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Study of the conditional flexibility effect of compressed chord on the overall stability of corrugated beams

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Abstract. In this paper, the calculation of cut corrugated beams loaded with uniformly distributed load in the plane of the wall, with a wall height of 333 and 500 mm (54 sizes), chord width from 160 to 400 mm and chord thickness from 6 to 30 mm for general stability in accordance with Building Codes (BC) 294.1325800.2017 is made. A geometric criterion has been defined which defines the boundaries of the load-carrying capacity of Russian corrugated beams between the flat bending form stability and the strength of the normal section under the action of the bending moment in the plane of the wall.

1 Introduction

Welded I-beams with transversely corrugated walls (hereinafter referred to as corrugated beams) have been used as elements of steel frameworks, structures of buildings and constructions since the 60s of the last century. The effectiveness of corrugated beams has been shown in works [1-10]. At the same time, corrugated beams are used both with a sinusoidal wall profile as well as triangular, trapezoidal and other shapes [7-8].

In [11-12] a methodology for calculating the overall stability of corrugated beams has been proposed using clause. 8.4 BC16.13330.2017 "Steel structures". It is proposed to use the methodology for rolled I-beams (formula Zh.4). The torsional moment of inertia *Jk* is determined by the results of calculations in PC LIRA-SAPR.

In [13-14] the issues of stress-strain state of corrugated beams and general stability of corrugated beams under bending are considered.

In the Russian normative documentation, the calculation of beams with transverse corrugated wall (corrugated beams) are regulated by BC 294.1325800.2017 with Amendments 1, 2, 3 "Steel structures. Design Rules", where section 20.6 deals with the general provisions, dimensions and calculation of the load-bearing capacity of corrugated beams with sinusoidal and triangular corrugations.

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Thus, paragraph 20.6.3.11 of BC 294.1325800.2017, with Amendments 1, 2, 3 defines the procedure for calculating the bending in the wall plane corrugated beams for stability, where instead of calculating the overall stability of the corrugated beam as such, the calculation for the stability of a single compressed chord as a centrally compressed rod according to BC 16.13330.2017 "Steel structures".

In this paper, we made the calculation of 54 cut corrugated beams from the domestic variety according to GOST 70571-2022 "Two-beam steel welded with a cross-corrugated wall for building structures. Range", loaded with uniformly distributed load in the plane of the wall, for general stability and strength under normal bending stresses in accordance with BC 294.1325800.2017. Based on the results of the calculation, conclusions were made as to which sections of the corrugated beam have the bearing capacity determined by the stability of the flat bending form, and for which sections the normal stress strength under the action of the bending moment.

2 Main Part

The paper considers 54 cut corrugated beams of domestic assortment according to GOST 70571-2022, loaded with uniformly distributed load q in the plane of the wall, of the span L = 6.0 m, with the fastening of the compressed chord from the plane of the wall with a pitch $l_{ef} = 2.0\ m$ (Fig. 1).

Sectional dimensions of the corrugated beams under study: Chord width $b_f = 160 \ldots 400\ mm$, chord thickness $t_f = 6 \ldots 30\ mm$, distance between the centres of gravity of the girder section $H_{c.gr.} = 339 \ldots 530\ mm,$ panel height $h_w = 333 \ldots 500\ mm$ (Fig. 2, Table 1).

