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Stress and strain state in beams with corrugated web and their use in hydraulic engineering structures

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Abstract

The paper presents a methodology for calculating stress and strain state in beams with corrugated web. The methodology has been developed by the authors and is simpler than the existing method of calculation. While calculating, the authors offer to change the corrugated web for a plane orthotropic plate with the reduced modulus of elasticity showing the same non-rigid characteristics as the corrugated web. The given mathematical notation calculates the reduced modulus of elasticity of a plane orthotropic plate simulating the performance of the corrugated web. The calculation in the paper is made for a beam with corrugated web used as a cross-beam plane gate in hydraulic engineering structures. The calculation results got by the authors while using their methodology are compared with those obtained by the finite-element method (FEM).

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Keywords: Beam; Corrugated-steel end; Deflexion; Modulus of elasticity; Orthotropic plate; Strain; Vertical deflection; Steel structures; Hydraulic engineering structures; Plane gate.

1. Introduction

Steel beams with corrugated web are widely used nowadays while constructing buildings and structures of different types [1, 2]. To the advantages of such beams we can refer their minor metal intensity which is first of all a result of decreasing its web thickness. Besides, strengthening transverse and longitudinal ribs previously used to support such webs buckling resistance are not used in these beams. Resistibility and deformation property of

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building constructions are described in various papers written by both foreign and Russian researchers [3, 4] and by the authors of this paper [5, 6, 7, 8, 9].

2. Analysis of the possibility of using steel beams with corrugated web in hydro-engineering constructions

The expansion of using steel beams with corrugated web can be promoted while integrating them into hydro-engineering constructions.

Steel constructions used now in hydraulic engineering structures can be subdivided into two groups:

- Constructions which are not used to retain water: structural element of hydroelectric station buildings [10], elements of other buildings and overhead structures, bridges, passageways, elevated roads;
- Constructions used to retain water: different types of flood-hatches and hydraulic gates [11], water gates.

Operating conditions of the structures belonging to the first group correspond to operating conditions of manufacturing buildings and constructions and of transport works.

Operating conditions of the structures belonging to the second group are quite different from operating conditions of traditional industrial and civil manufacturing buildings and constructions. These structures are constantly subjected to watering or just are surrounded by water. Using steel beams with corrugated web in these constructions require finding new engineering solutions for moisture extraction.

One of the main problems of using steel structures in hydraulic engineering structures is that of protecting these structures from corrosion environment aggressive actions. There special requirements for these steel structures including their elements thickness (they should be at least 5 mm thick), for example. These elements should also be done over by high-tech coverage for long-time effective corrosion prevention. Besides, such constructions are subjected to regular effective inspection and monitoring to prevent hydraulic engineering structures from critical damage and destruction [12, 13, 14, 15, 16] and to thorough complex structural scrutiny of building constructions [17, 18, 19].

