

# BUILDING CONSTRUCTIONS, BUILDINGS AND ENGINEERING STRUCTURES

## СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ



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### Prospects for the Use of LEGO Blocks for the Construction of Warehouse and Storage Facilities of the Agro-Industrial Complex

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#### Abstract

**Introduction.** The major task in designing warehouse and storage facilities whose building structures experience horizontal operational loads is not only ensuring strength, load-bearing capacity and permissible vertical deformations (residue), but also stability and operability under the action of horizontal operational loads caused by lateral pressure from the weight of liquids or bulk materials. Traditional constructions of such structures made of monolithic reinforced concrete or metal are characterized by high material consumption, labor intensity and duration of construction (assembly). The article explores the prospects for constructing warehouse and storage facilities from prefabricated blocks of various structures.

**Materials and Methods.** Applied structures and technologies for constructing warehouse and storage facilities have been analyzed, their main disadvantages and issues arising at the stages of construction and operation have been identified. New structures of LEGO blocks and technology for the assembly of prefabricated buildings and structures using the method of vertical reinforcement of masonry for perceiving horizontal operational loads are set forth. Mathematical modeling and calculation of the parameters of the stress-strain state (hereinafter referred to as SSS) of warehouse structures made of LEGO blocks under the action of permanent and temporary operational loads from the weight of liquids or bulk materials has been conducted.

**Research Results.** New designs of LEGO blocks have been developed, a technology of constructing prefabricated warehouse and capacitive objects from them has been set forth, the regional parameters of vertical reinforcement of masonry from LEGO blocks have been identified depending on the height of the structure and the level of filling containers with liquid and bulk materials.

**Discussion and Conclusion.** The results are recommended for use in the design and construction of warehouse and storage facilities for agricultural and other purposes. The introduction of such structures implies an increase in the pace of construction, enhanced quality control of construction and a scientific justification for monitoring a technical condition during operation of a facility.

**Keywords:** storage facilities, warehouses, prefabricated structures, LEGO blocks, mathematical modeling

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Оригинальное эмпирическое исследование

### Перспективы применения ЛЕГО-блоков для возведения складских и емкостных сооружений агропромышленного комплекса

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#### Аннотация

**Введение.** Основной задачей при проектировании складских и емкостных сооружений, строительные конструкции которых воспринимают горизонтальные эксплуатационные нагрузки, является не только обеспечение проч-

ности, несущей способности и допустимых вертикальных деформаций (осадок), но и устойчивость и работоспособность при действии горизонтальных эксплуатационных нагрузок, вызванных боковым давлением от веса жидкостей или сыпучих материалов. Традиционные конструкции таких сооружений из монолитного железобетона или металла отличаются высокой материалоемкостью, трудоемкостью и продолжительностью возведения (монтажа). В статье рассмотрены перспективы строительства емкостных и складских сооружений из сборных быстровозводимых блоков различных конструкций.

**Материалы и методы.** Выполнен анализ применяемых конструкций и технологий возведения емкостных и складских сооружений, выявлены их основные недостатки и проблемы, возникающие на стадиях строительства и эксплуатации. Предложены новые конструкции ЛЕГО-блоков и технология монтажа быстровозводимых зданий и сооружений с использованием метода вертикального армирования кладки для восприятия горизонтальных эксплуатационных нагрузок. Выполнено математическое моделирование и расчет параметров напряженно-деформированного состояния (далее – НДС) конструкций складских сооружений из ЛЕГО-блоков, возникающего при действии постоянных и временных эксплуатационных нагрузок от веса жидкостей или сыпучих материалов.

**Результаты исследования.** Разработаны новые конструкции ЛЕГО-блоков, предложена технология сооружения из них быстровозводимых складских и емкостных объектов, определены рациональные параметры вертикального армирования кладки из ЛЕГО-блоков в зависимости от высоты сооружения и уровня заполнения емкостей жидкими и сыпучими материалами.

**Обсуждение и заключения.** Полученные результаты рекомендуется использовать при проектировании и строительстве емкостных и складских сооружений сельскохозяйственного и иного назначения. Внедрение таких конструкций предполагает увеличение темпов строительства, улучшение контроля качества возведения и научное обоснование мониторинга технического состояния в процессе эксплуатации объекта.

**Ключевые слова:** емкостные сооружения, склады, быстровозводимые конструкции, ЛЕГО-блоки, математическое моделирование

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**Introduction.** The design and construction of warehouse and storage facilities has a number of features that are determined primarily by their purpose and the technological processes provided for at such facilities. In this article, we will consider agricultural facilities designed for long-term storage of bulk (grain, seeds, granular fertilizers, compound feed, etc.) and liquid (water, molasses, mineral fertilizers of the CAS type (carbamide-ammonia mixture)) materials.

For long-term storage of bulk materials in agriculture, one-story frame-type warehouses are commonly used whose structures and engineering systems are designed to store a certain type of products, e.g., grain, vegetable and potato, corn storages, etc. The design of the load-bearing structures of such warehouses depends on a product storage method and thereby the distribution of operational loads. While storing products (grains, seeds, vegetables) in bulk, considerable horizontal loads can be transferred to the warehouse walls depending on the filling height, specific gravity of products, as well as adhesion and friction between particles, similar to sand, crushed stone and other dispersed soils (materials).

