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NUMERICAL ANALYSIS OF STRESS-STRAIN STATE OF THE STEEL MODULAR BLOCK WITH CORRUGATED WEBS

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Abstract. Modular blocks are widely used in industrial and civil engineering both as stand-alone structures and combined into block-modular buildings. Modular block consists of the load bearing frame, wall fencing, roof and floor decking. The modular block, with wall fencing made of corrugated sheet continuously welded to the beams, is a spatial system, with beams and corrugated webs working together. The steel modular block for the gas pumping unit on a gas turbine power plant is considered in the paper. Assessment of the corrugated web thickness effect on the load bearing capacity of the block is performed. Numerical investigation of stress-strain state of the blocks with different thickness of corrugated web is carried out by the finite element method. The values of the ultimate destructive load on the blocks with different thickness of the corrugated web are determined. The values of the allowable load on the block and the criteria for its limitation have been established depending on the stress-strain state of the block and the causes of destruction.

For comparison, a calculation was made of a block with walls made of sandwich panels that are not included in the work of the frame. It is determined that ultimate load on the block with corrugated webs is 1,5-6 times greater than on the block with wall sandwich panels.

Key words: modular building, steel modular block, corrugated web, critical load, buckling, finite-element analysis

ЧИСЛЕННЫЙ АНАЛИЗ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ СТАЛЬНОГО МОДУЛЬНОГО БЛОКА СО СТЕНАМИ ИЗ ГОФРИРОВАННОГО ЛИСТА

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Аннотация. Строительство промышленных и гражданских зданий из модульных блоков получает широкое распространение благодаря эффективности и экономичности таких конструкций. Модульные блоки используют как отдельно стоящие сооружения, так и объединяют между собой в блочно-модульные здания. В статье рассмотрен стальной модульный блок газоперекачивающего аппарата на газотурбинной электростанции. Модульный блок, в котором гофрированная стенка, непрерывно приваривается к балкам, представляет собой пространственную систему с совместно работающими балками и стенкой. Выполнен численный анализ влияния толщины гофрированной стенки на несущую способность блока. Определена разрушающая нагрузка на блок и параметры напряженно-деформированного состояния конструктивных элементов блоков при различной толщине гофрированных стенок (1 мм, 2 мм, 2,5 мм и 3 мм). Установлены величины допускаемой нагрузки на блок и критерии ее ограничения, в зависимости от напряженно-деформированного состояния блока и причин разрушения. Для сравнения выполнен расчет блока с навесными стенами из сэндвич-панелей, не включающимися в работу каркаса. Получено, что разрушающая нагрузка для рассмотренных блоков с гофрированными стенками в 1,5-6 раз выше, чем для блока со стеновыми сэндвич-панелями.

Ключевые слова: модульное здание, стальной модульный блок, гофрированная стенка, критическая нагрузка, потеря устойчивости, конечно-элементный расчет

1. INTRODUCTION

Structures made of modular blocks are widely used in civil and industrial construction. Modular blocks are used as standalone structures as well as part of buildings consisting of several blocks.

A typical example of modular structure is shipping container. A standard ISO container represents a spatial block, with its frame composed of main beams and racks welded together. The cold formed hollow rectangular sections are used for beams and racks. The wall fencing of a standard container is made of corrugated sheet with a thickness of 2.5 mm, attached by continuous welds to the upper and lower main beams. Corner fittings are located at the corners of the container at the top and bottom of the columns, transmitting loads to supports and receiving loads from containers placed on top. The block works on a beam scheme with a span equal to its length.

Standard ISO containers can withstand heavy loads, primarily due to the combined action of load-bearing beams and columns with the corrugated sheet. Furthermore, due to the nature of load application on the container: about 80% of the allowable load is transmitted through the corner fittings to the container's columns, and only 20% of the load representing the payload on the container floor from the cargo weight. The permissible maximum weight of a loaded 12-meter container is limited to 30.4 tons [1], while the container can withstand a load of up to 192 tons. Therefore, it is permissible to stack up to 6 containers on top of each other.

When such a container is used as building structures, the load distribution will be different. The roof beams will bear snow load, technical loads from equipment placed on the roof and the payload. Therefore, for the use of standard containers in construction of buildings and structures [2], it is necessary to conduct special studies taking into account the actual structural design of the block, the loads acting on it, and other factors [3]. Several studies are dedicated to the analysis and design of modular blocks. Typical structural solutions for modular blocks are developed for use in building construction [4-7], questions regarding the selection of optimal cross-sections for load-bearing structures of the blocks are studied [7], standard connections between modular blocks are developed [8-10], etc.

When loads are applied to the roof of the container, the main beams experience bending and transfer the loads to the corrugated web. As a result, each plane of the longitudinal walls of the block can be represented as a beam with a corrugated web [11-15], where the flanges are the top and bottom longitudinal beams of the block frame. The load-bearing capacity of beams with corrugated webs is influenced by the shape of the corrugations, the presence, shape, and location of openings in the web [16-20].

Studying the influence of the profile and thickness of the corrugated web, the presence of door and window openings, as well as the localization and magnitude of the applied loads on the stress-strain state of the modular block is a relevant and practically significant task.

This article presents a numerical study of the stress-strain state of a steel modular block for a gas pumping unit on a gas turbine power plant. Blocks with different thicknesses of corrugated webs loaded with local and full roof loads were analyzed.

2. METHODS

Modular block for gas pumping unit (GP-block) is a space structure with sizes 12x3,2x3,2 m (length (L) x width (b) x height (H)). There are 4 support points in the corners of the block. Generally, block can be represented as a beam with the span 12 m. Distinctive feature of the considered block is its big height H in comparison to the span L: span to height ratio (L/H) of the block is 3,75. Beams with values of L/H ratio below 5 ($L/H < 5$) are deep beams. For deep beams the fundamental principle that a plane section before bending remains plane after bending is violated. For beams with small span-to-height ratio section warping should be taken into account. Stress distribution across the section of the deep beam is nonlinear due to the shear warping of the cross-section.

The considered block contains openings in the walls and roof, unlike standard ISO containers. Furthermore, the height and width of the GP-block are larger than the dimensions of standard containers.

The main beams and racks of the frame are constructed from cold-formed welded rectangular hollow sections. Walls of the block consists of corrugated sheets continuously welded to the top and bottom main beams. The floor and roof decking are made of flat steel sheets with a thickness of t=4 mm with L-stiffeners. The steel sheet is supported by secondary beams with hollow rectangular sections welded to the main longitudinal frame beams. In the roof there is a rectangular opening with sizes 3,2x4,9 m for tube of gas pumping equipment.

Structures of the considered block are made of steel S255 (GOST 27772-2015). Normative yielding stress is R_{yn}=245 MPa.

Numerical analyses of the stress-strain state of the blocks with various corrugated web thicknesses have been conducted.

