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Research paper

Experimental Studies of Energy-Efficient Beams in Buildings and Structures of the Oil and Gas Complex

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Abstract

This study presents the results of experimental tests of new structural solutions for beams with double profiled trapezoidal wall and uneven pitch of corrugations. Tests of such structures have been performed for the first time. This determined the goals and objectives of the experiment. The probabilistic characteristics (mathematical expectation, mean square deviation) of the strength of the profiled wall material and the limit parameters of the bearing capacity of beams elements with profiled walls have been determined. This further allows us to calculate the failure probability of structures belonging to this type in the form of a system of elements. Experimental tests in the nodes of beams with profiled walls gave the opportunity to assess the nature of the work in such structures, to build the dependence of deformation from loads in dangerous cross sections of the samples and graphs of the deflections to determine the characteristic space structures and the patterns of transition to the ultimate state. Experimental studies have shown the effectiveness of the profiled wall inclusion in the beam bending and confirmed the feasibility of its use for buildings and structures of the oil and gas complex. It was experimentally revealed that the plane stress state of the profiled wall is characterized by small values of normal stresses at the level of the middle axis with a tendency of increasing in the direction of connection with the shelves. The novelty of the research is in the experimental analysis of features of the new beam assemblies with a double profiled wall and confirmed the possibility of using corrugated thin-walled profiles in the beam walls. The prospect and advantages as for the application of the developed designs in industrial facilities of the oil and gas complex have been proved. Peculiarities of carrying out experiments of thin-walled designs are revealed.

Keywords: *box cross section, experimental studies, oil and gas complex, profiled wall, steel beam*

1. Introduction

Today are distributed made popular even further prefabricated facilities with the use of light and reliable steel structures in the form of enterprises for oil and gas processing, oil depots, storage warehouses, loading stations, fuel filling stations, pumping, compressor and oil pumping stations, loading and unloading racks, receiving and delivery oil units, oil product transshipment terminals, auto and gas stations. Such structures require the use of light resource-saving structures. Therefore, there is a need for the development and further research of effective design forms in order to promote and ensure the energy security of the state.

This study presents the experimental tests results of new constructive solutions to the beams nodes with double-contoured trapezoidal wall [1]. Tests of such structures were performed for the first time. This determined the goals and objectives of the experiment.

The program of experimental studies included the solution of the following tasks: to determine the stress-strain state of beam elements with a profiled wall in the elastic and elastic-plastic stages of work; to determine the actual form of the bearing capacity loss and the maximum load for the elements of the beams; to obtain the values of the nodes and beams with a profiled wall parameters for further statistical processing and probabilistic calculations; to assess the destruction nature of most stressed areas of three series of experimental samples of nodes and beams.

2. Main body

In the conditions of constant development of building structures, the priority is the development and implementation of energy-efficient constructional forms and solutions. A large number of outstanding scientists have been engaged in the problem of thin-walled structures, in particular beams with corrugated wall [2 – 10].

The study [2] is devoted to thin-walled simply supported sandwich beams: three and seven-layer beams. An original mathematical model is formulated, which includes the hypothesis of deformation of the beam`s cross section, inclusive of the displacement and strain fields, and rigidities of the layers in particular directions. The adequate model of three-layer beam with steel foam core has also been developed. The results are compared for three-layer beam and presented in Tables. It is concluded that such a seven-layer beam – plate band with three-layered facings is more resistant to the load than classical three-layered beams of the same mass with regard to strength and stability. Additional effect of the research consists in generalization of classical theories of sandwich plates.

