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TO THE QUESTION OF THE DETERMINATION OF GEOMETRIC CHARACTERISTICS OF THE SECTION OF CORRUGATED BEAMS WITH TRAPEZOIDAL WEBS BASED ON THE SIMULATION RESULTS

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Abstract: An algorithm for calculating the geometric characteristics of steel I-beams with plate corrugated webs of arbitrary type is proposed. The algorithm is implemented using the I-beam with plate trapezoid webs as an example. The determination of reduced area and moments of inertia in the axes of the cross section of the trapezoidal profile based on the finite element modeling of the beam with shell elements in calculations for bending and axial compression in the "ANSYS 14.5" software package is described. The verification procedure has been performed for a shell finite element model using the example of an I-beam with a standard flat web. A table has been compiled of geometric characteristics of rod corrugated elements of a trapezoidal profile in order to realize their finite element calculation using a rod diagram. An example of the calculation of a flat frame with a horizontal corrugated element, made in software package "LIRA-SAPR" using a flat rod diagram is given.

Keywords: shell finite element, rod finite element, simulation results, numerical analysis, maximum deflection, moment of inertia, software "ANSYS"

К ВОПРОСУ ОПРЕДЕЛЕНИЯ ГЕОМЕТРИЧЕСКИХ ХАРАКТЕРИСТИК СЕЧЕНИЯ ГОФРОБАЛОК С ТРАПЕЦЕИДАЛЬНЫМИ СТЕНКАМИ НА ОСНОВЕ КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ

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Аннотация: Предложен алгоритм вычисления геометрических характеристик стальных двутавровых балок с пластинчатыми гофрированными стенками произвольного вида. Алгоритм реализован на примере балок с трапецеидальными стенками. Описано нахождение приведенной площади и моментов инерции в осях поперечного сечения трапецеидального профиля на основе конечно-элементного моделирования балки оболочечными элементами в расчетах на изгиб и осевое сжатие в программном комплексе "ANSYS 14.5". Выполнена процедура верификация оболочечной конечно-элементной модели на примере для двутавровой балки со стандартной прямой стенкой. Составлена таблица геометрических характеристик стержневых гофро-элементов трапецеидального профиля с тем, чтобы реализовать их конечно-элементный расчет по стержневой схеме. Приведен пример расчета плоской рамы с горизонтальным гофроэлементом, выполненный в ПК "ЛИРА-САПР" с применением плоской стержневой схемы.

Ключевые слова: компьютерное моделирование, численный анализ, оболочечный конечный элемент, стержневой конечный элемент, момент инерции, программный комплекс «ANSYS»

INTRODUCTION

I-beams with plate corrugated webs have not widely used in the design of buildings and structures until a certain time [1]. In the past decade, it has been recognized that cold-formed steel beams of various corrugation configurations can be effectively used as bearing components of the framework.

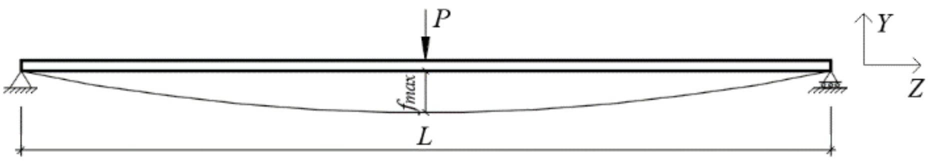


Figure 1. Calculation scheme.

The use of corrugated webs allows the use of thin plates without the need to install stiffeners, which contributes to reducing the weight and cost of the beam [2-4]. Economical expediency of corrugated elements is substantiated in [1, 5-8]. Same source notes main flaws in design of such constructions, which are mainly caused by lack of normative documents, literature and special computation software. The use of such structures is difficult the complexity to analyze their stress-strain state [9-14]. The standard scheme for calculating frameworks of buildings is based on a rod finite element model using geometric characteristics of the cross sections of rod elements. Meanwhile, tabulated values of the geometric characteristics are known for certain corrugation types – triangle [15] and wave types (SIN beams) [16]. For corrugations of an arbitrary profile there are no assortments containing bending, axial and other characteristics of section stiffness. This article proposes an algorithm for determining the geometric characteristics of corrugated beams using the example of beams with corrugated trapezoidal webs.