A finite element model of the GP-block has been developed using the computational program Simcenter Femap and depicted in Figure 1. The models with corrugated web thicknesses of 1 mm, 2 mm, 2,5 mm and 3 mm are considered.

Corrugated webs, roof and floor sheets, sections of the main beams are modeled by PLATE finite elements. The racks, secondary beams and stiffeners of the flat sheets are modeled by BEAM finite elements. Boundary conditions include constraints to prevent displacements in all linear directions at the four bottom corners of the block.

In addition to the cases with different corrugated sheets on the walls, an analysis was conducted on the model without corrugated webs to estimate the effect of the corrugated web presence on the stress-strain state of the block. In this case, the block has walls made of sandwich panels, which are hung on the frame structures and practically do not participate in load distribution. So, their effect on the behavior of the block can be neglected.

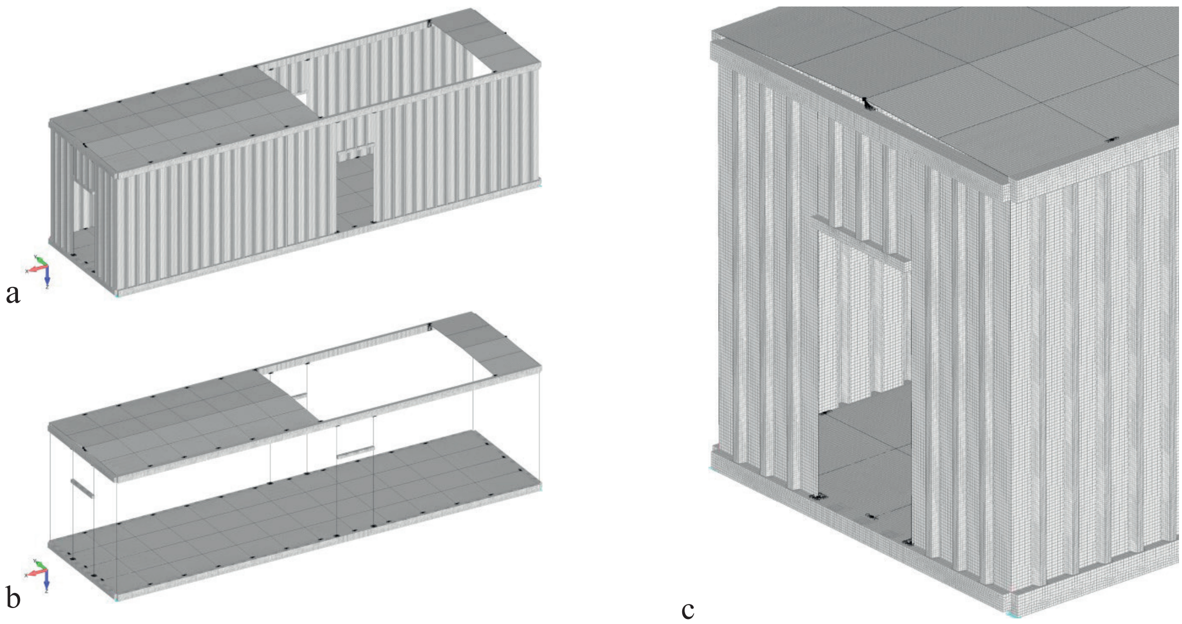


Figure 1. Finite-element model of block for gas pumping unit: a – with corrugated webs; b – without corrugated web (block with wall sandwich panels); c - fragment

Two loading schemes of the blocks are considered: "full load" – payload over the entire area of the roof and "local load" – payload over the local area of the roof. The uniform load was applied to the top longitudinal beam. (fig. 2).

Geometrical and physical nonlinear analyses have been made. Stress-strain curve for steel S255 according SP 16.13330.2017 is taken into analysis and shown on fig. 3. The values of stress and strain in the key points of the diagram are represented in table 1.

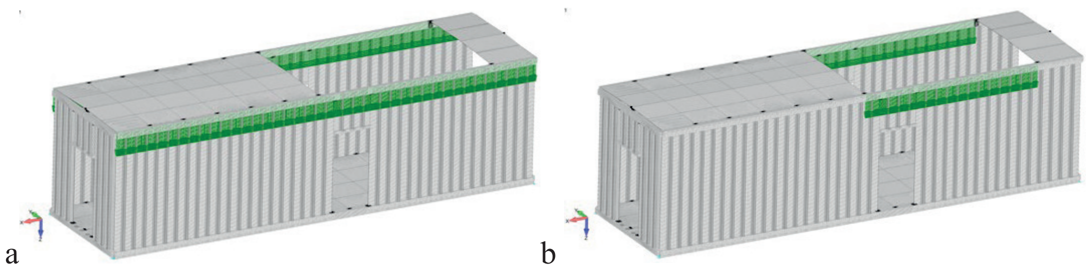


Figure 2. Schemes of loading: a – "full load"; b – "local load"

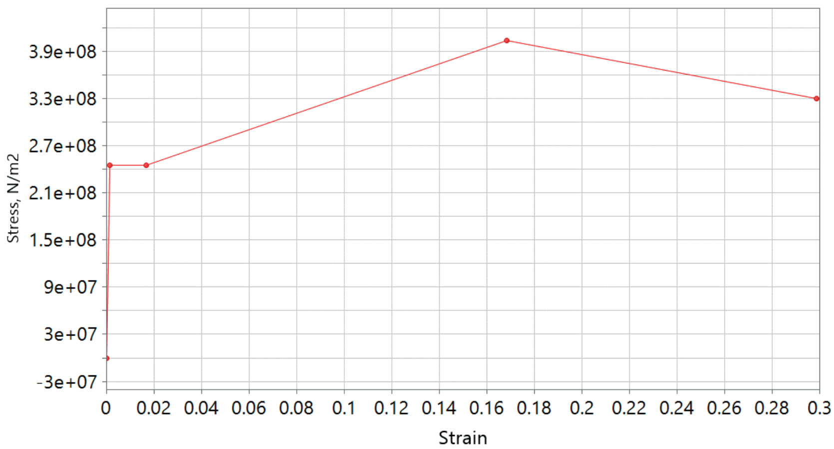


Figure 3. Stress–strain curve for steel S255 taken into analysis

Table 1. Characteristics of steel S255

Point of curve	$\bar{\varepsilon} = \varepsilon E / R_{yn}$	$\bar{\sigma} = \sigma / R_{yn}$	ε	σ, MPa
Yield strength (Beginning of yield plateau)	1	1	0,00119	245
End of yield plateau	14	1	0,01665	245
Ultimate strength	141,6	1,653	0,16840	404,99
Fracture	251	1,35	0,29850	330,75

The geometrically nonlinear analysis was performed using the step-by-step iterative method (ITER), with the following parameters: number of increments – 40, iterations before update – 25, convergence tolerances by load - 0.001.

The buckling and yielding criteria are established to determine the ultimate load on the particular structural elements of the block and on the block as whole.