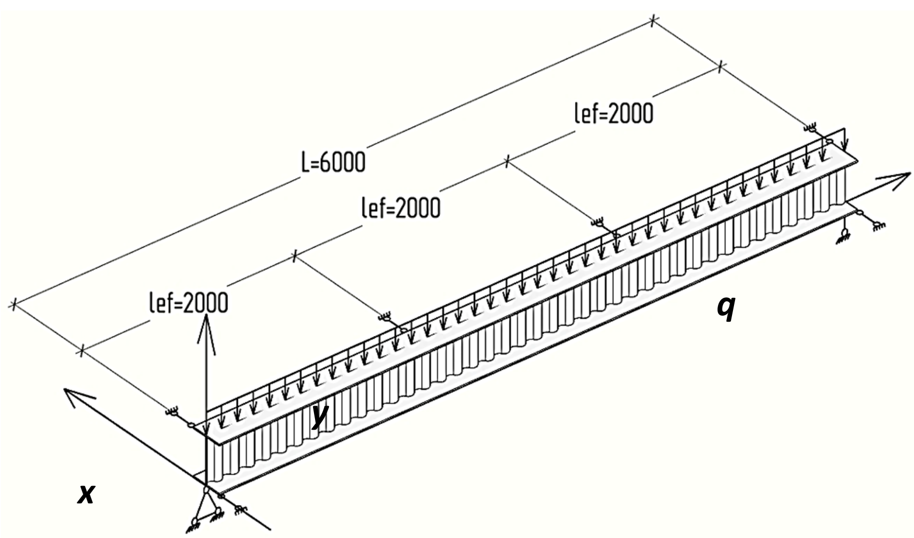

Fig. 1. Calculation diagram of the corrugated beams under study

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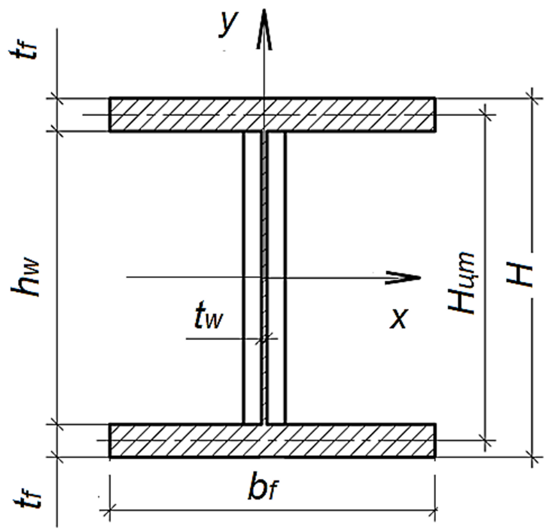

Fig. 2. Cross-section of the corrugated beams in question

Table 1. Dimensions of investigated corrugated beams (sample from variety selection in accordance with GOST 70571-2022 "Two-beam steel welded beams with cross-corrugated wall for building structures' assortment)

no.	Size by type	Chord width b_f, mm	Chord thickness t_f, mm	Distance between the chord centres of gravity $H_{c.gr.}$, mm	Panel height, h_w, mm
1	30SIN2.5LP160-6	160	6	339	333
2	50SIN2.5LP160-6	160	6	506	500
3	30SIN2.5LP160-8	160	8	341	333
4	50SIN2.5LP160-8	160	8	508	500
5	30SIN2.5LP180-6	180	6	339	333
6	50SIN2.5LP180-6	180	6	506	500
7	30SIN2.5LP180-8	180	8	341	333
8	50SIN2.5LP180-8	180	8	508	500
9	30SIN2.5LP200-6	200	6	339	333
10	50SIN2.5LP200-6	200	6	506	500
11	30SIN2.5LP200-8	200	8	341	333
12	50SIN2.5LP200-8	200	8	508	500
13	30SIN2.5LP200-10	200	10	343	333
14	50SIN2.5LP200-10	200	10	510	500
15	30SIN2.5LP200-12	200	12	345	333
16	50SIN2.5LP200-12	200	12	512	500
17	30SIN2.5LP220-8	220	8	341	333
18	50SIN2.5LP220-8	220	8	508	500
19	30SIN2.5LP220-10	220	10	343	333
20	50SIN2.5LP220-10	220	10	510	500
21	30SIN2.5LP220-12	220	12	345	333
22	50SIN2.5LP220-12	220	12	512	500

23	30SIN2.5LP220-15	220	15	348	333
24	50SIN2.5LP220-15	220	15	515	500
25	30SIN2.5LP250-10	250	10	343	333
26	50SIN2.5LP250-10	250	10	510	500
27	30SIN2.5LP250-12	250	12	345	333
28	50SIN2.5LP250-12	250	12	512	500
29	30SIN2.5LP250-15	250	15	348	333
30	50SIN2.5LP250-15	250	15	515	500
31	30SIN2.5LP250-20	250	20	353	333
32	50SIN2.5LP250-20	250	20	520	500
33	30SIN2.5LP300-12	300	12	345	333
34	50SIN2.5LP300-12	300	12	512	500
35	30SIN2.5LP300-15	300	15	348	333
36	50SIN2.5LP300-15	300	15	515	500
37	30SIN2.5LP300-20	300	20	353	333
38	50SIN2.5LP300-20	300	20	520	500
39	30SIN2.5LP300-25	300	25	358	333
40	50SIN2.5LP300-25	300	25	525	500
41	30SIN2.5LP350-15	350	15	348	333
42	50SIN2.5LP350-15	350	15	515	500
43	30SIN2.5LP350-20	350	20	353	333
44	50SIN2.5LP350-20	350	20	520	500
45	30SIN2.5LP350-25	350	25	358	333
46	50SIN2.5LP350-25	350	25	525	500
47	30SIN2.5LP350-30	350	30	363	333
48	50SIN2.5LP350-30	350	30	530	500
49	30SIN2.5LP400-20	400	20	353	333
50	50SIN2.5LP400-20	400	20	520	500
51	30SIN2.5LP400-25	400	25	358	333
52	50SIN2.5LP400-25	400	25	525	500
53	30SIN2.5LP400-30	400	30	363	333
54	50SIN2.5LP400-30	400	30	530	500

