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A flexible beam with corrugated web and its performance under bending: an experimental study

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Abstract. The paper studies the state of stress of a corrugated web which is a part of a hinged beam taking bending moment. Numerical results in this study were obtained by using the finite elements method. The main parameters of the research are the magnitude of the current workload, geometrical parameters of the corrugation and the type of corrugating. While collecting data on geometry calculation models of beams with corrugated webs the authors used an authorial software «Gofro». Triangulation of a finite element grids was performed by GMSH preprocesser. After through analysis of each parameter, the researchers determined the degree of participation of the corrugated web of a beam which is taking bending moment, and proved the advantage of the sinusoidal shape of the corrugation.

1 Introduction

The basic element of all buildings and structures is usually a frame structure consisting of beams. In order to to reduce the consumption of steel in manufacturing such a structure perforated [1-5] and corrugated [6-10] constructions have been invented. Steel beams with corrugated web are now actively used in buildings and structures of different application [3, 11-14]. When a beam with corrugated web takes a bending moment, it is typical that the web is not included in the work, i.e. there is no normal tension σ_x [15, 16]. Some areas which are close to the girders are an expection here.

Researchers of Kazakh branch of CNIImetallokonstrukcii [17] empirically determined the influence of corrugation parameters (that is corrugation length and height) on the degree of participation of the corrugated web in taking bending moment in comparison with the flat web of the same thickness. All research carried out in Kazakhstan was aimed at corrugated webs of triangular shape. If the shape of corrugation is different (wavy or trapezoid) the corrugated web degree of participation in taking the bending moment may differ from the results for triangular corrugation. Another parameter that can affect the corrugated web is its thickness. Thickness for wavy corrugation is about 2-3 mm [18] and for triangular corrugation it is 3-10 mm [19]. Therefore, a study of the participation of corrugated walls when taking a bending moment is quite relevant.

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The purpose of this research is to study the state of stress of corrugated webs while taking a bending moment. For this purpose the authors worked out a finite-elemental (FE) model of a beam with corrugated web. The model makes it possible to analyze the impact of the magnitude of the external load, thickness and parameters of the corrugation on the degree of the web participation in bending, as well as to explore the work of a web along the length of one wave of corrugation.

2 Development of a Numerical Model of Beams with Corrugated Web

To achieve this aim the authors carried out a numerical experiment to analyze the state of stress in corrugated webs based on finite elements method (FEM). Numerical results were received by studying hinged beams with L =6m span which were loaded uniformly by distributed load of q intensity (See Figure 1). The cross-section parameters (Figure 1): h_w = 500 mm, b_f = 200 mm, t_f = 10 mm.

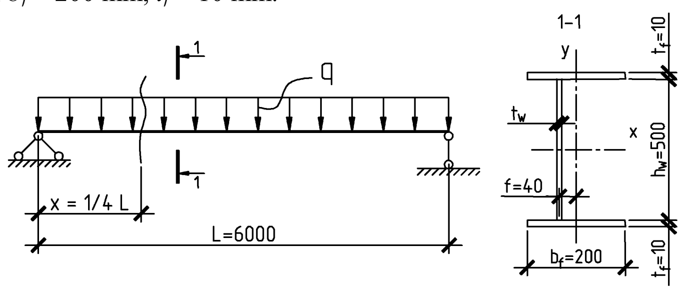

Fig. 1. Calculation model of a beam and cross-section area.

To analyze the stress state of the web two types of corrugation shape were taken: triangular and wavy. Finite elements number in the calculation model, as well as the geometry of corrugations (half wave length and height) are considered identical (see Figure 2): a = 150 mm and f = 40 mm, a/f = 150/40.

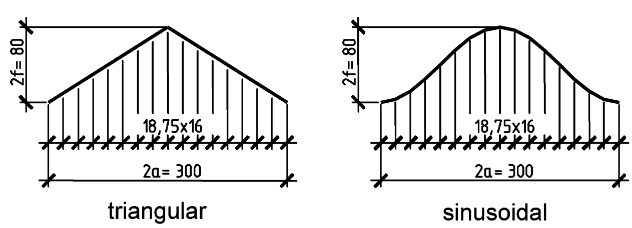

Fig. 2. Corrugations parameters and partitioning scheme of wave-length elements.

The calculated section to determine the height of the web is at a distance of ¼ of a span (half-wave here is 1.35 m to 1.5 m). The values of web participation in the work of the construction were determined graphically, as given below. To do this, the orthographic representation of direct stresses was placed across the marked grid of the web height.

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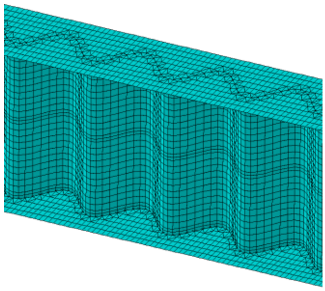
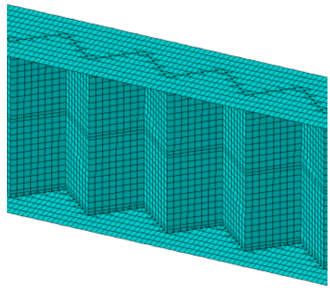
a  b 

Fig. 3. EC model of beams: (a) with a wavy web; (b) with a triangular-shaped web.

