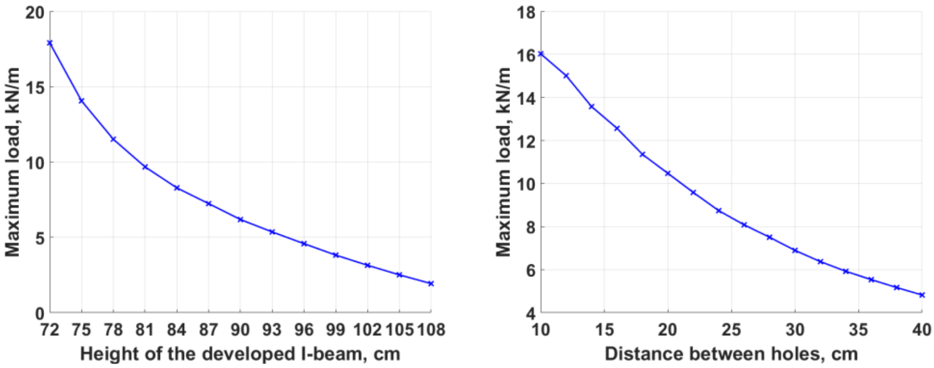
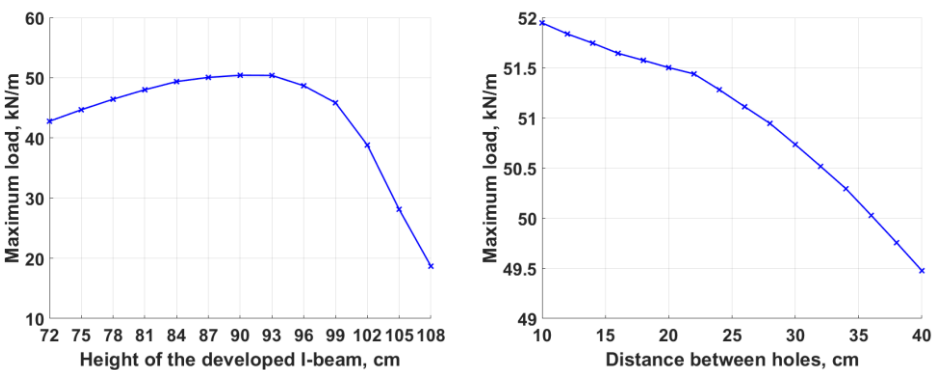


Fig. 2. a) geometric model; **b)** Fragment of the finite element model No. 1 (calculated) at the outermost hole; **c)** Fragment of the finite-element model No. 2 (test) at the outermost hole.



a) b)

Fig. 3. The choice of the shape of the web cut, at which the maximum stress values in the nodes the change in the cross sections does not exceed $\boldsymbol{R_u}$.
a) depending on the height of the developed I-beam;
b) depending on the distance between the holes.



a) b)

Fig. 4. The choice of the shape of the web cut, at which the maximum stress values in the flanges do not exceed $\boldsymbol{R_y}$.
a) depending on the height of the developed I-beam;
b) depending on the distance between the holes.

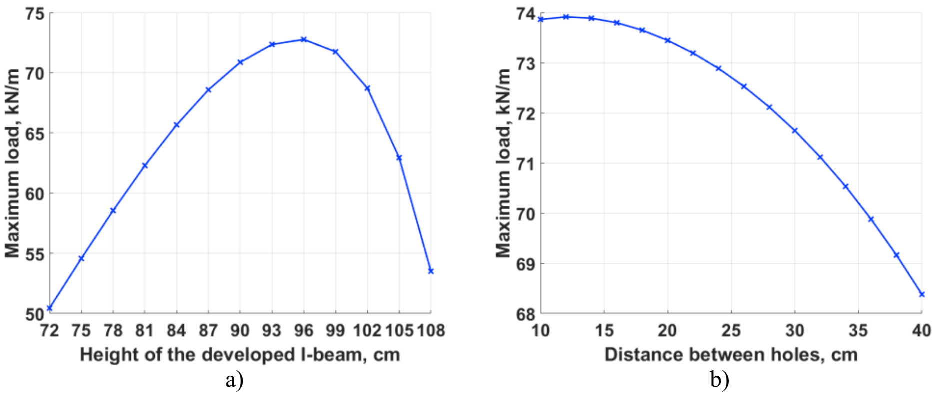


Fig. 5. The choice of the shape of the web cut, in which the deflection does not exceed the 1/200 span.
a) depending on the height of the developed I-beam;
b) depending on the distance between the holes.

Fig. 6. a) First (70,270 kN/m) and **b)** second (70,279 kN/m) buckling modes.

3 Conclusions

At this stage, dependencies are obtained for the ultimate load by three criteria: strength - at the points where the hole cross-sections change, strength - in the shelves and the maximum allowable deflections.

Based on the finite element method, the following

a) the optimum height of 90 cm. Of the developed I-beam from the original I-beam No. 60.

b) it is established that a decrease in the length of the bridge increases the strength and rigidity of the developed I-beam.

c) the stability of a developed I-beam is ensured even with the ratio $H / h = 1{,}8$.

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