For each compressed chord using Table 1, the critical force for loss of stability has been determined N_{cr} in the girder plane (in the *zy* plane according to Fig. 3) according to clause 20.6.3.4 of BC 294.1325800.2017, clause 7.1.3 of BC 16.13330.2017 according to the following formula:

$$N_{cr} = R_y * \varphi * A_b, \tag{1}$$

here Ry = 240 MPa - design resistance of steel C245 of the chord, γ_c = 1.0 is a duty factor, $A_b = b_f * t_f$ – compressed zone, φ – is the central compression resistance coefficient determined according to the formula (8), clause 7.1.3 of BC 16.13330.2017, depending on the value of conditional flexibility of the compressed chord between the points of support $\overline{\lambda_{b_y}}$ (in the *xz* plane). The notional flexibility of the chord is determined by the following formula:

$$\overline{\lambda_{b_y}} = \lambda_{b_y} * \sqrt{\frac{R_y}{E}} = \mu \frac{l_{ef}}{\sqrt{J_{b_y}/A_b}} * \sqrt{\frac{R_y}{E}}, \quad (2)$$

here μ is a length conversion factor, l_{ef} – calculated rod length in the *xz* plane, J_{b_y} is the moment of inertia of the compressed chord about the y-axis, $E = 2.08 * 10^5$ MPa – elastic modulus of the chord material.

In determining the notional flexibility of the compressed chord $\overline{\lambda_{b_y}}$ the calculated length l_{ef} The central compression girder was assumed to be equal to the girder stiffening step from the wall panel plane $l_{ef} = 2.0$ m, and a hinged attachment at the ends with a length conversion factor $\mu_y = 1.0$ (Fig. 1, 3).

Moment of inertia J_{b_y} was determined according to the formula for a rectangular cross-section:

$$J_{b_y} = \frac{{b_f}^3 t_f}{12} \quad (3)$$

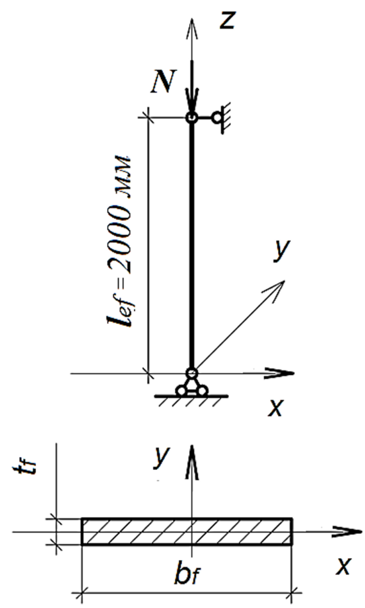

Fig. 3. Design diagram of compressed girder chord

According to the critical force found N_{cr} the value of the critical transverse load q_{cr} total loss of stability of the corrugated beam compression girder has been determined:

$$q_{cr} = 8 * N_{cr} * H_{c.gr.} * L^2 \quad (4)$$

The expression (4) is derived from the following relation in clause 20.6.3.4 of BC 294.1325800.2017 (Fig. 1, 2):

$$N = \frac{M_{x\,max.}}{H_{c.gr.}} \quad (5)$$

here $M_{x_{max.}} = q * L^2/8$ – maximum bending moment between the bracing points of the corrugated web, $H_{c.gr.}$ – is the distance between the centres of gravity of the girder chords. For the resulting critical load values q_{cr} the value of the maximum normal bending stress of the beam is determined

$$\sigma_{z_{max}} = \frac{q_{cr} * L^2}{8 * W_x} , \tag{6}$$

here W_x – the moment of resistance of the corrugated beam in relation to the *x*-axis, determined according to the formula:

$$W_x = \frac{J_x}{H}, \tag{7}$$

here $H = h_w + 2 * t_f$ is a full height section, J_x is a moment of inertia of the section relative to the axis *x*.