Theoretically, the buckling criterion can be defined as a sudden increase in displacement

increment Δδ at a constant load increment Δ*P*. Buckling can be identified on the graph as the inflection point of the displacement-load curve. The load corresponds to a sudden change in the slope of the tangent line to the displacement-load curve is considered the ultimate load according to the buckling criterion for the particular structural element.
The following equation is proposed to define the **buckling criterion**:

$$\frac{tg\alpha_{i+1}}{tg\alpha_i} \geq 3 , \qquad (1)$$

where $tg\alpha_{i+1} = \frac{\Delta\delta_{i+1}}{\Delta P_{i+1}}$, $tg\alpha_i = \frac{\Delta\delta_i}{\Delta P_i}$ - tangents of the displacement-load curve on the (i+1)-step and i-step of load increment, respectively.
Assuming a constant load increment $\Delta P_i = \Delta P_{i+1} = const$ equation (1) for the buckling criterion can be written as follows:

$$\frac{\Delta\delta_{i+1}}{\Delta\delta_i} \geq 3 , \qquad (2)$$

where $\Delta\delta_{i+1}$ and $\Delta\delta_i$ - displacement increments at the (i+1)-step and i-step of the load increment ΔP_i. respectively.
The graphical interpretation of the buckling criterion is depicted on fig. 4.

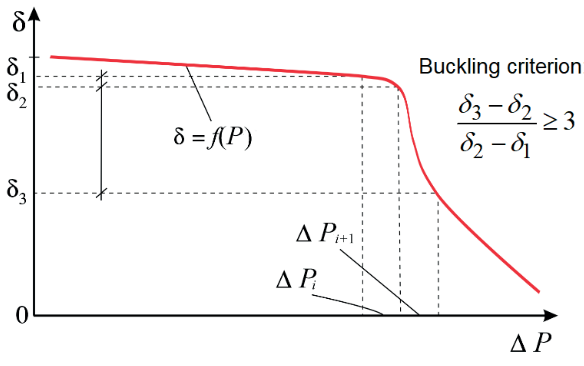


Figure 4. Graphical interpretation of the buckling criterion

To define the **yielding criterion**, we adopt the following condition: the criterion of yielding is met when the values of Von Mises strain *ε* falling within the specified range:

$$R_y / E \leq \varepsilon < \varepsilon_u \qquad (3)$$

where R_y – design resistance of steel determined based on the nominal value of yield strength; E=210000 N/mm^2 – modulus of elasticity of the steel; ε_u – ultimate strain corresponding to the ultimate tensile strength.

3. RESULTS AND DISCUSSION

In the results of carried out analyses the stress-strain state of the block with different corrugated web thickness is defined depending on load value and scheme of loading ("full load" or "local load"). The stress-strain parameters of the block structures in the key positions are determined (fig. 5):
- Von Mises stress and horizontal transverse (Y-direction) displacement of the corrugated web in the corner support zone (pos. A);
- Von Mises stress and horizontal transverse (Y-direction) displacement of the top longitudinal beam in the span (pos. B);
- Von Mises stress and vertical (Z) displacement of the roof sheet between stiffeners (pos. C).

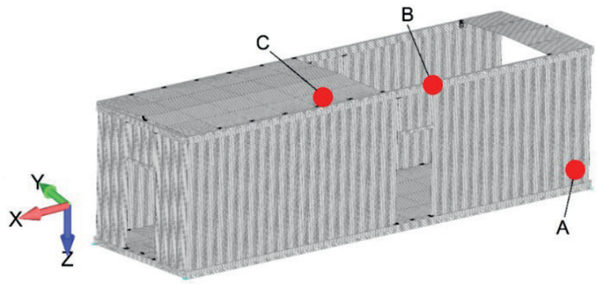


Figure 5. Key positions for determine stress-strain state of the block

Diagrams of displacement and Von Mises stress dependence from load in the key positions of the top longitudinal beam and corrugated web are represented on fig. 6 and 7. Curves depicted results for loading scheme "full load" are drawn by continuous line and for loading scheme "local load" - by dashed line.

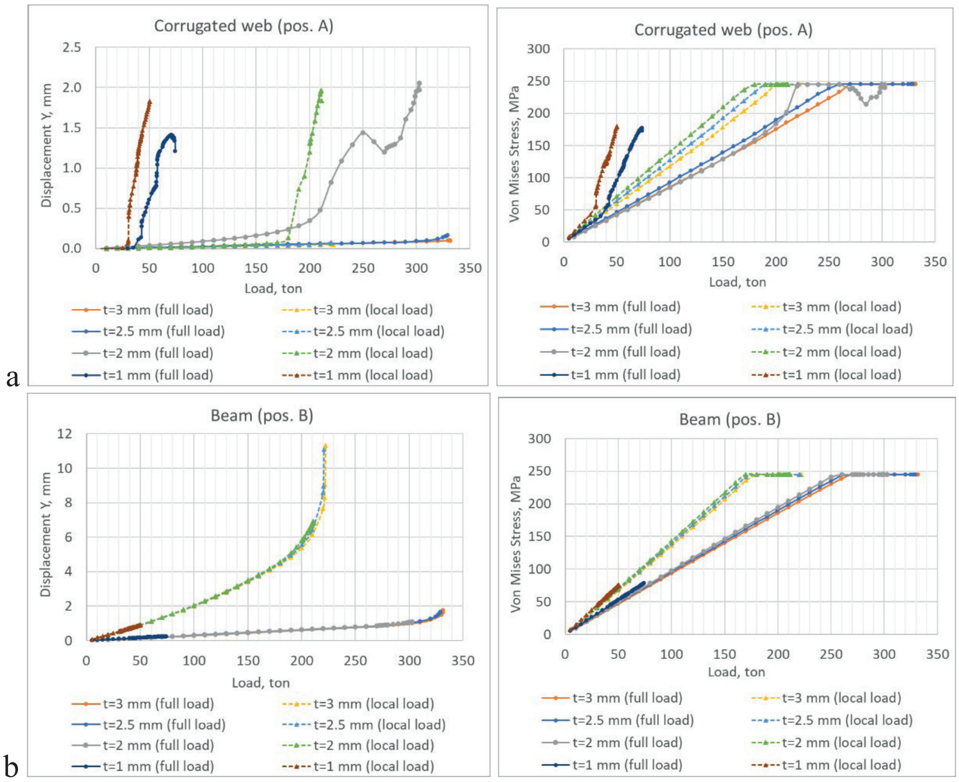


Figure 6. *Displacement – Load curves and Von Mises stress – Load curves in the key positions of the blocks: a – corrugated web; b – top longitudinal beam*