1. CALCULATION SCHEME MODEL

As an example, consider a single-span model (Figure 1).

The system of differential equations describing the displacement of the beam y (z) has the form given flexural shear

$$\begin{cases} \dfrac{dy(z)}{dz} = -\dfrac{M(z)}{E \cdot I}; \\ \dfrac{dy}{dz} = y(z) + \dfrac{k \cdot P}{G \cdot A_{2f}} \end{cases}, \quad (1)$$

Substituting from the second equation of system (1) into the first, we obtain the second order equation:

$$\frac{d^2 y}{dz^2} = -\frac{M(z)}{E \cdot I} + \frac{d}{dz} \cdot \left(\frac{k \cdot P}{G \cdot A_{2f}} \right), \quad (2)$$

where, P is the applied load, E and G are modulus of elasticity and shear modulus, respectively, I is the moment of inertia of the cross section, k is a factor related to the cross section shape, A_{2f} is the area of two flange, M is the bending moment.

The solution of the differential equat.2 taking into account the conditions for fixing the beam is as follows:

$$y = \frac{P \cdot L^2}{16 \cdot E \cdot I} \cdot z - \frac{P}{12 \cdot E \cdot I} \cdot z^3 + \frac{k \cdot P}{G \cdot A_{2f}} \cdot z, \quad (3)$$

Then, at $z=L/2$, we get at mid-span deflection with allowance for bending and shear deformations:

$$y_{z=L/2} = f_{\max} = \frac{P \cdot L^3}{48 \cdot E \cdot I} + \frac{k \cdot P \cdot L}{2 \cdot G \cdot A}, \quad (4)$$

From condition (4) we express the moment of inertia:

$$I = \frac{P \cdot L}{48 \cdot E \cdot \left(f_{\max} - \dfrac{k \cdot P \cdot L}{4 \cdot G \cdot A_f} \right)}. \quad (5)$$

where, A_f is the area of one flange.

This addiction can be used in determining the geometric characteristics of the cross section of steel I-beams with corrugated webs. In this case, the maximum deflection f_{max} is determined by automatic calculation using certified software systems that use the spatial model of FE of steel I-beams with corrugated webs.

2. ALGORITHM FOR DETERMINING GEOMETRIC CHARACTERISTICS OF THE CROSS-SECTION OF BEAMS WITH CORRUGATED WEBS OF ARBITRARY TYPE

The algorithm for selecting geometric characteristics of a section for an I-beam with a corrugated web from an arbitrary profile includes the following steps:

- revealing of analytical dependences of displacements from the applied load through stiffness parameters of the beam;
- selection of rational dimensions of the cross sections of beams;
- selection of rational dimensions I-beams with trapezoidal webs;
- definition of deflections based on the finite element model of the shell when bending the beam;
- determination of axial displacement based on shell finite element model under axial compression;
- determination of geometric characteristics of sections of beams with corrugated webs and tabulation of results.

2.1. Analytical dependences of displacements from the stiffness parameters of the beam.

Consider a corrugated beam with trapezoidal webs when loaded with concentrated forces P_x and P_y in the middle of a span in two planes (Figure 2 , Figure 3).

Based on the expression (5), we write down the relations for moments of inertia of cross sections of the beam in two planes.

a. Moment of inertia I_x:

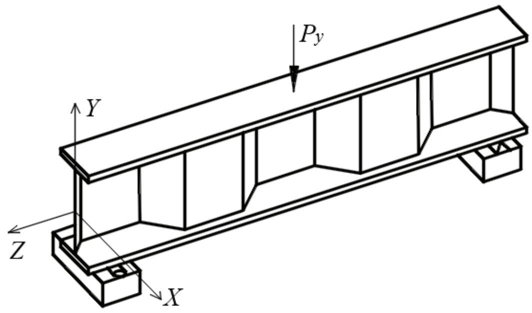


Figure 2. Isometric projection of calculation model with concentrated load at mid-span (in the plane ZOY).