Another common type of storage of agricultural products are bunker (storage) and silo (tower) tanks. In manufacturing or installing them, both monolithic reinforced concrete or reinforced concrete blocks and steel structures are used: metal sheets, thin-sheet wavy steel sections, etc.

There has been well-known scientific research conducted in the field of design and construction of warehouse and storage facilities, including agricultural ones reported in dissertations by Goldenberg L.I. [1], Sazanbaev S.K. [2], Streltsov I.V. [3], Karsunkin V.V. [4], Rashchepkin S.V. [5], Feidengold V.B. [6], Markovich A.S. [7], etc. In them the operation of structures of warehouse and storage facilities under various types of loads that occur both during construction and during operation of facilities, including loading and unloading processes was investigated accounting for technological features, climatic factors, etc. The methods of theoretical and structural mechanics were employed. Based on the research, rational designs of warehouses, silos, bunkers, elevators and other agricultural facilities have been developed, as well as rules and recommendations for the safe operation of such facilities accounting for the special features of the technological processes occurring in them and the requirements for ensuring climatic parameters (temperature, humidity, air mobility).

Such facilities are facing increased technical, economic and operational requirements, including ensuring high efficiency and reliability throughout the whole life cycle of a facility. The development of new constructive and technological solutions in designing, constructing, operating and dismantling of warehouse and storage facilities for the agro-industrial complex is thus an urgent scientific and practical task.

The aim of this article is to analyze the advantages and disadvantages of the existing warehouse and storage facilities used in the agro-industrial complex as well as to develop new design and technological solutions based on using prefabricated LEGO blocks to ensure high construction efficiency and long-term safety of such facilities.

**Materials and Methods.** The major research methods employed in preparing the study include:

- analysis of the results of modern scientific studies and of domestic and foreign experience in designing, constructing and operating warehouse and storage facilities;
- identification of the advantages and disadvantages of the structures being used, assessment of modern requirements for such facilities and outlining promising areas for improving them, including exploring the possibility of making use of prefabricated LEGO blocks for constructing load-bearing structures of warehouses and reservoirs;
- design work on developing and substantiating the parameters of universal LEGO blocks to allow reinforced masonry bearing structures of warehouses and reservoirs to be designed;
- design of mathematical models of warehouse structures built from LEGO blocks and study of their VAT parameters resulting from combinations of constant and operational loads from the lateral pressure of stored bulk and liquid materials while varying the height of the structure, of the filling (liquid level), physical and mechanical properties of bulk and density of liquid materials;
- development of the recommendations for designing load-bearing walls of warehouses and tanks (height, thickness, reinforcement, etc.) depending on the properties and height of the filling of stored products.

According to an analysis of the currently used structures of agricultural warehouses, single-storey frame buildings with one, two or more (less frequently) spans consisting of columnar foundations, columns, beams or floor trusses, cross-bars, girders, inclined connections, etc., have become common. Such buildings typically include external enclosing structures made of sandwich panels, corrugated board, and other lightweight elements that are not load-bearing ones and are not capable of withstanding a horizontal operational load from the lateral pressure of bulk material or products. In this case, additional load-bearing vertical walls (monolithic or prefabricated ones) have to be erected inside such warehouses that separate different materials or grades of stored products and absorbing lateral pressure (Fig. 1a). Construction of a metal frame and of monolithic reinforced concrete walls up to a certain height for filling bulk materials (products) (Fig. 1b) can be combined. This increases material consumption, labor intensity and cost of constructing warehouse and storage facilities. With a small filling height at the edges of the building, wall panels can also perceive a lateral load transmitting an operational load through load-bearing metal columns with buttresses and additional connections (Fig. 1c).

Similar design solutions are employed in foreign practice of building and operating warehouses of the agro-industrial complex. Fig. 2 shows typical buildings constructed by Accu-Steel, USA [8] and intended for storage of bulk agricultural products. Load-bearing walls perceiving horizontal pressure from bulk material are designed from low wall panels (Fig. 2a), masonry from reinforced concrete blocks (Fig. 2b) or LEGO blocks in combination with buttresses allowing an increase in a lateral load.

Solutions for warehouse and storage facilities with vertical monolithic reinforced concrete walls can provide both load-bearing capacity and stability under lateral loads and are also employed in the agro-industrial complex in the form of silo-type and warehouse-type storages (with a floor storage) [9]. However, they also possess a few disadvantages due to some structural, technological and operational factors. The major issues during construction of monolithic reinforced concrete storage facilities include: poor or unstable concrete quality (distinct "layering" or "rubble", a lot of unfilled cavities and obviously unvibrated layers) resulting in crumbling of wall concrete in horizontal sections and thereby a reduced service life and rapidly occurring emergencies. On top of that, construction of such facilities calls for a very high quality that can be provided by few construction organizations with extensive experience in the field. Reinforced concrete structures are more labor-intensive and 20-30% more costly, e.g., granaries with round metal silos of a large diameter that have begun to substitute them [10].