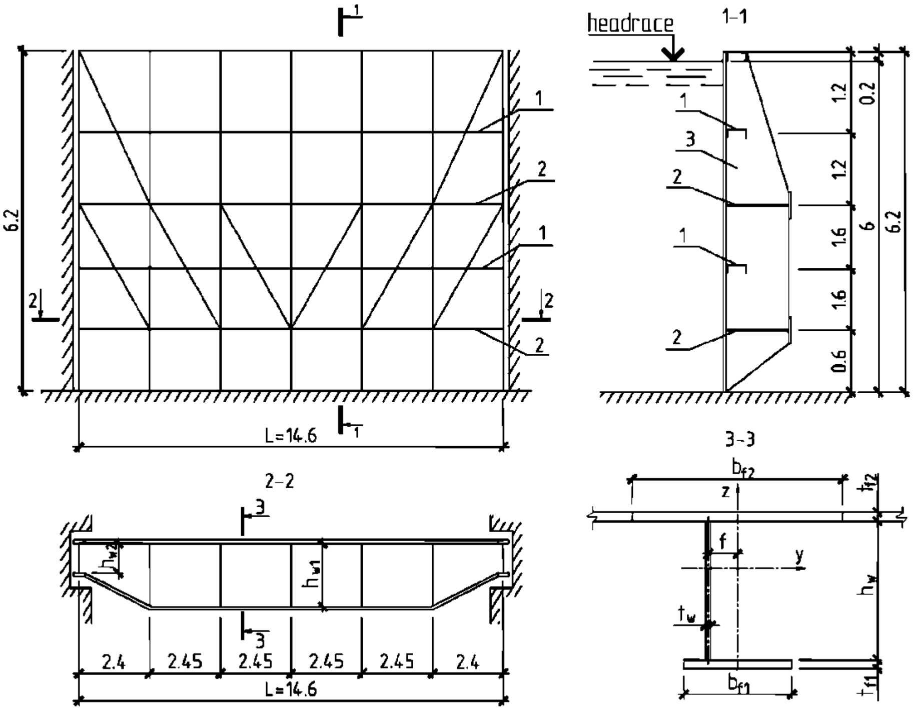


Fig. 1. Plain gates sizes and cross-bar design section: 1 – lengthwise beam, 2 – cross-bar, 3 – diaphragm plate.

Nowadays corrugations of sinusoidal, triangular and trapezoidal shapes are used widely all over the world [20]. Compered to their use in industrial building constructions steel beams with corrugated web when used in hydraulic engineering structures should have a thicker web because of their specific operating conditions.

One more factor which allows to effectively use beams with corrugated web in plain gates is their main drawback, that of their high steel expenses.

Let's analyze using beams with corrugated web in the hydraulic structures belonging to the second group and take a cross-bar as an example (Fig. 1). Proportioning a section of a cross-bar with a flat web and a cross-bar with a trapezoidal-shaped corrugated web has already been described [21].

According to our calculations a cross-bar with a flat solid web weight is 5034 kg, and a cross-bar with a corrugated web weight is 4771 kg. So, weight economy here is 5.2%; and if we change some corrugations characteristics weight economy reaches 8-10%. If we enlarge the gate width the economy can reach as much as 15%.

There are three main factors which help promote beams with corrugated web into plain gate constructions. They are:

- No centre-point loads which might influence the beams load-carrying ability;
- Cross-bars overall stability is provided by compression chord complete releasing;
- High steel expenses while using cross-bars and lengthwise beams with a flat solid web.

Moisture extraction can be performed while drilling a cross-bar corrugated web [22].

3. Stress distribution in a beam with corrugated web cross-section theoretical research and its analysis

While calculating beams with corrugated web it is believed that flanges of a beam take normal usual stress and webs of a beam take shearing stress [23, 24]. In reality beams with corrugated web work is different [25]. Parts of a web adjoining flanges take normal usual stress which is a result of flexure. By doing a test for triangular-shaped corrugations [26] the dependence of the corrugation characteristics (the pitch and height of corrugations) on the corrugated web performance in the moment of flection was described. There is still no description of stress distribution in the flange of other corrugations types.

4. Analytical solution for stress and deflection calculations

A new method of calculating beams with corrugated web can be introduced if we consider it to be a three-layer construction. The main hypothesis in calculating three-layer constructions is that the change of cross-sectional height in the middle layer modulus of elasticity can be presented as a mathematical relation. Such a relation for a beam with corrugated web leads to an analytical solution for stress distribution in a beam cross section [7].

4.1. Hypothesis and supposition

In this paper we introduce a new method for calculating stress and strain state in beams with corrugated webs under flexure with pressure.

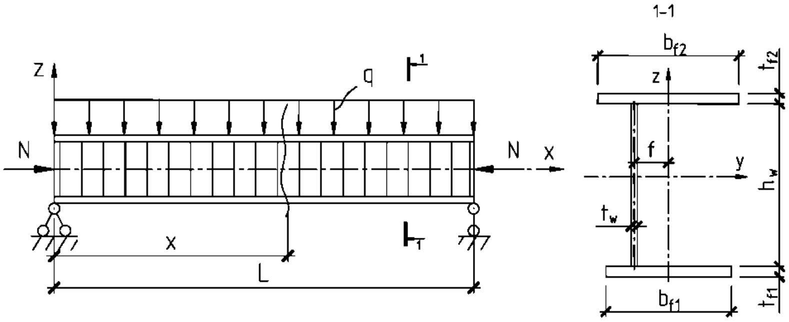


Fig.2. Calculation model of a beam and cross-section area.