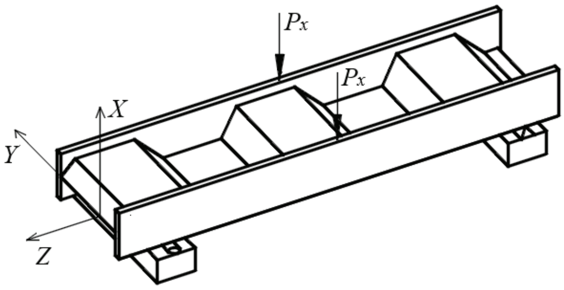


Figure 3. Isometric projection of calculation model with concentrated load at mid-span (in the plane ZOX).

$$I_x = \frac{P_y \cdot L^3}{48 \cdot E \cdot \left(f_{\max,y} - \dfrac{3 \cdot P_y \cdot L}{20 \cdot G \cdot A_f} \right)}, \qquad (6)$$

b. Moment of inertia I_y:

$$I_y = \frac{P_x \cdot L^3}{48 \cdot E \cdot \left(f_{\max,x} - \dfrac{3 \cdot P_x \cdot L}{20 \cdot G \cdot A_f} \right)}. \qquad (7)$$

where, P_x and P_y are applied loads, $f_{\max,x}$ and $f_{\max,y}$ are maximum deflections along axis X and Y.

To determine the reduced area, which is a geometrical parameter under axial impact, the beam is loaded with an axial compressive force P_z (Figure 4).

Formula for determining axial deformation:

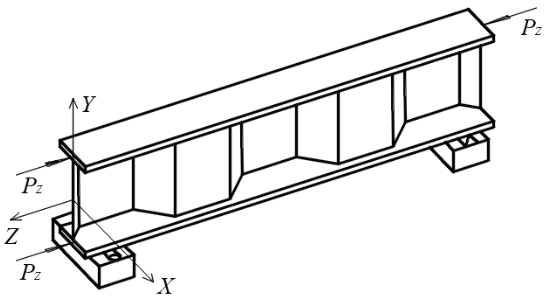


Figure 4. Isometric projection of calculation model with concentrated load along axis Z (in the plane ZOY).

$$\Delta = \frac{P_z \cdot L}{E \cdot A}, \quad (8)$$

where, Δ is amount of Z-axis displacement.
From here, reduced area is determined by the expression:

$$A = \frac{P_z \cdot L}{E \cdot \Delta}. \quad (9)$$

2.2. Selection of cross-sectional dimensions of beams with corrugated web.

For the study were selected five models of I-beams with trapezoidal webs (BTW1- BTW5). The parameters of the sections of beams were taken in the range of the external height H from 200 to 600 mm with a step of 100 mm (Table 1), which corresponds to assortments of welded I-beams with flat wall.

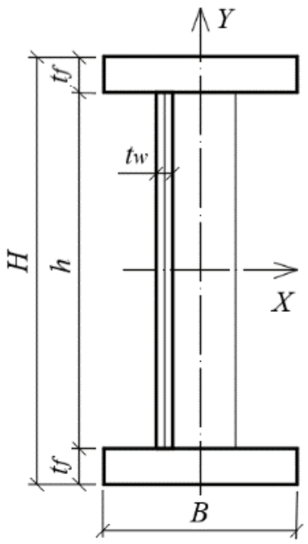


Figure 5. Cross section of models BTW.

Table 1. Parameters of cross section of models BTW.