Beams with corrugated walls and flat plate flanges have been used in buildings on over the world for many years [3]. In the design of these beams, the longitudinal stiffness of the corrugated wall is assumed to be negligible and so the moment capacity is derived entirely from the flanges while the shear capacity of the beam is based on the shear strength of the wall alone. The advantage of beams with corrugated webs is the increased resistance to shear buckling without the need to weld stiffeners to the web. Despite the extensive use of beams with corrugated webs, there are no formal Australian or American design rules for the shear capacity of the corrugated web. In this paper, design equations based on the direct strength method are derived for the shear capacity of beams with trapezoidal corrugated webs. Finite element analysis results from the previous research have been analysed to determine the local shear buckling coefficient which is used to calculate the local shear buckling force in the design equations. The proposed design equations are then compared with previous shear test results on beams with corrugated webs and the reliability analysis is performed to calculate the capacity factor.

An experimental study of a simply supported beam with a cantilever in the elasticity range has been conducted for the first time to investigate the distribution of shear stress and normal strain in a non-prismatic beam with corrugated steel webs (CSWs) [4]. In the elastic stage, the experimental results are in good agreement with the results of the three-dimensional (3D) finite element analysis for the test beam. The theoretical and experimental results demonstrate that it is not reasonable to assume that the corrugated webs bear all the vertical shear force in a non-prismatic beam with CSWs because of the effect of the variable cross section; this phenomenon is quite different from that in the case of prismatic beams. It would be overly conservative to calculate the shear stress in a non-prismatic beam with CSWs while ignoring the carrying capacity of the concrete flanges (especially the inclined bottom flange). The authors also found that the shear stress in the steel wall does not reach its maximum value in the middle-supported section. Namely, the root section is not the most critical section, although it withstands the maximum vertical shear force and hogging bending moment near the middle supports of continuous beams. In addition, the quasi-plane assumption proved to be valid in the test beam, as the normal stress in the concrete flanges is distributed linearly. The longitudinal bending moment is resisted mostly by axial forces in the concrete flanges, and the CSWs offer little resistance to the longitudinal bending moment caused by the accordion effect.

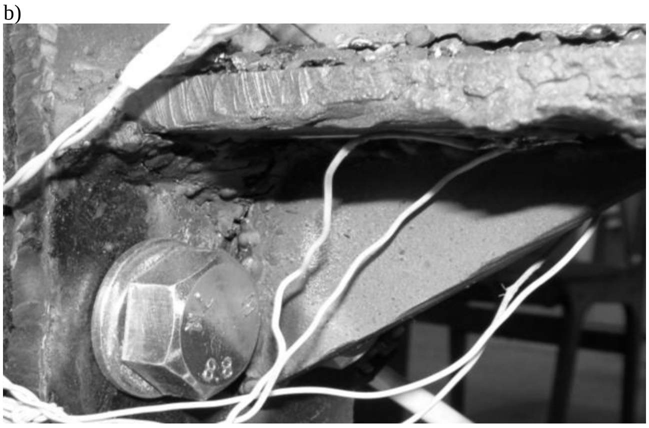
The work [5] is focused on presenting the thermal and mechanical response of sinusoidal corrugated wall beams subjected to high temperatures. Two tests were performed to monitor the behavior of isolated elements and composite slabs designed with corrugated wall beams. Different aspect ratio beams exposed to standard fire temperatures and one beam also subjected to mechanical load were tested in the first experiment. The second study was conducted on a real-scale building compartment designed using corrugated wall beams – concrete slab composite floor. The results obtained from experimental works reveal the real temperature distribution in the steel profile and the fire performance of sinusoidal corrugated wall beams.

The steel beams of corrugated wall represent a relatively new structural system which emerged in the past two decades [10]. A thin corrugated wall affords significant weight reduction of these beams, compared with hot-rolled or welded ones. In the solutions existing on the market, the flanges are made of flat plates welded to the sinusoidal wall sheet, requiring specific welding technology. A new solution is proposed in this paper, according to which the beam is composed by a wall of trapezoidal cold-formed steel sheet and flanges of built-up cold-formed steel members. The connections between flanges and wall can be done by self-drilling screws or by spot welding.