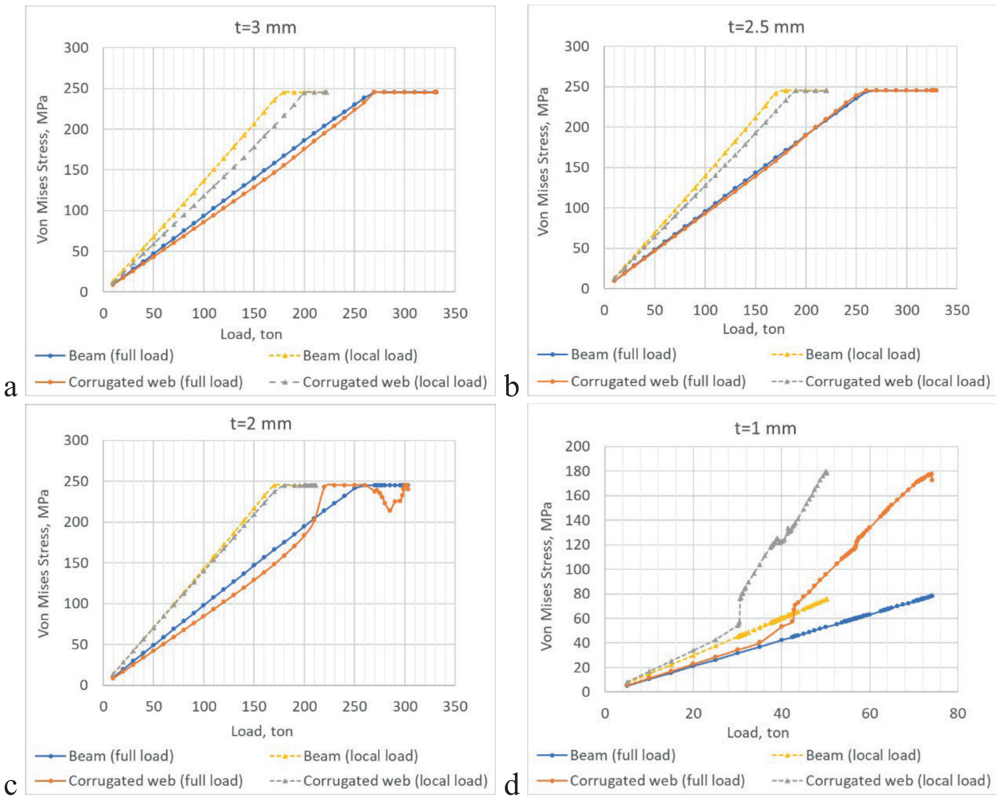


Figure 7. *Von Mises stress – Load curves for blocks with corrugated web thickness (t): a – t=3 mm; b – t=2.5 mm; c – t=2 mm; d – t=1 mm*

Von Mises stress in the key positions of the structural elements of the considered blocks are represented in table 3.

The values of ultimate load P_{ult} for the considered modular blocks are obtained in the results of numerical analyses and represented in table 4. Ultimate load for each structural element and block entire is the load when buckling or yielding criterion for the appropriate structure is reached – see equation (1-3) and fig. 4.

Table 3. Von Mises stress in the structural elements of considered modular blocks

Corrugated web thickness	Load, ton	Von Mises stress, MPa					
		Roof sheet (pos. C)		Top longitudinal beam (pos. B)		Corrugated web (pos. A)	
		Full load	Local load	Full load	Local load	Full load	Local load
t=1 mm	30	7,41	6,40	31,62	45,06	34,42	54,42
	40	9,94	8,54	42,14	60,26	53,12	122,70
	50	12,48	10,67	52,65	75,40	95,59	179,72
	50,3	-	10,74	-	75,87	-	178,88
	70	17,75	-	73,72	-	168,50	-
	74,2	18,89	-	78,16	-	172,45	-
t=2 mm	50	12,14	10,72	49,21	70,86	42,10	70,71
	130	37,83	28,21	127,34	187,37	110,67	181,35
	160	62,90	38,43	156,43	232,49	138,22	223,83
	170	71,73	54,83	166,07	245,00	148,22	237,17
	180	79,48	67,47	175,69	245,00	159,11	245,00
	210	98,10	91,00	204,30	245,00	202,08	245,00
	211,2	-	90,66	-	245,00	-	245,00
	220	103,38	-	213,75	-	245,00	-
	260	122,85	-	245,00	-	245,00	-
	300	142,53	-	245,00	-	245,00	-
	302,8	143,16	-	245,00	-	239,88	-
t=2,5 mm	50	12,06	10,71	47,97	69,07	46,47	64,21
	130	37,32	27,99	124,10	182,54	120,33	165,82
	160	62,00	36,28	152,43	226,41	148,31	206,23
	180	78,71	67,39	171,17	245,00	167,98	233,40
	190	85,59	76,74	180,50	245,00	178,59	245,00
	220	102,70	97,12	208,26	245,00	209,44	245,00
	220,6	-	97,64	-	245,00	-	245,00
	260	122,05	-	245,00	-	245,00	-
	325	154,03	-	245,00	-	245,00	-
	329,7	156,83	-	245,00	-	245,00	-
t=3 mm	50	11,99	10,69	46,93	67,54	42,98	59,25
	130	36,93	27,82	121,39	178,41	111,43	153,50
	160	61,30	34,41	149,08	221,23	137,60	191,72
	180	78,11	67,14	167,40	245,00	155,48	216,82
	200	91,24	84,32	185,60	245,00	175,26	245,00
	220	102,20	97,05	203,66	245,00	195,11	245,00
	222,1	-	98,50	-	245,00	-	245,00
	270	126,18	-	245,00	-	245,00	-
	330	155,65	-	245,00	-	245,00	-
	331,8	156,66	-	245,00	-	245,00	-
Without corrugated web	10	26,80	20,54	50,56	102,49	-	-
	20	85,16	83,11	130,94	245,00	-	-
	30	207,17	101,28	245,00	245,00	-	-
	40	245,00	88,39	245,00	245,00	-	-
	50	245,00	-	245,00	-	-	-

For example, buckling of the top longitudinal beam and corrugated web is characterized by an abrupt increase of its Y-displacements. This can be observed on the displacement-load curves (fig. 6).

The yielding criterion for structural element is determined by the load applied to the block that causes the yield stress in structural element (see fig. 7).

In the table 4, cells containing the ultimate load, corresponding to the earliest attainment of the buckling or yielding criterion for one of the structural elements are highlighted in color. This load can be used as allowable load - the upper limit to the load that can be applied to the block without causing failure of its structural elements.