Accepted models	H, mm	h, mm	B, mm	t_f, mm	t_w, mm
BTW1	200	184	100	8	2
BTW2	300	282	150	9	3
BTW3	400	374	200	13	3
BTW4	500	468	200	16	4
BTW5	600	564	200	18	4

2.3. Selection of trapezoidal webs dimensions for calculation models.

Studies of various trapezoidal profiles were performed in [17,18]. The results of these researches have shown that the most rational in terms of bearing capacity is a beam with a corrugation angle φ = 45%. Optimal sizes of parameters a, b and d were determined on basis of comparative automated calculations. The corrugation parameters corresponding to the accepted models are given in table 2 and in Figure 6.

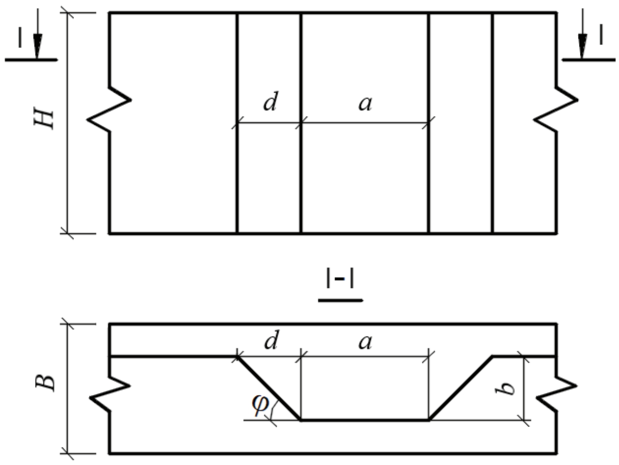


Figure 6. Trapezoidal web dimensions.

Table 2. Parameters of corrugated web beams.

Models	b, mm	a, mm	d, mm	φ,
BTW1	50	180	50	45°
BTW2	76	150	76	45°
BTW3	100	200	100	45°
BTW4	80	200	80	45°
BTW5	100	300	100	45°

2.4. Numerical determination of displacement value based on shell finite element model.

The study consisted in calculation of beams based on shell finite element model. Preliminary verification of this model was performed using a flat wall I-beam as an example and subsequent comparison of results with theoretical values of deflections taking into account the shear deformations. Results obtained by numerical analysis in software package "ANSYS", correlated with the analytical calculation with a maximum error of 0.93%, which is within the limits of permissible (taking into account the fact that errors adopted in the construction design should not exceed 3%).

Next, the calculation was carried out corrugated beams BTW1-5 to determine:

a) maximum deflections in a beam loaded with concentrated forces in two planes (Figure 2 , Figure 3);
b) axial deformation of the beam under axial impact (Figure 4).

The calculation was performed in software package "ANSYS 14.5", where shell finite elements SHELL181 were used. Generation of a grid of quadrangular type was made automatically. The size of finite elements was within 47 mm on long side. Near the junction of webs and flanges, the mesh dimensions were reduced to 7 mm.

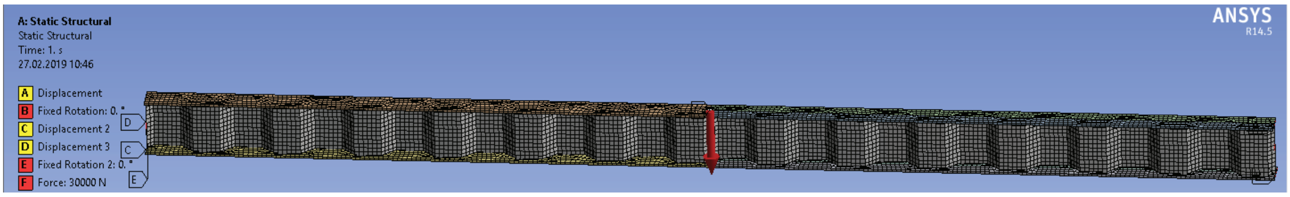


Figure 7. Finite element model of a beam.