When designing corrugated beams for bending (clause 20.6.3 of BC 294.1325800.2017) it is assumed that the bending moments are taken up only by the chords, so the moment of inertia I_x is calculated according to the formula:

$$J_x = 2\left(J_{b_x} + A_b * H_{c.gr.}{}^2\right) = 2\left(\frac{b_f * t_f{}^3}{12} + b_f * t_f\left(\frac{H_{c.gr.}}{2}\right)^2\right) \tag{8}$$

The results of the calculations are presented in Table 2.

Table 2. Calculation results

no.	Size by type	**Chord width b_f, mm**	**Chord thickness t_f, mm**	**Distance between the central gravity of the chords $H_{c.g.}$, mm**	**Added flexibility of the compressed chord between the bracing points $\bar{\lambda}_{b_y}$**	**Critical compressive force N_{cr}, kN**	**Critical load q_{cr}, kN/m**	**Maximum normal bending stresses in the beam elements $\sigma_{z_{max}}$, MPa**
1	30SIN2.5 LP160-6	160	6	339	4.41	206.54	15.56	218.93
2	50SIN2.5 LP160-6	160	6	506	4.41	206.54	23.22	217.69
3	30SIN2.5 LP160-8	160	8	341	4.41	275.39	20.87	220.16
4	50SIN2.5 LP160-8	160	8	508	4.41	275.39	31.09	218.52
5	30SIN2.5 LP180-6	180	6	339	3.92	237.21	17.87	223.50
6	50SIN2.5 LP180-6	180	6	506	3.92	237.21	26.67	222.23
7	30SIN2.5 LP180-8	180	8	341	3.92	316.27	23.97	224.75

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8	50SIN2.5 LP180-8	180	8	508	3.92	316.27	35.70	223.08
9	30SIN2.5 LP200-6	200	6	339	3.53	267.63	20.16	226.94
10	50SIN2.5 LP200-6	200	6	506	3.53	267.63	30.09	225.66
11	30SIN2.5 LP200-8	200	8	341	3.53	356.83	27.04	228.21
12	50SIN2.5 LP200-8	200	8	508	3.53	356.83	40.28	226.51
13	30SIN2.5 LP200-10	200	10	343	3.53	446.04	34.00	229.46
14	50SIN2.5 LP200-10	200	10	510	3.53	446.04	50.55	227.37
15	30SIN2.5 LP200-12	200	12	345	3.53	535.25	41.04	230.69
16	50SIN2.5 LP200-12	200	12	512	3.53	535.25	60.90	228.21
17	30SIN2.5 LP220-8	220	8	341	3.21	397.19	30.10	230.93
18	50SIN2.5 LP220-8	220	8	508	3.21	397.19	44.84	229.21
19	30SIN2.5 LP220-10	220	10	343	3.21	496.49	37.84	232.19
20	50SIN2.5 LP220-10	220	10	510	3.21	496.49	56.27	230.07
21	30SIN2.5 LP220-12	220	12	345	3.21	595.79	45.68	233.43
22	50SIN2.5 LP220-12	220	12	512	3.21	595.79	67.79	230.93
23	30SIN2.5 LP220-15	220	15	348	3.21	744.74	57.59	235.26
24	50SIN2.5 LP220-15	220	15	515	3.21	744.74	85.23	232.19
25	30SIN2.5 LP250-10	250	10	343	2.82	571.89	43.59	235.36
26	50SIN2.5 LP250-10	250	10	510	2.82	571.89	64.81	233.21
27	30SIN2.5 LP250-12	250	12	345	2.82	686.27	52.61	236.62
28	50SIN2.5 LP250-12	250	12	512	2.82	686.27	78.08	234.07
29	30SIN2.5 LP250-15	250	15	348	2.82	857.83	66.34	238.47
30	50SIN2.5 LP250-15	250	15	515	2.82	857.83	98.17	235.35
31	30SIN2.5 LP250-20	250	20	353	2.82	1143.78	89.72	241.46
32	50SIN2.5 LP250-20	250	20	520	2.82	1143.78	132.17	237.44