The methodology is based on the following:

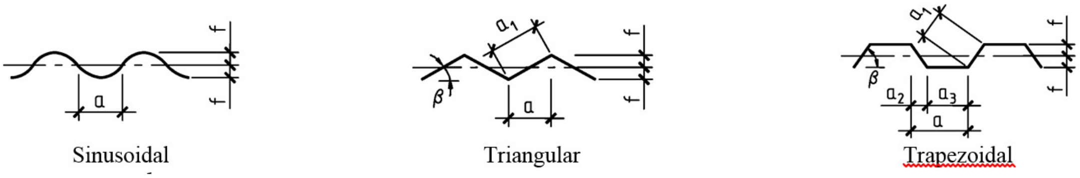
- Flat cross-section hypothesis is working;
- Beams elements are subjected to shearing;
- While working there is a linear dependence between deformation and stress.

For calculating stress and strain state in beams with corrugated webs the authors offer to change the corrugated-web for a plane orthotropic plate with the same bulk and elasticity characteristics. Elastic constants for the plane orthotropic plate depend on the type and size of corrugation and are defined while comparing the corrugated plate deformation with the flat plate deformation under similar stress conditions.

Reduced shift module is as follows [5]:

$$G_{cor} = G \cdot {}^{a}\!/_{s} \tag{1}$$

where G – is a shift module for isotropic material; a – semicrinkle length; s – semicrinkle length of arc or panel (see Fig. 3).



Sinusoidal Triangular Trapezoidal

Fig.3. Profile of corrugated web.

We take the reduced modulus of elasticity from the paper of L.E. Andreeva [27]:

$$E_{cor.x} = {}^{E}\!/_{k_1} \tag{2}$$

where E – is a elasticity module for isotropic material; k_1 – anisotropy coefficient depending on the corrugation shape, pitch, height and depth of web.

It is believed that normal usual stress rapidly falls from a beam flange to a beam axis. Building in flange influence on the corrugated web diminishes accordingly its distance from the flange to the axis and it is small to negligible when far enough. So, it allows us to consider that the reduced modulus of elasticity in the web according its cross-sectional height is described by a power function. Then the formula for the cross-section is as follows:

$$E(z) = \begin{cases} E \ \mathit{if} \ z \in \left[(0,5 \cdot h_w); (0,5 \cdot h_w + t_{f2}) \right] \\ \left((E - E_{cor.x}) \cdot \left(\left| \dfrac{2 \cdot z}{h_w} \right| \right)^n + E_{cor.x} \right) \mathit{if} \ z \in \left[-(0,5 \cdot h_w + t_{f1}); (0,5 \cdot h_w + t_{f2}) \right] \\ E \ \mathit{if} \ z \in \left[-(0,5 \cdot h_w + t_{f1}); -(0,5 \cdot h_w) \right] \end{cases} \tag{3}$$

in which z – a height coordinate; $n = \sqrt{k_1} \cdot \sqrt[3]{\dfrac{1}{B_{cor}}}$ – a coefficient taking into account building in flange influence on the corrugated web work (see Fig. 4); $B_{cor} = \dfrac{\pi^2 \cdot S_{x.f2} \cdot E}{L^2 \cdot t_w \cdot G}$ – flexibility coefficient; $S_{x.f2}$ – first moment of the flange to the axis.