There was performed test specimen, the reference node of the beams with the intermediate beam insert (Fig.1, a). This move made it possible to determine the research program, design features and parameters of experimental designs. This study was carried out on a test machine (hydraulic press) with concentrated force, which is in the middle of the span.

a)

b)



c)

Fig.1: The preparation and results of the trial test of the prototype:

a – test installation during the experiment; b, c – the nature of the sample destruction (plate, fixing the flange of the beam to the shelf and the beam wall area to the flange)

This approach made it possible to find out the most dangerous sections, to clarify the choice of the tensor resistor location, to reveal the nature of the destruction of the structure (Fig.1, b, c), and finally determine the experiment program (Fig.2).

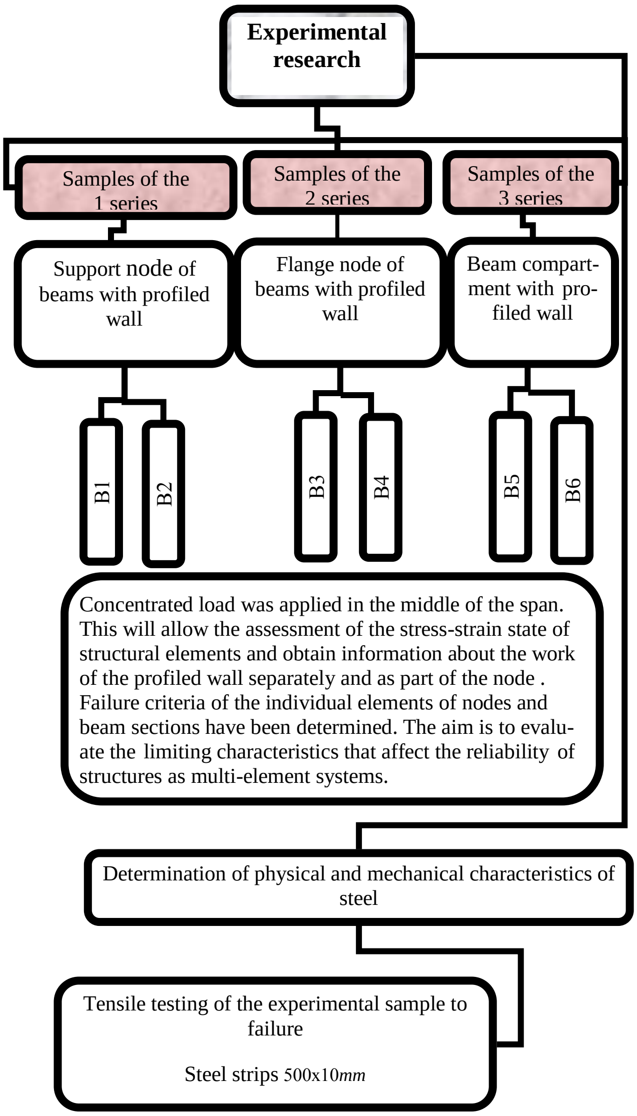


Fig.2: Experimental research programme

According to the objectives of the study, the paper presents three series of beam elements prototypes with a profiled wall.

In order to identify the most appropriate design solution, determine the actual bearing capacity and obtain data on the stress-strain state, a number of experimental studies was performed on a series of beam assemblies samples with a two-bar insert, a series of beams with a flange assembly. Separately, a series of profiled wall beams were tested to determine the local strain from the concentrated load on the most stressed areas. The main purpose of the experiment (Fig.3) is to determine the actual strain plot in the most dangerous sections (preeporn and close to the flange node of the segment). Samples and series 1 (B1, B2), series 2 (B3, B4) and series 3 (B5, B6) have the same geometric parameters: height and thickness of the profiled wall h_w=500 *mm* and t_w=0,7 *mm* ($2t_w$=1,4 *mm*), shelves width b= 100*mm* and thickness t=10 *mm*. The width and thickness of the flanges (support ribs) are respectively b_f=100 *mm* and t_f=10 *mm*. The length of the long and short horizontal sections of the profiled sheet is $a_{1,max}$=60 *mm* and $a_{1,min}$=30 *mm*, and the length of the inclined section is a_2=54 *mm*, the step of the profiled sheet is s=2a=152,5 *mm*. Another feature of such constructions is that the beam wall consists of two profiled sheets H45J×915 according to GOST 14918, which are welded around the perimeter using the slats (steel plates) section of 3x30. The corrugations having uneven steps join directly to belts of the sheets. The common parameter for the three samples series: beam height H_b=520 *mm*, belts and flanges used in the section of 10×100 *mm*.