Then the authors introduced calculation models for a FEM study and conducted a series of numerical experiments while using "LIRA" computational system. While collecting data on geometry calculation models of beams with corrugated webs the authors used an authorial software «Gofro» [20]. Triangulation of a finite element grids was performed by GMSH preprocessor [21]. The calculation model based on triangular and rectangular finite elements of universal enveloped type has six degrees of freedom. FE length is approximately 20 mm. Figure 2 shows a scheme of partitioning of wave-length elements FE network tends to concentrate in the places where the web is adjoined to flanges. Physical characteristics of finite elements correspond to those of S255 steel: R_y = 240 mPas, E = 206000 mPas. Calculations were performed in the elastic stage.

3 Analysis of the magnitude of the web taking a bending moment

Initially, the researches made an analysis of the web work and checked the dependency between the height of the part and the applied load (bending moment) with 3 mm web thickness. For this we took a beam with wavy outlines of corrugations (see Fig. 3 a) and different values of distributed load. A section was taken at the top of the waves (as shown in Table 1). The results showed that the load does not affect the degree of participation of web in its work. Figure 4 illustrates normal tensions along the web depth.

Table 1. Magnitude of the web work under different loading.

№	q, kN/m	$M_{1/4}$, kNm	a_w, mm
1	40	135	38
2	50	168.5	38
3	60	202.5	38
4	70	236.5	38
5	80	270	38

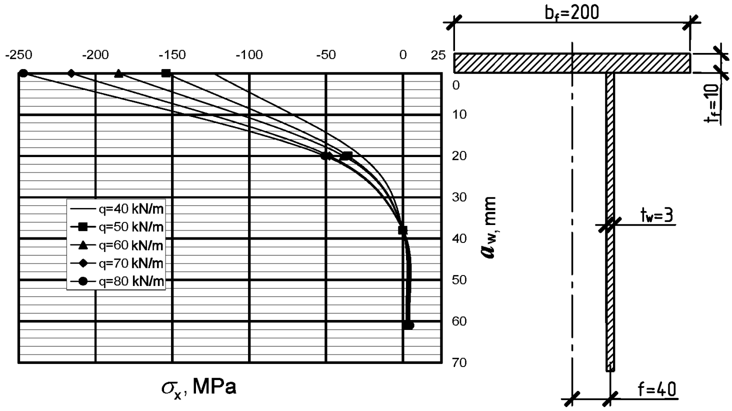


Fig. 4. Normal tensions along the web depth under different loading.

In the next phase of the research the work of the web along the length of one wave corrugation was studied. The height of the bending moment of the web was studied in 5 sections (see Figure 5). These following section are:

- two section at the tops of corrugation (1-1, 5-5);
- one section on the axis of the beam (3-3);
- wo sections at a distance *a*/2 form the top of corrugation (2-2, 4-4).

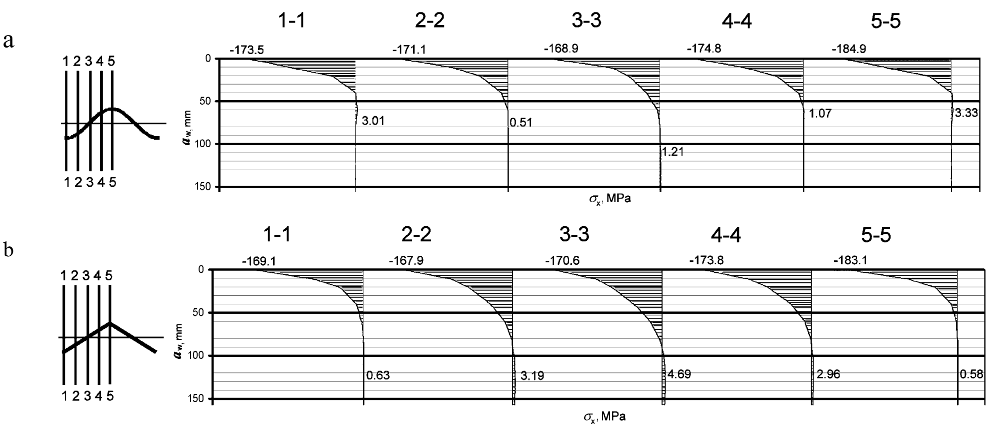


Fig. 5. The place of the section and its influence on the height of web work along the corrugation length: (a) sinusoidal shape of the corrugation; (b) triangular hape of the corrugation.