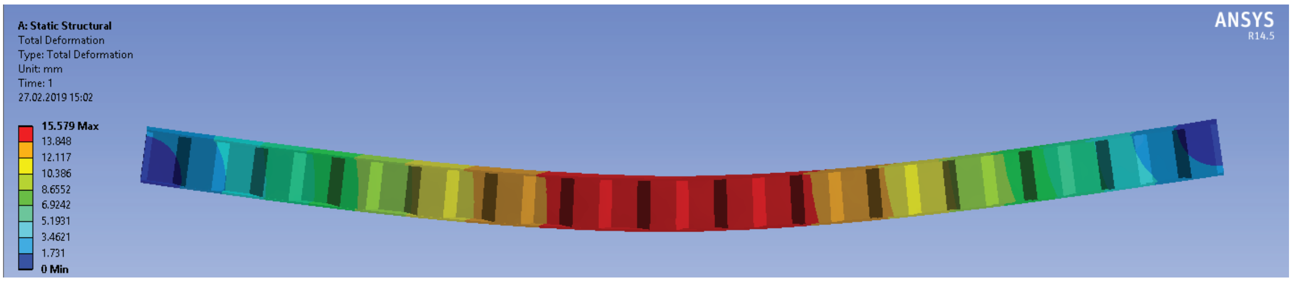
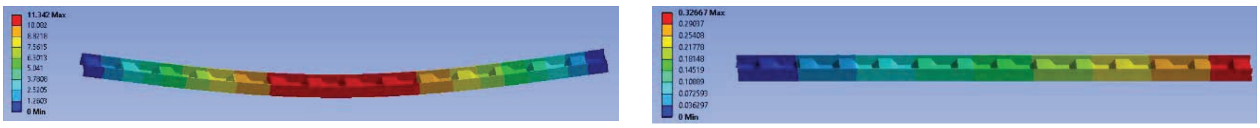


Figure 8. Deformed scheme in YZ plane for the BTW1 model.



a) b)

Figure 9. Deformed scheme for the BTW1 model: a) in XZ plane; b) deformed circuit for axial compression.

The maximum axial displacements and deflections obtained in the calculation are shown in Table 3.

Table 3. Results of calculation.

Models	$f_{max,y}$, mm	$f_{max,x}$, mm	Δ, mm
BTW1	15.6	11.34	0.326
BTW2	11.1	12.2	0.25
BTW3	10.45	11.2	0.247
BTW4	19.1	33.7	0.34
BTW5	17.45	43.7	0.38

2.5. Calculations of geometric characteristics. Using obtained maximum deflections ($f_{\max,y}$, $f_{\max,x}$) using the formula (4), moments of inertia about the axes of cross section X and Y were determined for each model of corrugated beams. Reduced area is determined by formula (9). In calculations were used material characteristics

$$E=200\ \text{kN/mm}^2,\quad G=76{,}9\ \text{kN/mm}^2.$$

Determination of moments of resistance and radius of gyration, perform on the basis of well-known analytical formulas for strength of materials [19].

$$W_x = \frac{I_x}{H/2}, \tag{10}$$

$$i_x = \sqrt{\frac{I_x}{A}}\ . \tag{11}$$

W_y , i_y - were determined similarly by formulas (10), (11). Static moment of the half-section area relative to the X - axis was calculated by following formula:

$$S_x^{1/2} = \left(\frac{H}{2} - t_{\mathrm{f}}\right)\cdot t_w \cdot \frac{1}{2}\cdot\left(\frac{H}{2} - t_{\mathrm{f}}\right) + B\cdot t_{\mathrm{f}}\cdot\left(\frac{H}{2} - \frac{t_{\mathrm{f}}}{2}\right). \tag{12}$$

3. RESULTING TABLE OF GEOMETRIC CHARACTERISTICS OF SECTIONS OF BEAMS WITH CORRUGATED WEB

According to research results, was compiled a table of parameters and geometrical characteristics of welded I-beam with a corrugated web (similar to tabulated values standard I-beams). The resulting table can be used to solve the problem of the finite-element analysis of flat frames according to rod diagram, which greatly simplifies the calculation compared to calculation using shell model.