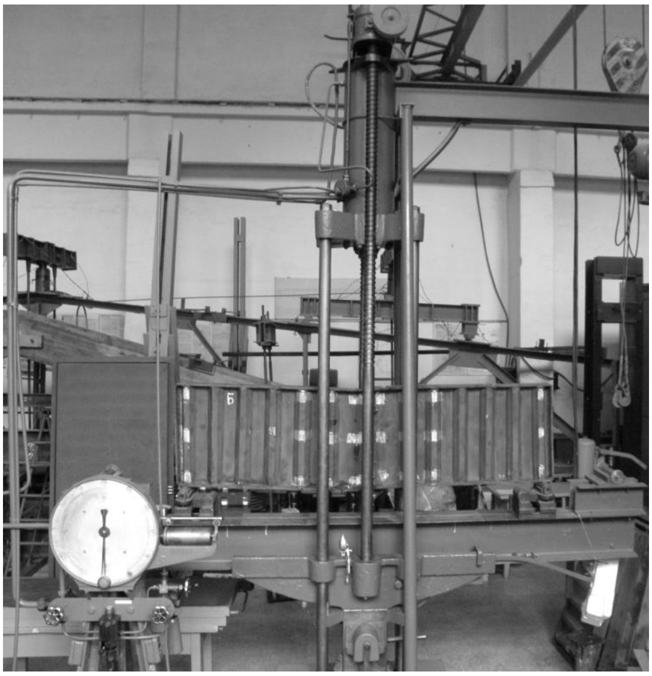


Fig.3: Installation for testing (universal testing machine)

Samples of units and series consist of span L=2220 *mm* (two sections of beams), twelve bolts M20 grade (class 8.8), fragment of the column (I№24).

Sample knots of the series 2 (Fig.3), span L=1980 *mm* as consist of like the first one two beam compartments and are connected by six bolts, grade and class of the previous series. Separately tested fragments of beams with a profiled wall, span L=990 *mm*, which were included in the series 3 of prototypes. The spans of the research structures were limited by the possibilities of the venue.

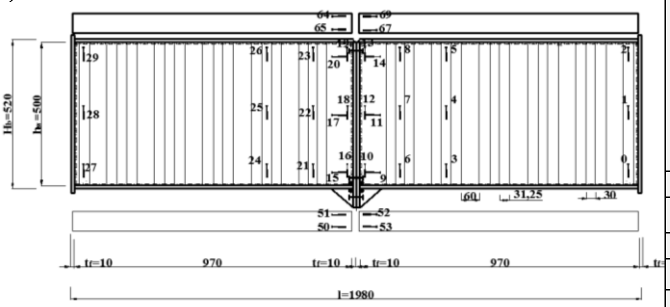
In order to assess the reliability to create the most disadvantageous combination of forces, it is necessary to choose the method, order and scheme of loading of the test object. In our case, the static load was applied to the samples. First of all, the test was carried out under trial load, which provided an opportunity to check the strain gauge equipment, deflection and reliability of fastening. During the experiment, all load samples were applied gradually, which was equal to 1/7-1/10 of the load, that is, 5 *kN* by a single-span design scheme with hinged support on the sides and concentrated force in the middle of the span. Each of the experimental samples was subjected to a short-term concentrated load up to the loss of load-carrying capacity. The nature of fracture in elastic and elastic-plastic stages of structures was investigated.