Calculation results revealed some peculiarities of the web work along the wave-length corrugation. For triangular-shaped corrugations the web bending moment within one wave changes in 1.5 times. For sinusoidal-shaped corrugations it changes from 1.5 times in t_w = web thickness is 1 ... 3 mm to 2 times when web thickness is t_w = 4 ... 10 mm. And for both shapes of corrugation the lowest value occurs on the tops of corrugation (fig. 5, section 1-1, 5-5), and the value is highest at the location of the axis of symmetry of the beam (fig. 5, section 3-3). It should be noted that for wavy webs (described by sinusoidal law) the change of the value takes place on a similar law describing the geometry of the web, but with the period 2 times less as in the previous case (fig. 5 a).

The authors also made an analysis of the influence of web thickness on the degree of participation of the web in the work. To calculate the influence of web thickness on the degree of participation of the corrugated web the researchers took constant parameters of length and height of the corrugation while changing web thickness within the range of 1 mm to 10 mm. Only the section on the top of corrugation was analyzed (section 1-1, fig. 5), because in this place the value of web participation is the lowest. In the calculations this circumstance gives some excess strength to the remaining sections of the corrugated web.

Table 2. Magnitude of the web work with different web thickness.

№	t_w, mm	$\overline{\lambda}_w$	a_{wsin}, mm	a_{wtrian}, mm	δ, %
1	1	17.07	30	60	100
2	2	8.53	34	61	79.4
3	3	5.67	38	61	60.5
4	4	4.26	41	61	48.8
5	5	3.41	46	62	34.8
6	6	2.85	51	63	23.5
7	7	2.44	53	64	20.8
8	8	2.13	55	65	18,2
9	9	1.89	57	70	22.8
10	10	1.71	59	76	28.8

The results given in Table 2 show that in triangular-shaped corrugations the part of the web taking the bending moment remains unchanged and begins to increase abruptly only with the web thicknesses of more than 8 mm (as Figure 6 shows). In wavy corrugations the height of the web depends on its thickness.

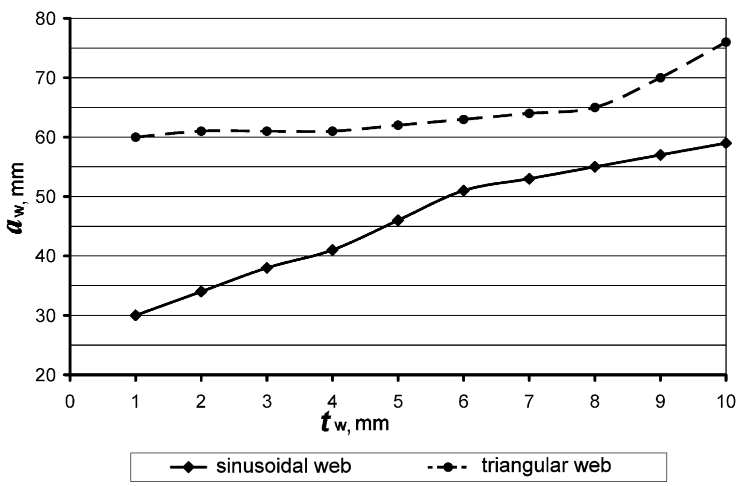


Fig. 6. The part of the web taking the bending moment.

Analyzing the results of the work of corrugated web of wavy and triangular shapes (Table 2), it should be noted that a triangular-shaped web work is more intense than a wavy web work (on condition they are of the same flexibility) $\overline{\lambda}_w$. Defining the difference between the values of the bending moment of a triangular-shaped web to a wavy web, it can be concluded that:

- in thin webs $\overline{\lambda}_w > 5.5$ (t_w = 1, 2, 3 mm) the difference is 60-100%;
- in medium webs it is $3.2 \leq \overline{\lambda}_w \leq 5.5$ (t_w = 4, 5 mm)-35-49%;
- in thick webs it is $\overline{\lambda}_w < 3.2$ (t_w = 6, 7, 8, 9, 10 mm) - 18-29%.

The last stage of the study was held to analyze the impact of the corrugation parameters on the degree of web participation in the work. To the corrugation parameters we refer half wave length a and half wave height f. The geometry of the corrugation is characterized by a/f ratio. Figure 2 shows that if corrugation height is $f = 0$, $a/f \to \infty$. In this case the web is flat and, consequently, its work equals $a_w = h_w/2$. Papers [23, 24] present calculations of beams with corrugated web, where corrugation is $a/f = 3.875$ and $a/f = 30$. These calculations show that the lower a/f is the smaller part of the web works at a bending moment.

4 Conclusion

The research yielded the following conclusions:

1. The height of the web under normal tension does not depend on the magnitude of the current load. It is determined by the geometrical parameters of the corrugation, web thickness and the corrugation type.
2. The degree of participation of the web differs within one half wave. In the tops of the corrugation the height of the web is 1.5-2 times lower than in the section located on the axis of symmetry.
3. Triangular-shaped web work is more intense than a wavy web work (on condition they are of the same flexibility): in thin webs the difference is 60-100%, in medium webs it is 35-49%, in thick webs it is 18-29%.

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