Table 4. Ultimate load P_{ult} for the considered modular blocks

Corrugated web thickness	Structural element	Ultimate load P_{ult}, ton		Criterion
		Full load	Local load	
t=1 mm	Roof sheet	-	-	-
	Corrugated web	**40**	**30**	**Buckling**
		-	-	Yielding
	Top longitudinal beam	-	-	-
	Block entire	74,2	50,3	Buckling of the corrugated web
t =2 mm	Roof sheet	130	160	Buckling
	Corrugated web	**210**	**170**	**Buckling**
		220	180	Yielding
	Top longitudinal beam	-	210	Buckling
		260	170	Yielding
	Block entire	302,8	211,2	Buckling of the corrugated web
t =2,5 mm	Roof sheet	130	160	Buckling
	Corrugated web	-	-	Buckling
		260	190	Yielding
	Top longitudinal beam	325	220	Buckling
		260	**180**	**Yielding**
	Block entire	329,6	220,6	Buckling of the top longitudinal beam
t=3 mm	Roof sheet	130	160	Buckling
	Corrugated web	-	-	Buckling
		270	200	Yielding
	Top longitudinal beam	330	220	Buckling
		270	**180**	**Yielding**
	Block entire	331,8	222,1	Buckling of the top longitudinal beam
Without corrugated web	Roof sheet	40	-	Yielding
	Top longitudinal beam	50	40	Buckling
		27,5	**20**	**Yielding**
	Block entire	50	40	Buckling of the top longitudinal beam

Depending on the corrugated web thickness the following types of failure modes of the block are defined (fig. 8):

- 1st type: destruction of the corrugated web (buckling);
- 2nd type: destruction of the top longitudinal beams (yielding and subsequent buckling).

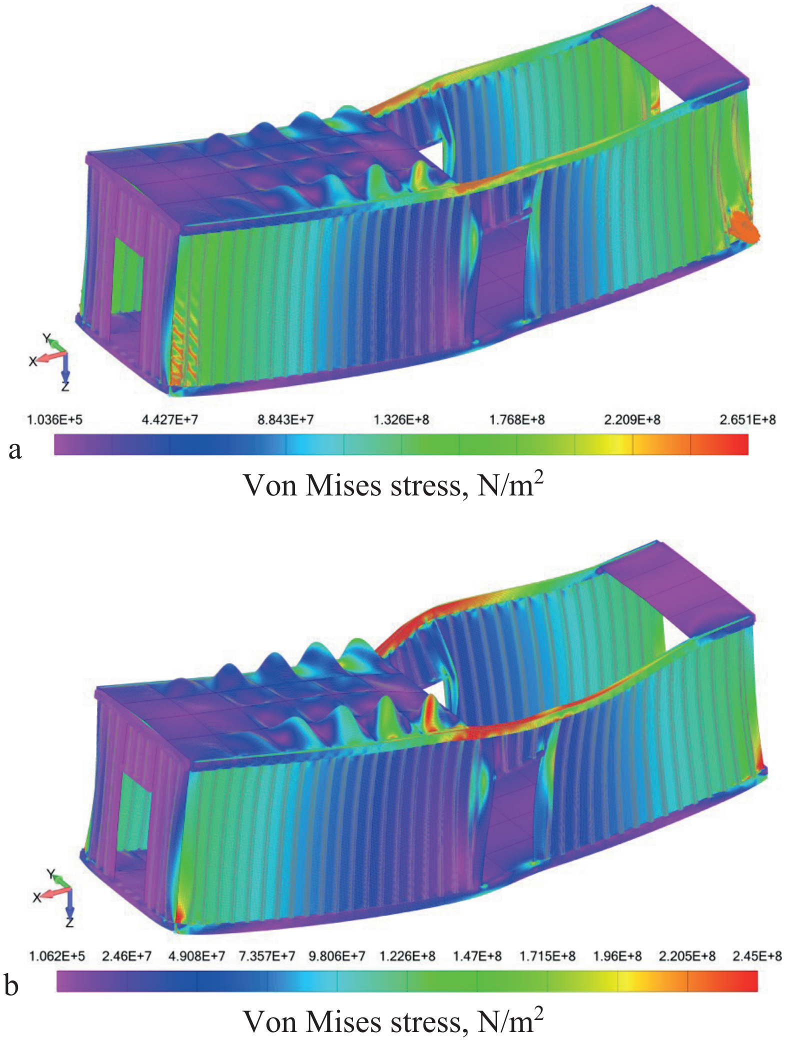


Figure 8. Failure modes of the block: a – buckling of the corrugated web (corrugated web thickness 2 mm); b – destruction of the top longitudinal beam (corrugated web thickness 3 mm)

The failure of the blocks with 2,5 mm and 3 mm thick corrugated web is caused by destruction of the top longitudinal beams and correspond to 1st type of failure mode. The ultimate load for loading scheme "full load" is about 330 tons and for scheme "local load" – 220 tons. This is the critical buckling load for top longitudinal beams. Yielding of the top longitudinal beams and corrugated web is observed before failure of the block. Buckling of the corrugated web 2,5 mm and 3 mm thick is not reached during the loading.

The failure of the blocks with corrugated web 1 mm and 2 mm thick is occurred by 1st type because of the corrugated web buckling. When the load reaches some critical value, the corrugated web begin bulges out from the plane of the block wall in the corner zones near the supports. Mainly the shear stresses cause local buckling of the corrugated web. At the same time, the block overall retains its load-bearing capacity. With increasing load, the area of the corrugated web experienced buckling increases. The finite element analysis continues until the ultimate load is reached, at which complete failure of the block occurs.

With a corrugated web thickness of 2 mm, yielding is observed at a load of 220 tons, while at a load of 260 tons, yield stress is noted in the top longitudinal beams. With a corrugated web thickness of 1 mm, the load causing yielding is not reached for all structural elements until failure of the block.

The values of ultimate load on the block loaded by "local load" scheme are on average 25% lower in comparison with "full load" loading scheme.

It should be noted that during the loading process, there is a local loss of stability in certain sections of the roof sheet (fig. 9).

In all loading scenarios of the block under the "full load" scheme, the critical load for the roof sheet was 130 tons, while under the "local load" scheme, it was 160 tons. Areas of the decking that have buckle are taken out of operation, but overall, the block retains its load-bearing capacity and can withstand further increases in load. Therefore, the buckling of the roof sheet was not considered as a criterion for limiting the allowable load on the block.

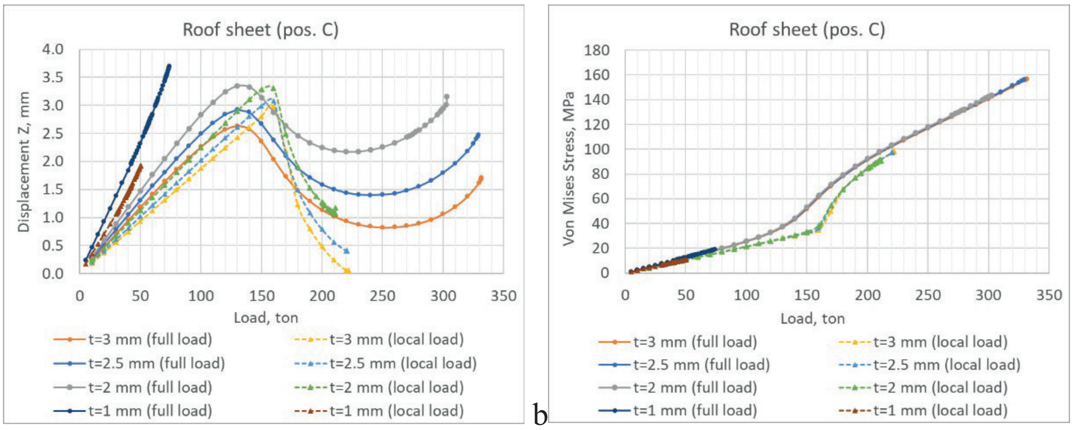
a b


Figure 9. Diagrams for roof sheet: a – displacement-load curves; b – Von Mises stress – load curves

The failure of the block without the corrugated web occurs due to the buckling of the top longitudinal beam. The ultimate load for calculating a block without the corrugated web is 1.5-6 times lower than for a block with a corrugated web (see Table 4).