During the experiment, all the studied samples were tested on a universal testing machine (Fig.3) with a maximum force of 500 kN and with a scale division price of the 0.1 *kN*. Deflection values were obtained for all the tested samples. The deflection meter with the division price of 0.01 *mm* was located in the middle of the span on a fixed support.

In order to obtain measurements of the relative deformations of the series 1 and series 2 of structures in the corresponding cross sections of the samples on a specially prepared surface were pasted strain gauges with a base of 20 mm, the nominal resistance of 200.40 – 200.79 Ohms and the sensitivity of 2.15. For series 3 used strain gauges with a base of 30 *mm* and the sensitivity factor of 2.19, the nominal resistance is 201.5-201.9 Ohms. The strain gauges were glued at each control point on both sides of the structures. For 1, 2 series of test specimens this was done in order to find part of the local deformations that the profiled wall near the flanges perceives.

The layout of the tensor resistors for the second series of tested samples with corresponding cross sections is fed to Fig.4. Sensors were glued on the walls of structures mutually perpendicular to each other, in areas close to the top and bottom shelf, as well as in the middle of the wall. For series 1 and 2 samples, the sensors were placed in cross sections close to the flanges and support areas, and for series 3 in the concentrated force application area. In General, the location of load cells was made in such a way as to further obtain the values of transverse and longitudinal deformations in the most dangerous sections.

a)



b)

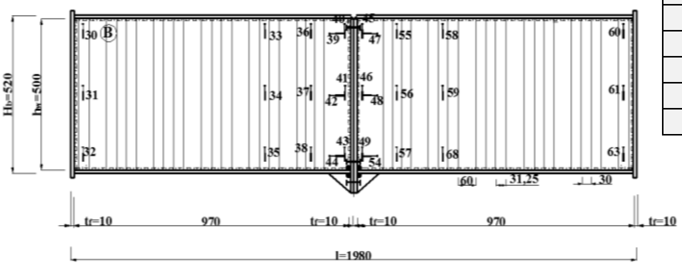


Fig.4: The layout of strain gauges in experimental samples B3 and B4

Under static loading, the plastic and elastic properties, as well as the strength of the metal, were evaluated by the results of tensile tests of flat specimens (Fig. 5). In experimental tests, all profiled sheets had the same manufacturing technology, shape, size, so we assume that their mechanical characteristics are identical. This made it possible to find the mechanical properties of the wall (Table. 1), guided by the test results of 10 samples. All three series of experimental designs were made of profiled sheets H45J×915. Therefore, the part of each wall is carved on one flat specimen of rectangular cross section 500×10 mm. Cutting blanks for all samples were carried out by mechanical means.

Tensile tests of steel strips were carried out on a universal machine, which provided the possibility of uniform loading and centering of the sample in the grips. When approaching the flow area, the steps were reduced to 0.1 kN. Strain measurement was carried out before the limit state.

Fig.6 shows the tensile diagram "σ-ε" of three samples in which there is no flow area. It should be noted that after fixing the yield point further finding of deformations was not carried out, although all the samples were brought to destruction. In the statistical processing of mechanical tests, the normal distribution law was adopted and further statistical characteristics (mathematical expectation, mean square deviation, standard and calculated resistance, coefficient of variation), the limits of proportionality, yield and strength were found (Table. 2).

According to statistical data, it was found that for all experimental samples according to GOST 27772-88 steel is close to the class of steel S 245, has normative supports $R_{yn} = 245 MPa$ and $R_{un} = 370 MPa$.

The data concerning mean values of yield stress, variability and coefficient of variation were used. There was found the standard deviation of border fluidity and normative boundary yield strength of steel (Tabl. 3). Standard and design resistance of steel equal to 240 MPa was determined and corresponds to steel class S 245.