Table 4. Geometric parameters of steel I-beams profiles with corrugated web.

Models	Cross-section specifications, cm					Corrugation specification, cm			
	H	B	t_f	t_w	h	b	a	d	φ
1	2	3	4	5	6	7	8	9	10
BTW1	20.0	10.0	0.8	0.2	18.4	5.0	10.0	5.0	45°
BTW2	30.0	15.0	0.9	0.3	28.2	7.6	15.0	7.6	45°
BTW3	40.0	20.0	1.3	0.3	37.4	10.0	20.0	10.0	45°
BTW4	50.0	20.0	1.6	0.4	46.8	8.0	20.0	8.0	45°
BTW5	60.0	20.0	1.8	0.4	56.4	10.0	30.0	10.0	45°

Table 5. Geometric parameters of steel I-beams profiles with corrugated web.

Area, cm^2	Mass per 1m, kg	I_x, cm^4	W_x, cm^3	i_x, cm	I_y, cm^4	W_y, cm^3	i_y, cm	$S_x^{1/2}$, cm^3
11	12	13	14	15	16	17	18	19
19.68	16.13	1484.2	148.42	8.68	136	27.2	2.63	85.3
35.46	29.24	5712	380.8	12.7	520	69.3	3.83	226.3
63.22	51.54	18922	946.1	17.3	1765.5	176.6	5.3	555.6
82.72	67.8	38312	1532.48	21.52	2172	217.2	5.13	1212.45
94.56	77.3	61893	2063.1	25.6	2472	247.2	5.11	1763.4

4. CALCULATION OF A FLAT FRAME WITH CORRUGATED ELEMENTS

Using the geometrical characteristics of corrugated beams, it was possible to perform calculations of flat frames according to rod diagram. Let us give an example of the calculation of a flat frame with a horizontal corrugated element, made in software «LIRA-SAPR» using a flat rod diagram.

Example. Consider the frame shown in Fig. 11. For this frame requires: a) build the internal forces diagrams(the axial force *N*, the shear *Q*, and the bending moment *M*); b) determine the maximum normal and stress shearing in the rod of the column and beam.

Initial data: *L=12* m; *q=14* kN/m; *E=200* kN/mm^2.

The cross section of the beam - corrugated beam with plate trapezoidal web (BTW5), columns – the standart I-beam with flat wall (50ШС2). The geometric characteristics of the cross section for the beam are selected from Table 5 and 6.

Calculated geometric characteristics of the cross section of elements: elements 1 and 2: $I=7{,}22\cdot10^{-4}$ m^4; $W=29{,}5\cdot10^{-4}$ m^3; $A=176{,}25\cdot10^{-4}$ m^2; $S_x^{1/2}=16{,}65\cdot10^{-4}$ m^3; the element 3: $I=6{,}2\cdot10^{-4}$ m^4; $W=2{,}63\cdot10^{-4}$m^3; $A=94{,}56\cdot10^{-4}$ m^2; $S_x^{1/2}=17{,}63\cdot10^{-4}$ m^3.

Assign stiffnesses rod elements: for elements 1 and 2: *EI=144400* kN · m^2; *EA=3525000* kN; for element 3: *EI=124000* kN · m^2;
EA=1891200 kN.

Calculation results

a. The internal forces diagrams, received in software «LIRA-SAPR» shown in Fig. 11, Fig.12.

b. The calculation of normal stresses in rods of column and beam of frame:

$$\sigma_{i,\frac{\max}{\min}} = \frac{N_i}{A_i} \pm \frac{M_i}{W_i}, \quad (13)$$

where, $i = 1, 2, 3$ – numbers of rod.