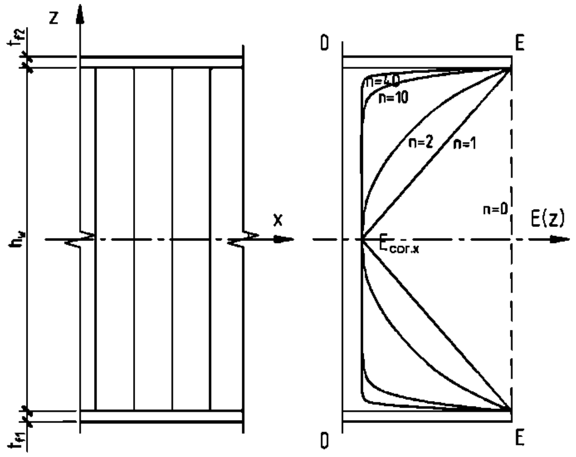


Fig. 4. The change in the elasticity module along the height of the web according to n – parameter.

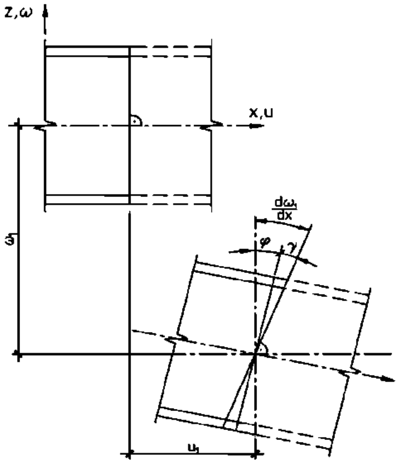


Fig. 5. Cross section area with account of shearing.

Shear modulus changes according to the following:

$$G(z)=\begin{cases} G\ if\ z\in\left[\left(0{,}5\cdot h_w\right);\left(0{,}5\cdot h_w+t_{f2}\right)\right] \\ G_{cor}\ if\ z\in\left[-\left(0{,}5\cdot h_w+t_{f1}\right);\left(0{,}5\cdot h_w+t_{f2}\right)\right] \\ G\ if\ z\in\left[-\left(0{,}5\cdot h_w+t_{f1}\right);-\left(0{,}5\cdot h_w\right)\right] \end{cases}. \tag{4}$$

4.2. Normal stress distribution

Longitudinal and cross movement of the cross-section joints are defined by the dependence (see Fig. 5):

$$\begin{aligned} &u(x,z)=u_1(x)+z\cdot\left(-\gamma+\frac{dw_1}{dx}\right) \\ &w(x,z)=-w_1(x) \end{aligned} \tag{5}$$

where $u_1(x)$ – llongitudinal movement of the axial force γ – angle of cross-section shear to the vertical shear; $w_1(x)$ – beam deflection with account of flexural deformation and shearing strain.

Reduction of cross-sectional area and its joints can be seen after differentiating:

$$\varepsilon_{xx}=\frac{du(x,z)}{dx}=\frac{du_1}{dx}+z\left(-\frac{d\gamma}{dx}+\frac{d^2w_1}{dx^2}\right). \tag{6}$$

Hook's law with longitudinal extension is as follows:

$$\sigma_x=E(z)\varepsilon_{xx}. \tag{7}$$

When we take (6) while applying Hook's law (7) and with changes described in Paper [7], we get a formula for defining direct stress in an arbitrary point of nonsymmetrical cross-section area:

$$\sigma_x = E(z)\varepsilon_{xx} = E(z)\left(A^* \cdot N + B^* \cdot M + z \cdot \left(B^* \cdot N + D^* \cdot M\right)\right). \tag{8}$$

When $N = 0$ and symmetrical cross-section ($B_0 = 0$):

$$\sigma_x = E(z) \cdot z \cdot D^* \cdot M = E(z) \cdot z \cdot \frac{M}{D_0}. \tag{9}$$

When corrugation height is $f = 0$ we get a formula for calculating stress in beams with flat wall:

$$\sigma_x = E(z) \cdot z \cdot \frac{M}{D_0} = E \cdot z \cdot \frac{M}{E \cdot I_y} = \frac{M}{I_y} \cdot z, \tag{10}$$

where I_y – moment of inertia ratio of the cross-section area about y axis.