The corrugated web significantly reduces the stresses in the beams. For example, under a load of 50 tons according to the "full load" scheme, the stresses in the beams of a block without the corrugated web are 245 MPa, which corresponds to the yield stress. With the presence of the corrugated web, the Von Mises stress determined in the beam under the same load is on average 5 times lower (see fig. 10). At the same time, the thickness of the corrugated web has a negligible effect on the stress value in the beam (see Table 5).

Table 5. Comparison of the Von Mises stress in the structural elements of block with and without corrugated web

Structural element	Loading scheme	Corrugated web thickness				
		Without corrugated web	t=1 mm	t=2 mm	t=2,5 mm	t=3 mm
Top longitudinal beam	Full load	245,00	52,65	49,21	47,97	46,93
	Local load	-	75,40	70,86	69,07	67,54
Roof sheet	Full load	245,00	12,48	12,14	12,06	11,99
	Local load	-	10,67	10,72	10,71	10,69

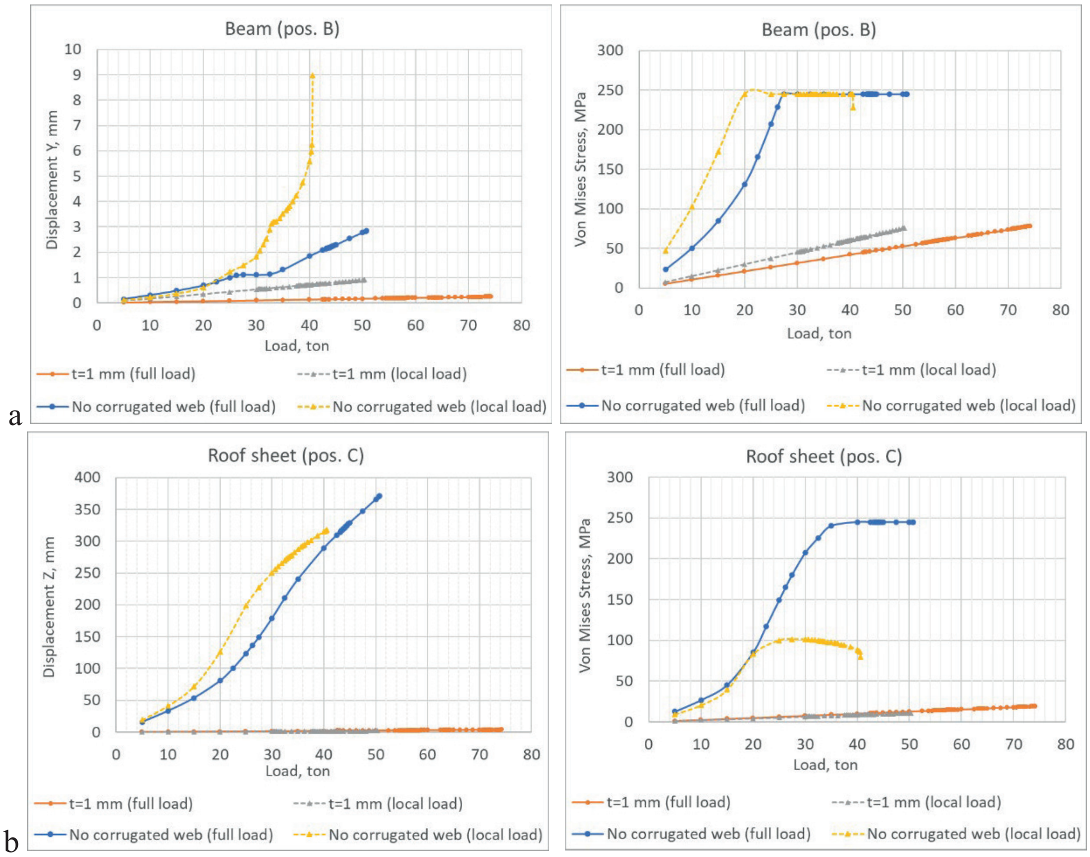


Figure 10. Comparative diagrams for blocks with and without corrugated webs: a – top longitudinal beam; c – roof sheet

Table 6 shows the values of the maximum allowable load on the block P_{max} and the ultimate load P_{ult} that caused block failure, as obtained in the results of the carried-out finite-element analyses. To ensure the necessary reliability of the structures, the allowable load on the block P_{max} is taken as 95% of the ultimate load, corresponding to the earliest attainment of the buckling or yielding criterion (see highlighted cells in table 4). For web thicknesses of 1 mm and 2 mm, the allowable load was limited by buckling criterion corresponding to the onset of local buckling of the corrugated web. For larger web thicknesses (2.5 mm and 3 mm), the limitation of allowed load is adopted by the yielding criterion, which is the onset of yielding strain in the top longitudinal beams.

Table 6. Allowable and ultimate load on the block

Corrugated web thickness	Allowable load P_{max}, ton		Ultimate load P_{ult}, ton		Criterion
	Full load	Local load	Full load	Local load	
Without corrugated web	25	19	50,8	40,6	Yielding of the top longitudinal beam
t=1 mm	38	28	74,2	50,3	Buckling of the corrugated web
t =2 mm	199	161	302,8	211,2	Buckling of the corrugated web
t =2,5 mm	247	161	329,6	220,6	Yielding of the top longitudinal beam
t=3 mm	256	171	331,8	222,1	Yielding of the top longitudinal beam

The adopted limitation of the allowable load on the block that provided in table 6, ensures a reserve of block load-bearing capacity, amounting to 49%, 34%, 25%, and 22% for blocks with corrugated web thicknesses of 1 mm, 2 mm, 2.5 mm, and 3 mm, respectively. The calculation results showed that local buckling of the corrugated web does not lead to complete failure if the block, and the block is able to withstand increased loads. Experimental tests on full-scale specimens of beams with corrugated webs [21, 22] also indicate that a beam with a partially buckled web retains its load-bearing capacity.

The presence of reserves allows ensuring the reliability of the block and increases its resistance to various emergency situations associated with the disruption of normal equipment operation, sudden changes in loads, explosions, and impacts [23].

The prospects for further research include the development of methods and tools for practical calculation of modular block structures.