Table 1: Physical and mechanical characteristics of the profiled wall material

№ sample	Limit of proportionality	Deformation of the border proportionalities	Yield strength	Deformation of tensile strength	Tensile strength	Elastic modulus
	σ_{pr}	ε_{pr}	σ_y	δ_u	σ_u	E
	MPa	%	*MPa*	%	*MPa*	*MPa*
1	260	0,124	270	0,16	330	$2{,}1\cdot10^5$
2	240	0,12	250	0,216	314	$2{,}0\cdot10^5$
3	280	0,136	285	0,15	386	$2{,}06\cdot10^5$
4	220	0,096	240	0,113	343	$2{,}3\cdot10^5$
5	270	0,14	280	0,15	328	$1{,}93\cdot10^5$
6	280	0,138	285	0,214	357	$2{,}03\cdot10^5$
7	280	0,14	285	0,236	371	$2{,}0\cdot10^5$
8	260	0,124	280	0,199	336	$2{,}1\cdot10^5$
9	280	0,14	290	0,226	330	$2{,}0\cdot10^5$
10	280	0,134	290	0,21	346	$2{,}09\cdot10^5$
Σx_i	2650		2755		3440	$20{,}61\cdot10^5$

Fig.5: Tensile testing of flat samples

Table 2: The statistical characteristics of the profiled wall material

Limit of proportionality, *MPa*	Yield limit, *MPa*	Tensile strength *MPa*
Mathematical expectation		
265	275,5	344
Standard deviation		
6,89	5,74	7,24
Normative resistance		
248,66	261,89	326,87
Estimated resistance		
	249,42	311,3
Coefficient of variation		
0,03	0,02	0,02

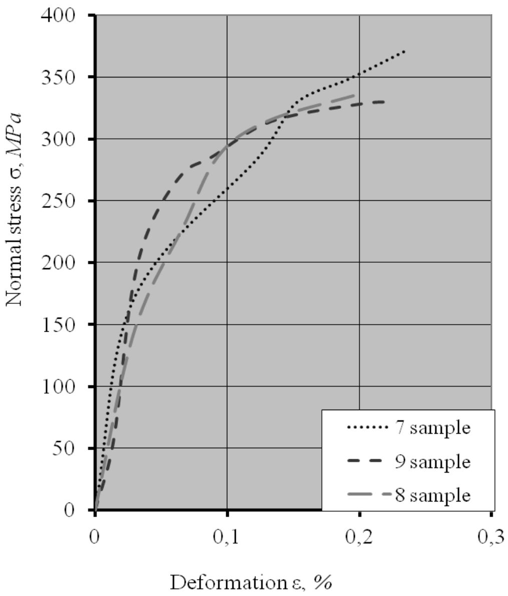


Fig.6: Graphic dependence "σ – ε"

The calculated resistance of steel in tension, compression and bending (profiled sheets) is taken R_y =220*MPa*, and the calculated cutting resistance is R_s =130*MPa*. It is determined that the steel profiled sheets belong to the class S 245 and meet all the regulatory requirements.

Table 1 – Determination of steel profiled sheets strength characteristics

GOST 380-71*				Calculated value		
Steel grade (class)	The average value of the yield strength	Coefficient of variation	Safety factor	The standard deviation value of yield strength	Standard yield strength of steel	Design resistance of steel
	$\bar{\sigma}_y$, *MPa*	v_m	γ_m	$\hat{\sigma}_y$, *MPa*	R_{yn}, *MPa*	R_y, *MPa*
S245	305	0,08	1,05	24,4	247,17	235,40
S235	285	0,08	1,05	22,8	230,96	219,96
Technical requirements 14-1-3023-80				Calculated value		
S245	280	0,055	1,1	15,4	233,8	221,4

During the experiment of samples B3 and B4, a linear dependence of deformations in the shelf and the wall of the beam adjacent to it, except for the fracture site, was found. Deformation in the wall of the beam at the belts is slightly less than that of the shelf. At the distance of 5 *cm* (load cell zone) and the slope of the deformations growth occur at the level of the wall to the shelf.