4.3. Shearing stress distribution

Shearing stress in any joint of cross-section area can be obtained from elemental equilibrium differential condition:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} = 0 \,. \tag{11}$$

Taking integral of (11) equation we get

$$\tau_{xz}(x, z_1) = -\int_0^{z_1} \frac{\partial \sigma_{xx}}{\partial x} dz = -Q\int_0^{z_1} \left(B^* \cdot E(z) + D^* \cdot E(z) \cdot z\right) dz \,. \tag{12}$$

For an I-beam shearing stress characteristics are as follows:

$$\tau_{xz}(x, z_1) = \begin{cases} -Q \displaystyle\int_{z_1}^{0{,}5 \cdot h_w + t_{f2}} \left(B^* \cdot E(z) + D^* \cdot E(z) \cdot z\right) dz \; \mathit{if}\; z \in \left[(0{,}5 \cdot h_w);(0{,}5 \cdot h_w + t_{f2})\right] \\ -Q\left(\dfrac{t_w}{t_w} \cdot \displaystyle\int_{z_1}^{0{,}5 \cdot h_w} \left(B^* \cdot E(z) + D^* \cdot E(z) \cdot z\right) dz + \dfrac{b_{f2}}{t_w} \cdot \displaystyle\int_{0{,}5 \cdot h_w}^{0{,}5 \cdot h_w + t_{f2}} \left(B^* \cdot E(z) + D^* \cdot E(z) \cdot z\right) dz\right) \; \mathit{if}\; z \in \left[-(0{,}5 \cdot h_w);(0{,}5 \cdot h_w)\right] \\ -Q\left(\displaystyle\int_{z_1}^{-0{,}5 \cdot h_w} \left(B^* \cdot E(z) + D^* \cdot E(z) \cdot z\right) dz + \dfrac{t_w}{b_{f1}} \cdot \displaystyle\int_{-0{,}5 \cdot h_w}^{0{,}5 \cdot h_w} \left(B^* \cdot E(z) + D^* \cdot E(z) \cdot z\right) dz + \right. \\ \left. \quad + \dfrac{b_{f2}}{b_{f1}} \cdot \displaystyle\int_{0{,}5 \cdot h_w}^{0{,}5 \cdot h_w + t_{f2}} \left(B^* \cdot E(z) + D^* \cdot E(z) \cdot z\right) dz\right) \qquad \mathit{if}\; z \in \left[-(0{,}5 \cdot h_w + t_{f1});-(0{,}5 \cdot h_w)\right] \end{cases} \tag{13}$$

For a symmetrical cross-section ($B_0 = 0$) shearing stress (12) can be calculated according to the formula of strength of materials:

$$\tau_{xz}(x, z_1) = \frac{Q \cdot B_y^{cut}}{b(z) \cdot D_0} \tag{14}$$

where B_y^{cut} is elastic first moment of cut off part of a cross-section area for a flange [7].

4.4. Calculating deformations

The dependency relations for calculating deflections with account of shear can be obtained while taking integral of (13) differential equation.

When N=0 from (8) equation we get angular deflection and angle of flexure:

$$\frac{dw_1}{dx} = \varphi = -\gamma + \int_0^x M \cdot D^* dx + C_1 \tag{15}$$

$$w_1 = -\int_0^x \gamma dx + \int_0^x \int_0^x M \cdot D^* dx dx + C_1 x + C_2 \tag{16}$$

where C_1 and C_2 are arbitrary constants obtained from the boundary conditions.

Middle shear angle can be shown like that:

$$\gamma = \frac{\alpha Q}{R_0} \tag{17}$$

where $R_0 = \int_A 1 \cdot G(z) dA = 2 \cdot b_f t_f G + t_w h_w G_{cor}$ is shear stiffness; α – coefficient taking into account unequal distribution of shearing stress.