Finite-element computational models of various levels of detail (LOD-cm) are used in design [24]. The use of highly detailed finite-element models for practical design is not always justified due to their complexity. In such cases, simplified equivalent models that describe the actual stress-strain state of the structure with sufficient engineering accuracy are used. For example, the corrugated web of beams can be replaced with an equivalent flat sheet [25, 26] or beam elements. A similar approach can be applied for the analysis of the stress-strain state of the modular blocks. For this purpose, based on numerical studies using high-detailed computational models, it is necessary to determine the characteristics of simplified equivalent models.

Another way to solve the practical problem of a modular block design is to use artificial intelligence, which can predict the stress-strain state and load-bearing capacity of the block based on given input parameters such as block dimensions, corrugated web thickness, applied load, etc.

4. CONCLUSIONS

As a result of the carried out numerical studies of the stress-strain state of the modular block for gas pumping unit, the following findings are obtained:

1. The load-bearing capacity of the considered modular blocks with corrugated webs is 1.5-6 times higher than that of a block with hanging wall cladding, such as sandwich panels.
2. The corrugated web, continuously welded to the beams, significantly relieves the beams, reducing stresses in them by 5 times compared to the case of its absence.
3. The following failure modes of the blocks with corrugated webs are defined:
- 1st type: destruction of the corrugated web (buckling) - observed for the blocks with corrugated web thicknesses of 1 mm and 2 mm);
- 2nd type: destruction of the top longitudinal beams (yielding and subsequent buckling) - observed for the blocks with corrugated web thicknesses of 2.5 mm and 3 mm).
4. Criteria for limiting the allowable load on the modular block are defined depending on the type of failure mode. The allowable load is taken as 95% of the ultimate load causes either yielding stress in the top longitudinal beams or buckling of the corrugated web.
5. The values of the maximum allowable load on the block with different thicknesses of the corrugated web and without it are determined based on the adopted criteria. Limiting the load on the block by allowable value provides a reserve of load-bearing capacity of the block ranging from 49% to 22% for corrugated web thicknesses from 1 to 3 mm, respectively.
6. The type and localization of the payload on the block affect its load-bearing capacity. The ultimate load on the block loaded by the "local load" scheme is on average 25% lower compared to the "full load" loading scheme.

REFERENCES

1. **Turkay Y.** (2019) Design and analysis of a lightweight composite shipping container made of carbon fiber laminates. *Logistics*, vol. 3, no. 3, 18.
2. **Kotnik J.** (2008) *Container architecture*, Barcelona: Links Books.
3. **Giriunas K., Sezen H., Dupaix R.B.** (2012) Evaluation, modeling, and analysis of shipping container building structures. *Engineering Structures*, vol. 43, pp. 48-57.
4. **Tusnin A.R.** (2017) Stal'noy karkas maloetazhnogo zdaniya [Steel framework of a low-rise building]. *Industrial and Civil Engineering*, no. 11, pp. 18-22. (In Russ.).
5. **Tusnin A.R., Varaksin P.A.** (2018) Tipovoy stal'noy karkas pyatietazhnogo zdaniya [Standard Steel Frame of a 5-Story]. *Industrial and Civil Engineering*, no. 10, pp. 45-49. (In Russ.).
6. **Su M., Yang B., Wang X.** (2022) Research on integrated design of modular steel structure container buildings based on BIM. *Advances in Civil Engineering*, vol. 2022, 4574676.
7. **Ha T.-H., Cho B.-H., Kim H., Kim D.-J.** (2016) Development of an efficient steel beam section for modular construction based on six-sigma. *Advances in Materials Science and Engineering*, vol. 2016, 9687078.
8. **Nadeem G., Safiee N.A., Abu Bakar N., Abd Karim I., Mohd Nasir N. A.** (2021) Connection design in modular steel construction: A review. *Structures*, vol. 33, pp. 3239-3256.
9. **Ma H., Huang Z., Song X., Ling Y.** (2023) A Study on Mechanical Performance of an Innovative Modular Steel Building Connection with Cross-Shaped Plug-In Connector. *Buildings*, vol. 13, no. 9, 2382.
10. **Tusnina O.A.** (2017) Konstruktivnye resheniya uzlov stal'nogo karkasa dlya maloetazhnykh zhilykh zdaniy [Structural Solutions of Joints of a Steel Frame for Low-Rise Residential Buildings]. *Industrial and Civil Engineering*, 2017, no. 11, pp. 23-27. (In Russ.).
11. **Gataullina K.R.** (2023) Effektivnost' primeneniya balok s gofrirovannoy stenkoy v balochnoy kletke [Efficiency of using beams with corrugated webs in a beam platform]. *Young Scientist*, no. 20 (467), pp. 85-90. (In Russ.).
12. **Bryantsev A.A., Absimetov V.E., Lalin V.V.** (2017) Effektivnost' primeneniya dvutavrov s gofrirovannymi stenkami v proizvodstvennykh zdaniyakh [Effective application of I-beams with corrugated webs in the industrial building]. *Construction of Unique Buildings and Structures*, no. 3(54). pp. 93-104. (In Russ).
13. **Bal'zannikov M.I., Kholopov I.S., Solov'ev A.V., Lukin A.O.** (2013) Primenenie stal'nykh balok s gofrirovannoy stenkoy v gidrotekhnicheskikh sooruzheniyakh [Using Steel Beams with Corrugated Web in Hydraulic Structures]. *Vestnik MGSU*, no. 11, pp. 34-41. (In Russ.).
14. **Tian Z.** (2023) Review of Research on Corrugated Web Steel Beams. *Journal of Engineering Mechanics and Machinery*, vol. 8(4), pp. 11-14.
15. **Al-Kannoon M.A., Suhiel I.A.** (2020) Experimentally flexural behaviour study of steel beams with corrugated webs. *IOP Conf. Series: Materials Science and Engineering*, vol. 888, 012084.
16. **Solov'ev A.V., Lukin A.O., Alpatov V.Yu., Savost'yanov V.N.** (2012) Uchet osobennostey raboty balok s gofrirovannoy stenkoy v raschetakh na stesnennoe kruchenie [Account for performance of corrugated web beams in the analysis of constrained torsion]. *Vestnik MGSU*, no. 11, pp. 105-112. (In Russ.).
17. **Al-Mawashee H.S. and Al-Kannoon M.A.-A.** (2021) Flexural Strength of Castellated Beams with Corrugated Webs. *Journal of Physics: Conference Series*, vol. 1973, 012213.