Normal stresses in cross sections of sample B3 mainly correspond to theoretical assumptions. Deviations of stresses in the compressed and stretched zone are stipulated by the flange connection inside the beam and the presence of the reinforced bolt connection in the lower belt (4 bolts), which works for tension. The same explains the offset of the neutral axis from the gravity center of the beam. The destruction of the beams occurred when the gap in the region of the weld of the beam wall and flange appeared. The wall of the beam in the area of connection with the flange suffered local damage (separation from the shelf in short sections, bends). This is due to local stresses that occur after the beginning of the weld failure.

Experimental testing of samples B3 and B4 for bending showed that at stresses approaching the yield point, there is an increase in displacements according to almost geometrically linear law. But in the future, destruction is achieved. The work of experimental samples acquires the nonlinear form with load drop and stress increase. There is also a transition of the proportionality limit. Also, deformation curvature of the cross section of the wall should be noted as one of the possible causes of geometric nonlinearity. For the experimental samples B3 and B4, the occurrence and further development of damage in the profiled walls led to the loss of the bearing capacity of the structures.

3. Conclusions

Let's summarize the results of the experiment. At the load of 140 *kN* in areas close to the flange (Fig.7, a), we note the gap of the weld. The load began to decrease when the strain reached its maximum .

a) b) c)

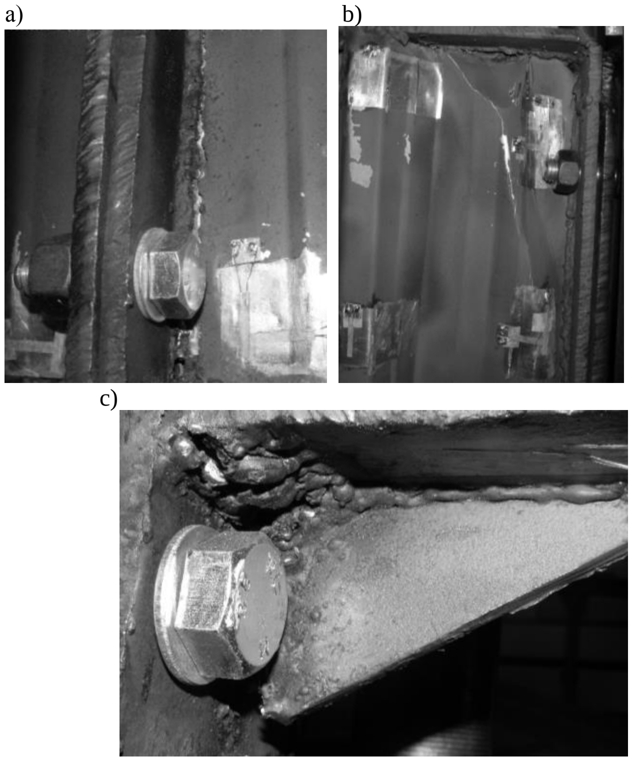


Fig.7: Forms of bearing capacity loss in experimental tests of series 2 samples: a), b) the rupture of the weld in the areas near the flanges; c) the separation plate (fixing flange beams to the shelf)

As a result of the experiment, data on a small curvature of the wall were obtained. This was due to the action of the shear load in the areas of wall attachment to the support edge and in the areas of wall near the shelves (in places of greatest stresses). In the middle of the compartments, as well as in the height in the longitudinal direction of the buckling (wall sections deplanation) did not occur. Therefore, the issue of joint work of the two walls as a spatial structure is not appropriate to raise. The wall is flexible enough and in the longitudinal direction generally allows some deformation. If there is a need to ensure the operation of two walls as one structural element, there is a possibility of using screws or other measures of unfastening. Also, during the physical experiment, the separation of the wall from the upper belt with subsequent distortion of the cross-section shape has been noticed (Fig.7, b). With the efforts of stretching the lower belt is characterized by the destruction of the plate, which fixes the flange of the beam to the shelf (Fig.7, c). It should be noted that during the test, the rate of increase in the load corresponded to the rate of increase in deformations.