When elasticity parameters are of variable section, α-coefficient for nonsymmetrical cross-section can be presented as follows:

$$\begin{aligned} \alpha &= R_0 \cdot \left(D^*\right)^2 \cdot \int_A \frac{\left(B_y^{cut}\right)^2}{G(z) \cdot \left(b(z)\right)^2} dA = \\ &= R_0 \cdot \left(D^*\right)^2 \left(\int_{0,5 \cdot h_w}^{0,5 \cdot h_w + t_{f2}} \frac{\left(B_{y.f2}^{cut}(z)\right)^2}{G \cdot b_{f2}} dz + \int_0^{0,5 \cdot h_w} \frac{\left(B_{y.w2}^{cut}(z)\right)^2}{G_{cor} \cdot t_w} dz + \int_{-0,5 \cdot h_w}^{0} \frac{\left(B_{y.w1}^{cut}(z)\right)^2}{G_{cor} \cdot t_w} dz + \int_{-0,5 \cdot h_w - t_{f1}}^{-0,5 \cdot h_w} \frac{\left(B_{y.f1}^{cut}(z)\right)^2}{G \cdot b_{f1}} dz \right) \end{aligned} \tag{18}$$

where $B_{y.f2}^{cut}(z)$; $B_{y.f1}^{cut}(z)$; $B_{y.w1}^{cut}(z)$; $B_{y.w2}^{cut}(z)$ from Paper [7].

The beam with corrugated web general deflection is as follows:

$$w = w_M + w_Q \tag{19}$$

where w_M is the moment deflection; w_Q is the shear load deflection.

For the evenly distributed load and when x = L/2 we get the following:

$$w = \frac{5 \cdot q \cdot L^4}{384} \cdot D^* + \alpha \cdot \frac{q \cdot L^2}{8 \cdot R_0}. \tag{20}$$

Paper [7] shows the final relations (20) for the most frequent cases of loading.

5. An example of calculations based on the methodology described in the paper

To apply the formula we have obtained, let’s take a pin-ended beam (Fig. 2). The beam is subjected to the constant evenly distributed load q=100 kN/m. The corrugation shape is sinusoidal. The modulus of steel elasticity is $E = 2{,}06 \cdot 104$ kN/cm^2, the shear modulus is $G = 0{,}8 \cdot 104$ kN/cm^2. We tested two beams with different corrugation characteristics (see Table 1).

Table 1. Corrugation characteristics.

№	L, m	h_w, mm	t_w, mm	$b_{f1}= b_{f2}$, mm	$t_{f1}= t_{f2}$, mm	a, mm	f, mm	k_1	$E_{cur.x}$ kN/cm^2	G_{cur} kN/cm^2	n
BGS-1	9	750	2.5	200	12	77.5	20	414.2	49.7	6871	41.9
BGS-2	6	500	8	200	12	150	5	3,34	6160	7978	4.83

The verify our results based on (10), (14) and (20) we calculated the same beams characteristics using a widely applied methodology described in Papers [23, 24] and using by the finite-element method (FEM) in the modern automated system “Lira”. The simulation of the beams and the finite element grid we used is described in Paper [28].

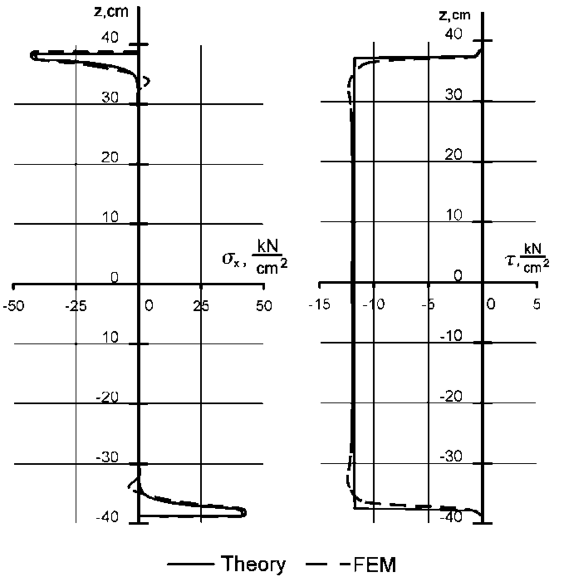


Fig. 6. Normal and shear stress distribution diagrams in BGS-1 beam with x=L/4.