33	30SIN2.5 LP300-12	300	12	345	2.35	836.59	64.14	240.37
34	50SIN2.5 LP300-12	300	12	512	2.35	836.59	95.19	237.79
35	30SIN2.5 LP300-15	300	15	348	2.35	1045.74	80.87	242.25
36	50SIN2.5 LP300-15	300	15	515	2.35	1045.74	119.68	239.09
37	30SIN2.5 LP300-20	300	20	353	2.35	1394.32	109.38	245.29
38	50SIN2.5 LP300-20	300	20	520	2.35	1394.32	161.12	241.21
39	30SIN2.5 LP300-25	300	25	358	2.35	1742.90	138.66	248.21
40	50SIN2.5 LP300-25	300	25	525	2.35	1742.90	203.34	243.27
41	30SIN2.5 LP350-15	350	15	348	2.02	1233.32	95.38	244.89
42	50SIN2.5 LP350-15	350	15	515	2.02	1233.32	141.15	241.69
43	30SIN2.5 LP350-20	350	20	353	2.02	1644.42	129.00	247.96
44	50SIN2.5 LP350-20	350	20	520	2.02	1644.42	190.02	243.83
45	30SIN2.5 LP350-25	350	25	358	2.02	2055.53	163.53	250.91
46	50SIN2.5 LP350-25	350	25	525	2.02	2055.53	239.81	245.92
47	30SIN2.5 LP350-30	350	30	363	2.02	2466.63	198.98	253.75
48	50SIN2.5 LP350-30	350	30	530	2.02	2466.63	290.51	247.95
49	30SIN2.5 LP400-20	400	20	353	1.77	1894.33	148.60	249.94
50	50SIN2.5 LP400-20	400	20	520	1.77	1894.33	218.90	245.78
51	30SIN2.5 LP400-25	400	25	358	1.77	2367.91	188.38	252.92
52	50SIN2.5 LP400-25	400	25	525	1.77	2367.91	276.26	247.88
53	30SIN2.5 LP400-30	400	30	363	1.77	2841.50	229.21	255.78
54	50SIN2.5 LP400-30	400	30	530	1.77	2841.50	334.66	249.93

The interpretation of the calculation results in table 2 is as follows: if the maximum normal bending stresses in the beam elements $\sigma_{z_{max}}$ less than the assumed design resistance R_y = 240 MPa - The load-bearing capacity of the corrugated beam is limited by the stability of the flat bending form. Otherwise, it is limited by the bending moment strength.

Table 1 shows that for corrugated beams with numbers 1-30, the loss of flat bending stability occurs before the normal-stress strength condition is violated, i.e. these beams must be calculated/checked for overall stability. For beams 30-54, the normal bending stress strength condition must be calculated/verified first.

In order to visualise the results of the calculation, a graph is plotted using the data in Table 2 $\sigma_{z_{max}}\ (MPa)$ from the reduced flexibility of the compressed chord between the bracing points $\overline{\lambda_{b_y}}$ (Fig.4).