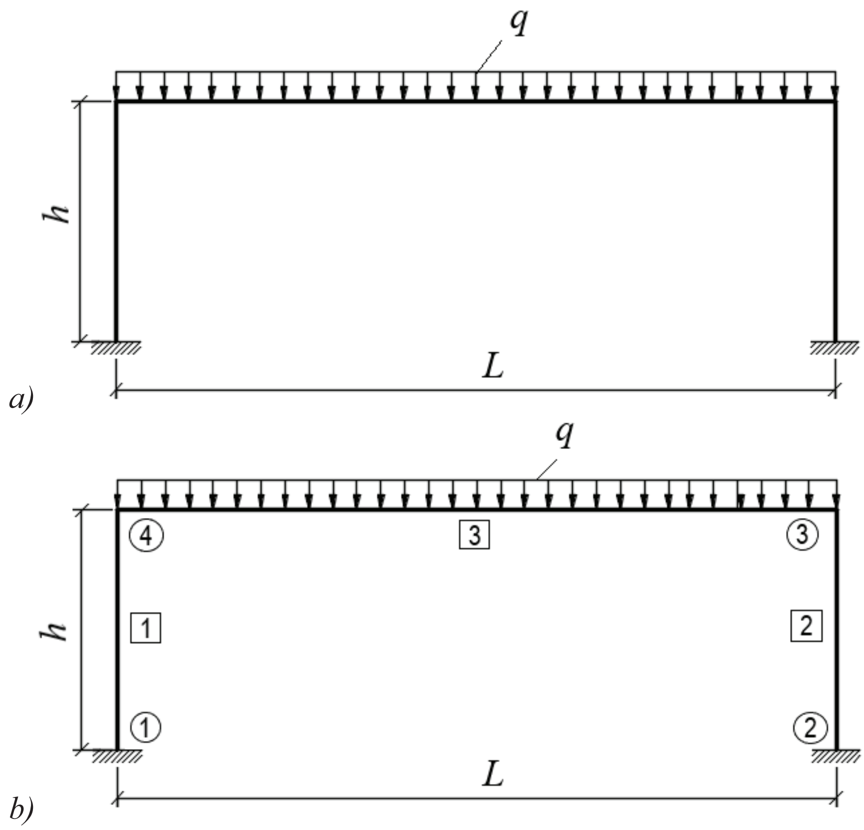


Figure 10. The rod model of a flat steel frame: a) frame geometry; b) calculation scheme.