18. **Elamary A.S., Saddek A.B., Alwetaishi M.** (2017) Effect of corrugated web on flexural capacity of steel beams. *International Journal of Applied Engineering Research*, vol. 12(4), pp. 470-481.
19. **Kumar U.M., Reddy D.P., Patel R.R., Pandian M.S., Karthikeyan K.** (2018) A study on flexural capacity of steel beams with corrugated web. *International Journal of Civil Engineering and Technology*, vol. 9(4), pp. 679-689.
20. **Kudryavtsev S.** (2018) Influence of web openings on bearing capacity of triangularly corrugated web beam. *IOP Conf. Series: Materials Science and Engineering*, vol. 365, 042034.
21. **Zubkov V., Lukin A., Alpatov V.** (2018) Experimental research of beams with corrugated web. *MATEC Web of Conferences*, vol. 196, 01005.
22. **Zubkov V.A., Lukin A.O.** (2013) Eksperimental'nye issledovaniya vliyaniya tekhnologicheskikh i konstruktsionnykh parametrov na nesushchuyu sposobnost' metallicheskikh balok s gofrirovannoy stenkoy [Experimental research into the influence produced by processrelated and structural parameters on the bearing capacity of metal beams with corrugated webs]. *Vestnik MGSU*, no. 2, pp. 37-46. (In Russ.).
23. **Alekseytsev A.V.** (2023) Ensuring the safety of steel moment frames subjected to uncertain impacts. *Buildings,* vol. 13, no. 8, 2038.
24. **Tusnina O., Alekseytsev A.** (2023) LOD of a computational numerical model for evaluating the mechanical safety of steel structures. *Buildings*, vol. 13, no. 8, 1941.
25. **Sherman D., Fisher J.** (1971) Beams with corrugated webs. Proceedings of the *1st International Specialty Conference on Cold-Formed Steel Structures (Rolla, Missouri, August 19-20, 1971)*, pp. 198-204.
26. **Ye Z., Berdichevsky V.L., Yu W.** (2014) An equivalent classical plate model of corrugated structures. *International Journal of Solids and Structures*, vol. 51(11-12), pp. 2073-2083.

СПИСОК ЛИТЕРАТУРЫ

1. **Turkay Y.** (2019) Design and analysis of a lightweight composite shipping container made of carbon fiber laminates // Logistics, 2019, Vol. 3, no. 3, 18.
2. **Kotnik J.** Container architecture. Links Books, Barcelona, 2008, 253 pages.
3. **Giriunas K., Sezen H., Dupaix R.B.** Evaluation, modeling, and analysis of shipping container building structures // Engineering Structures, 2012, Vol. 43, pp. 48-57.
4. **Туснин А.Р.** Стальной каркас малоэтажного здания // Промышленное и гражданское строительство, 2017, № 11. С. 18-22.
5. **Туснин А.Р., Вараксин П.А.** Типовой стальной каркас пятиэтажного здания // Промышленное и гражданское строительство, 2018, № 10. С. 45-49.
6. **Su M., Yang B., Wang X.** Research on integrated design of modular steel structure container buildings based on BIM // Advances in Civil Engineering, 2022, Vol. 2022, 4574676.
7. **Ha T.-H., Cho B.-H., Kim H., Kim D.-J.** Development of an efficient steel beam section for modular construction based on six-sigma // Advances in Materials Science and Engineering, 2016, Vol. 2016, 9687078.
8. **Nadeem G., Safiee N.A., Abu Bakar N., Abd Karim I., Mohd Nasir N. A.** Connection design in modular steel construction: A review // Structures, 2021, Vol. 33, pp. 3239-3256.
9. **Ma H., Huang Z., Song X., Ling Y.** A Study on Mechanical Performance of an Innovative Modular Steel Building

Connection with Cross-Shaped Plug-In Connector // Buildings, 2023, Vol. 13, no. 9, 2382.
10. **Туснина О.А.** Конструктивные решения узлов стального каркаса для малоэтажных жилых зданий // Промышленное и гражданское строительство. 2017. № 11. С. 23-27.
11. **Гатауллина К.Р.** Эффективность применения балок с гофрированной стенкой в балочной клетке // Молодой ученый, 2023, № 20(467). С. 85-90.
12. **Брянцев А.А., Абсиметов В.Э., Лалин В.В.** Эффективность применения двутавров с гофрированными стенками в производственных // Строительство уникальных зданий и сооружений, 2017, №3 (54). С. 93-104.
13. **Бальзанников М.И., Холопов И.С., Соловьев А.В., Лукин А.О.** Применение стальных балок с гофрированной стенкой в гидротехнических сооружениях // Вестник МГСУ, 2013, № 11. С. 34-41.
14. **Tian Z.** Review of Research on Corrugated Web Steel Beams // Journal of Engineering Mechanics and Machinery, 2023, Vol. 8(4), pp. 11-14.
15. **Al-Kannoon M.A., Suhiel I.A.** Experimentally flexural behaviour study of steel beams with corrugated webs // IOP Conf. Series: Materials Science and Engineering, 2020, Vol. 888, 012084.
16. **Соловьев А.В., Лукин А.О., Алпатов В.Ю., Савостьянов В.Н.** Учет особенностей работы балок с гофрированной стенкой в расчетах на стесненное кручение // Вестник МГСУ, 2012, № 11. С. 105-112.
17. **Al-Mawashee H.S. and Al-Kannoon M.A.-A.** Flexural Strength of Castellated Beams with Corrugated Webs // Journal of Physics: Conference Series, 2021, Vol. 1973, 012213.
18. **Elamary A.S., Saddek A.B., Alwetaishi M.** Effect of corrugated web on flexural capacity of steel beams // International Journal of Applied Engineering Research, 2017, Vol. 12(4), pp. 470-481.
19. **Kumar U.M., Reddy D.P., Patel R.R., Pandian M.S., Karthikeyan K.** A study on flexural capacity of steel beams with corrugated web // International Journal of Civil Engineering and Technology, 2018, Vol. 9(4), pp. 679-689.
20. **Kudryavtsev S.** Influence of web openings on bearing capacity of triangularly corrugated web beam // IOP Conf. Series: Materials Science and Engineering, 2018, Vol. 365, 042034.
21. **Zubkov V., Lukin A., Alpatov V.** Experimental research of beams with corrugated web // MATEC Web of Conferences, 2018, Vol. 196, 01005.
22. **Зубков В.А., Лукин А.О.** Экспериментальные исследования влияния технологических и конструкционных параметров на несущую способность металлических балок с гофрированной стенкой // Вестник МГСУ, 2013, №. 2. С. 37-46.
23. **Alekseytsev A.V.** Ensuring the safety of steel moment frames subjected to uncertain impacts // Buildings, 2023, Vol. 13, no. 8, 2038.
24. **Tusnina O., Alekseytsev A.** LOD of a computational numerical model for evaluating the mechanical safety of steel structures. Buildings, 2023, Vol. 13, no. 8, 1941.
25 **Sherman D., Fisher J.** Beams with corrugated webs // Proceedings of the 1st International Specialty Conference on Cold-Formed Steel Structures. Rolla, Missouri, August 19-20, 1971, pp. 198-204.
26. **Ye Z., Berdichevsky V.L., Yu W.** An equivalent classical plate model of corrugated structures // International Journal of Solids and Structures, 2014, Vol. 51(11-12), pp. 2073-2083.

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