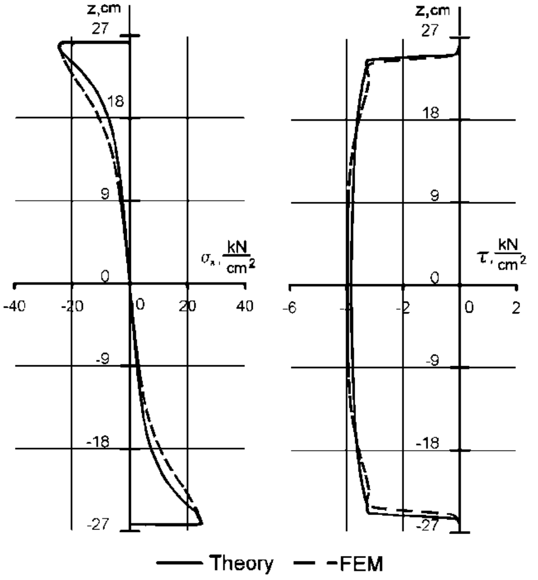


Fig. 7. Normal and shear stress distribution diagrams in BGS-2 beam with x=L/4.

The calculation results presented in Table 2 show that the methodology introduced in the paper can be used to calculate a beam with corrugated wall work. The maximum difference (when compared with FEM results) is 3.7%. Figures 6 and 7 are stress distribution diagrams. Comparing the results obtained the authors’ new methodology and the existing formula we can conclude that flat corrugations miscalculation can reach 14.6%.

To verify the authors’ new methodology 15 more beams with various corrugated web characteristics were calculated. The difference in values obtained by this methodology and in those obtained by the finite-element method for normal stress in extreme fiber is 0.5-5%; for shearing stress in the web with height $h_w/2$ is 1-4%; for vid-span deflection is 2-8%.

Table 2. Comparing the results: stress and deflections.

Characteristics	The authors' methodology	Methodology described in papers [23,24]	FEM	$\Delta_1 = \frac{i_{author} - i_{general}}{i_{author}} \cdot 100\%$	$\Delta_2 = \frac{i_{author} - i_{FEM}}{i_{FEM}} \cdot 100\%$
Normal stress in extreme fiber (x=L/4), kN/cm^2, form. (15)	$\frac{41.81}{24.43}$	$\frac{41.52}{27.46}$	$\frac{41.8}{24.1}$	$\frac{0.69}{12.4}$	$\frac{0.02}{1.4}$
Shearing stress in a web (x=L/4), kN/cm^2, form. (19)	$\frac{11.82}{3.84}$	$\frac{12.0}{3.75}$	$\frac{11.9}{3.96}$	$\frac{1.6}{2.3}$	$\frac{0.7}{3.0}$
Mid-span deflection, mm. form. (25)	$\frac{66.6}{23.95}$	$\frac{66.26}{27.45}$	$\frac{69.17}{24.4}$	$\frac{0.5}{14.6}$	$\frac{3.7}{1.8}$

Note: the value above the line is for BGS-1 beams, the value below the line is for BGS-2 beams, *i* – is a corresponding parameter for comparing.

6. Conclusion

The research yielded the following conclusions:

- It is possible to use steel beams with corrugated web in hydro-engineering construction, meanwhile it is required to protect them from corrosive medium;
- While calculating a lengthwise beam with corrugated web used as a cross-beam plane gate it is proved that changing a lengthwise beam with a flat web for a lengthwise beam with corrugated web allows to reduce metal intensity for 5-10%. Still new engineering solutions and additional theoretical research and practical tests are required to introduce these structures into use;
- The paper presents a new analytical solution for stress distribution in a beam with corrugated web cross-section area;
- The methodology introduced in the paper allows to calculate stress and deflections in a beam with corrugated web with various corrugation characteristics to a high precision.

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