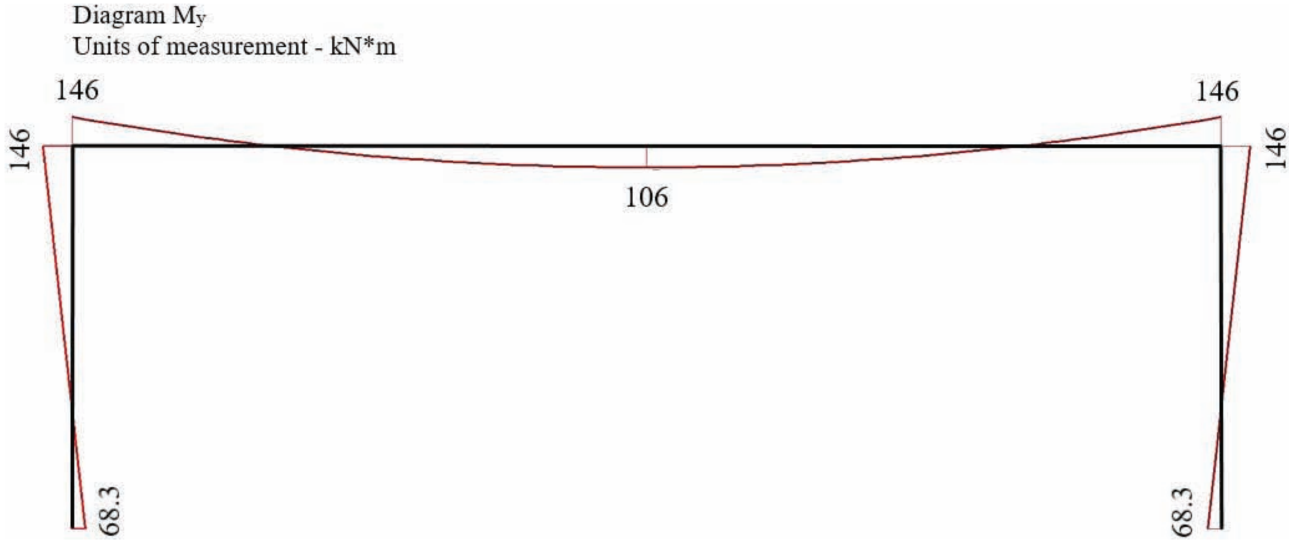
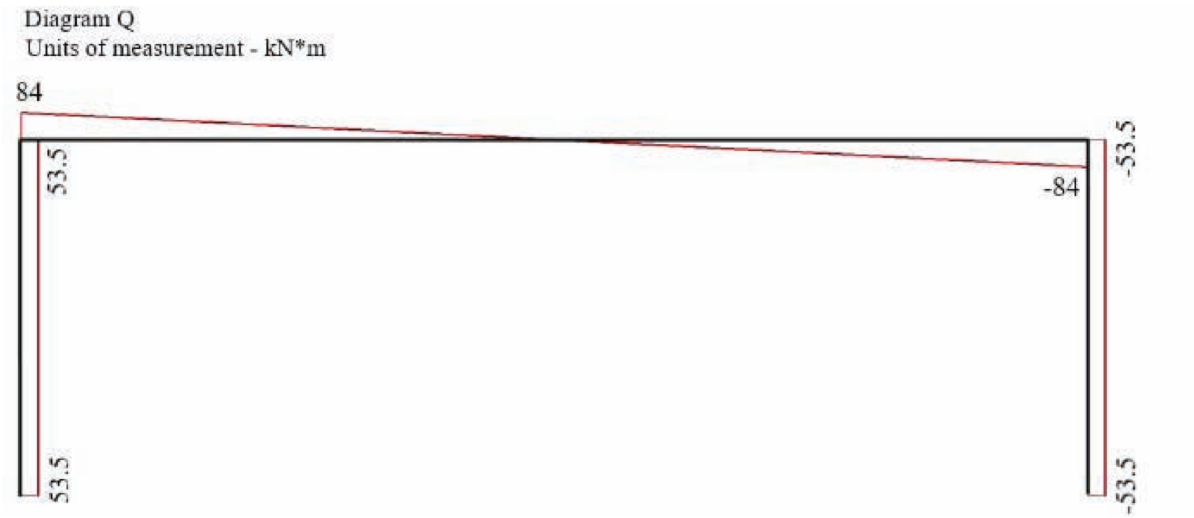


Figure 11. The calculation in Software "LIRA-SAPR": the diagram of bending moment M_y.



a)

b)

Figure 12. The calculation in Software "LIRA-SAPR": a) the diagram of shear Q ; b) the diagram of axial force N.

Table 6. Results of calculations.

Elements	$\sigma_{i,\max}$, MPa	$\sigma_{i,\min}$, MPa
1	44,7	-54,4
2	44,7	-54,4
3	65,2	-76,43

c. The calculation of stress shearing in rods of column and beam of frame:

$$\tau_i = \frac{Q \cdot S_x^{1/2}}{I_x \cdot t_w}. \quad (14)$$

Table 7. Results of calculations.

Elements	τ_i , MPa
1	8,23
2	-8,23
3	59,73

CONCLUSION

1. The developed method makes it possible to determine the values of geometric characteristics for corrugated web I-beams with various corrugation configurations.
2. The use of the obtained geometric characteristics makes it possible to carry out the calculation of flat frames with corrugated elements according to the rod scheme.
3. Further research direction involves the generalization of the above method to solving problems of static calculation of spatial rod structures with corrugated elements.

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