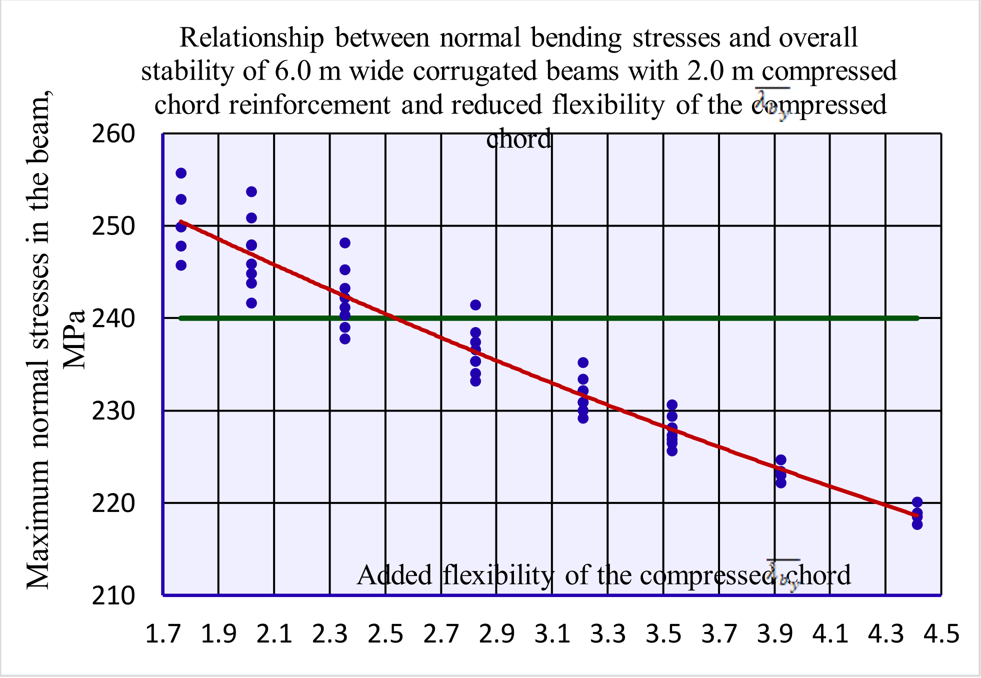

Fig. 4. The dependence of normal bending stresses and overall stability on the reduced flexibility of the compressed chord $\overline{\lambda_{b_y}}$ between bracing points for 6.0 m long corrugated beams with a compressed chord bracing at 2.0 m intervals

The graph in Fig. 4 shows that if the flexibility of the compressed chord is more than $\overline{\lambda_{b_y}} > 2.55$, the loss of flat bending stability occurs before the maximum bending stress of the beam reaches the design resistance *Ry* = 240 MPa.

3 Conclusion

For a sample of 54 cut corrugated beams of the Russian variety according to GOST 70571-2022, span $L = 6.0$ m, with an estimated length from the wall plane $\ell_{ef} = 2.0$ m with $R_y = 240$ MPa, bent by uniformly distributed transverse load in the wall plane, the critical load of loss of overall stability is determined as q_{cr}, and the acting maximum normal bending stresses.

The boundary of conditional flexibility of the compressed chord between the bracing points is determined $\overline{\lambda_{b_y}}$ separating the areas where the load-bearing capacity is limited by the stability of the flat bending form and the bending normal stress strength in the beam:

- at $\overline{\lambda_{f_y}} > 2.55$ the loss of flat bending stability occurs before the maximum bending stress of the corrugated beam is reached *Ry;*
- at $\overline{\lambda_{f_y}} < 2.55$ achieving maximum bending stresses in the corrugated beam *Ry* comes before the loss of flat bend stability.

References

1. S. A. Makeev, N. G. Silina, Z. N. Sokolovskiy, "Development and approbation of mathematical model of spatial deformation of corrugated beams", ISSN: 0869-7019, Industrial and Civil Engineering, 18-25, **4** (2021)
2. T. L. Dmitrieva, Using beams with corrugated beams in modern design, Izvestiya vuzov, Invest. Construction. Real Estate, **4(15)**, 132-139 (2015)
3. A. A. Bryantsev, Effectiveness of I-beams with corrugated walls in industrial buildings, Construction of unique buildings and structures, 3(54), 93-104 (2017)
4. D. D. Zaborova, Yu. P. Dunayevskaya, Advantages and peculiarities of corrugated beams application in construction, Construction of unique buildings and structures, **7(22)**, 36-53 (2014)
5. N. L. Tishkov, Improvement of steel I-beam design with thin cross-corrugated wall, Bulletin of Tomsk State Architectural and Construction University, **22(2)**, 104-111 (2020)
6. G. M. Ostrikov, Yu. S. Maksimov, V. V. S. Dolinskiy, V. V. Maksimov, Stroitelnaya mekhanika i raschet sooruzheniy, **1**, 68-70 (1983)
7. F. Denan, The study of lateral torsional buckling behavior of beam with trapezoid web steel section by experimentally and finite element analysis, IJRRAS 2 (3). March. 232-240 (2010)
8. F. Denan, Nonliner analysis of triangular web profile steel section under bending behaviour, Lecture Notes in Civil Engineering, 9, 463–472 (2019)
9. A. L. Vasiliev, Robust ship corrugated bulkheads, Leningrad, Shipbuilding, 316 (1964)
10. Y. S. Maksimov, Lightweight Steel Structures of Industrial Building Coverings, Express Information. Alma-Ata: KazTsNTIS Gosstroi KazSSR, 41 (1987)
11. S. A. Makeev, Development of Methodology of Corrugated Girder Calculation for General Stability, Industrial and Civil Engineering, **12**, 50-58
12. S. A. Makeev, Method of Calculation of Welded I-beams with a Transverse Corrugated Wall for General Stability, Industrial and Civil Engineering, **2**, 4-9 (2022)
13. A. L. Stepanenko, Steel I-beam bars with a corrugated wall, Ph.D. thesis, Khabarovsk State Technical University, Khabarovsk (2001)
14. P. I. Egorov, D. thesis "Investigation of stress-strain state of steel beams and columns of I-beams with thin corrugated wall", Pacific State University, Khabarovsk (2010)