References

[1] Pichuhin S. F., Chichulin V. P., Chichulina K. V. "Staleva balka z poperechno profilovanou stinkou korobchastoho pererizu z nerivnomirnym krokom hofriv", 45328, (2009), 4 p.

[2] Magnucka-Blandzi E. "Bending and buckling of a metal seven-layer beam with crosswise corrugated main core – Comparative analysis with sandwich beam", *Composite Structures, Vol. 183,* (2018), pp: 35-41, https://doi.org/10.1016/j.compstruct.2016.11.089

[3] Papangelis J., Trahair N., Hancock G. "Direct strength method for shear capacity of beams with corrugated webs", *Journal of Constructional Steel Research, Vol.137,* (2017), pp:152-160, https://doi.org/10.1016/j.jcsr.2017.06.007

[4] Zhou M., Yang D., Zhang J., An L. "Stress analysis of linear elastic non-prismatic beams with corrugated steel webs", *Thin-Walled Structures, Vol.119,* (2017), pp: 653-661, https://doi.org/10.1016/j.tws.2017.07.027

[5] Vácha J., Kyzlík P., Both I., Wald F. " Beams with corrugated wall at elevated temperature, experimental results", *Thin-Walled Structures, Vol.98,* (2016), pp: 19-28, https://doi.org/10.1016/j.tws.2015.02.026

[6] Moga, C., Guțiu, Ș. I., Danciu, A. D. "Material Consumption Reduction by Using Steel Girders with Corrugated Webs", *Procedia Engineering, Vol.*181, (2017) , pp: 234–241, https://doi.org/10.1016/j.proeng.2017.02.384

[7] Kövesdi B., Jáger B., Dunai L. "Bending and shear interaction behavior of girders with trapezoidally corrugated webs", *Journal of Constructional Steel Research, Vol.*121, (2016) , pp: 383–397, https://doi.org/10.1016/j.jcsr.2016.03.002

[8] Lopes G. C., Couto C., Real P.V., Lopes N. "Elastic critical moment of beams with sinusoidally corrugated webs", *Journal of Constructional Steel Research*, Vol.129, (2017), pp: 185–194, https://doi.org/10.1016/j.jcsr.2016.11.005

[9] Leblouba M., Talha Junaid M., Barakat S., Altoubat S., Maalej M. "Shear buckling and stress distribution in trapezoidal wall corrugated steel beams", *Thin-Walled Structures*, Vol.113, (2017), pp: 13–26, https://doi.org/10.1016/j.tws.2017.01.002

[10] Dubina D., Ungureanu V., Experimental investigations of cold-formed steel beams of corrugated wall and built-up section for flanges**,** *Thin-Walled Structures*, Vol.90, (2015) , pp: 159–170, https://doi.org/10.1016/j.tws.2015.01.018

[11] Pichugin S., Zyma O., Vynnykov P. "Reliability Level of the Buried Main Pipelines Linear Part " *Recent Progress in Steel and Composite Structures – Proceedings of the 13th International Conference on Metal Structures,* ICMS 2016, (2016), pp: 551–558, https:// doi.org/ 10.1201/b21417-76

[12] Piskunov, V. G., Goryk, A. V., & Cherednikov, V. N. (2000). Modeling of transverse shears of piecewise homogeneous composite bars using an iterative process with account of tangential loads. 1. construction of a model.Mechanics of Composite Materials, 36(4), 287-296. doi:10.1007/BF02262807