Fig. 1. Examples of domestic metal-framed structures of warehouses for storing agricultural products: *a* – with prefabricated inner walls accepting horizontal operational load; *b* – with external load-bearing reinforced concrete walls at the filling height; *c* – with wall panels, rod buttresses and additional connections



Fig. 2. Examples of typical buildings for the agro-industrial complex of Accu-Steel, USA: *a* – vaulted form made of metal frame and fabric covering with low side panels (Advantage series); *b* – with a gable roof made of metal frame, external and internal walls made of reinforced concrete blocks to accommodate an operational horizontal load (Crossover series); *c* – a parabolic-shaped frame made of metal trusses and low load-bearing walls made of reinforced concrete LEGO blocks with the same buttresses (Integrity series) [8]

Metal containers (silos, bunkers, tanks, etc.) are also commonly used in the agro-industrial complex for storing both bulk and liquid products. Along with the unquestionable advantages of such structures (compactness due to a vertical location, durability, quick installation, easy operation during loading and unloading), they possess a few disadvantages, particularly:

- high thermal conductivity of metal that might have a negative effect on the storage of products such as grain;
- danger of corrosion wear of metal and need for constant corrosion protection during operation;
- condensation of moisture on the inner walls that might cause spoilage of grain, its self-heating and loss of its consumer, feed and seed properties;
- high sensitivity of vertical tanks to uneven laying of the base. Based on our experience, a few cases of rolls and over-design deformations of metal tanks used for storing liquid foodstuffs are known causing their further operation to become impossible without costly measures taken in order to level the rolls and strengthen the foundations [11]. Constant geotechnical monitoring [12] is also needed accounting for the mutual influence of both the reservoirs themselves on each other and the surrounding buildings [13];
- stress-strain state of the metal shell of the tanks that constantly changes due to loading and unloading, and the absolutely flexible "metal bottom – ground base" system for typical tanks with ring foundations built only under the walls [14].

Based on the analysis of the advantages and disadvantages of the existing structures of warehouse and storage facilities for the agro-industrial complex, the following conclusions can be made:

- most frame buildings used for this are considerably limited in their height due to an inability to perceive considerable horizontal operating loads caused by lateral pressure of bulk products or materials (grain, potatoes, fertilizers, etc.);
- the task of developing effective design solutions to ensure high construction rates and reliable operation with considerable lateral pressure on the load-bearing walls is a relevant one;
- a promising direction for improving structures of buildings in the agro-industrial complex is the use of prefabricated concrete LEGO blocks;
- the major issues with introducing such structures is the insufficient load-bearing capacity while working on horizontal operating loads, as most of these blocks are laid "on the dry" and do not have masonry reinforcement.

We are attempting to develop and scientifically substantiate the parameters of reinforced masonry made of concrete LEGO blocks to allow for the construction and operation of high storage facilities with a high degree of loading (to a high filling height) while maintaining stability and reliability throughout the whole life cycle of a facility.

**Research Results.** Concrete LEGO blocks are being manufactured by a variety of companies both in Russia and abroad. There is a well-known positive experience in designing and constructing buildings made of LEGO blocks (Fig. 3a) and LEGO bricks (Fig. 3b) in Siberia [15].

The size of a regular block: length – 500 mm; height – 220 mm; width – 250 mm. The special geometry of the shaped blocks ensures convenient installation and reliable connection.

Depending on the type of a building, three different technologies of construction from LEGO blocks are recommended [15]:

- laying with no mortar;
- mortar-free installation with reinforcement;
- laying on mortar.

As the major disadvantages of such blocks, in [15] an impossibility of erecting tall buildings and structures, insufficient testing of the use of such blocks in construction practice, as well as the lack of a regulatory framework are outlined.

The IS GROUP Engineering and Construction production group produces foundation LEGO blocks of the FBS series (Fig. 4) [16].

Manufacturers point the following out as the major advantages of such blocks [16]:

- fast construction – a structure with an area of about 50 m<sup>2</sup> can be erected in as little as an hour;
- no need for bonding mortar or reinforcement – the tongue-and-groove joint system is not only convenient, but also allows one to save on the purchase of mortar and fittings;
- multiplicity – LEGO blocks are easy to assemble and easy to disassemble. They can be used multiple times and applied on a range of objects and for different purposes;

- reliable adhesion – the building blocks are characterized by a high level of adhesion accuracy to secure structural strength throughout their entire service life and to enable them to withstand a wide range of loads and impacts;
- independence from a season – LEGO blocks can be built regardless of the time of year and weather conditions. The product itself and its assembly technologies are "weather-resistant". One does not have to wait for favourable weather or special temperatures to install it, which means neither downtime no money losses are involved;
- LEGO blocks are ideal for construction of prefabricated temporary buildings and low-load structures. This is a cutting-edge highly aesthetic European technology that delivers high-quality results at affordable costs. The required number of blocks is purchased once and reused following a demolition.



Fig. 3. Prefabricated structures used in Siberia:

*a* — LEGO blocks, *b* — LEGO bricks; *c* — an example of masonry made of polystyrene concrete blocks with no mortar [15]

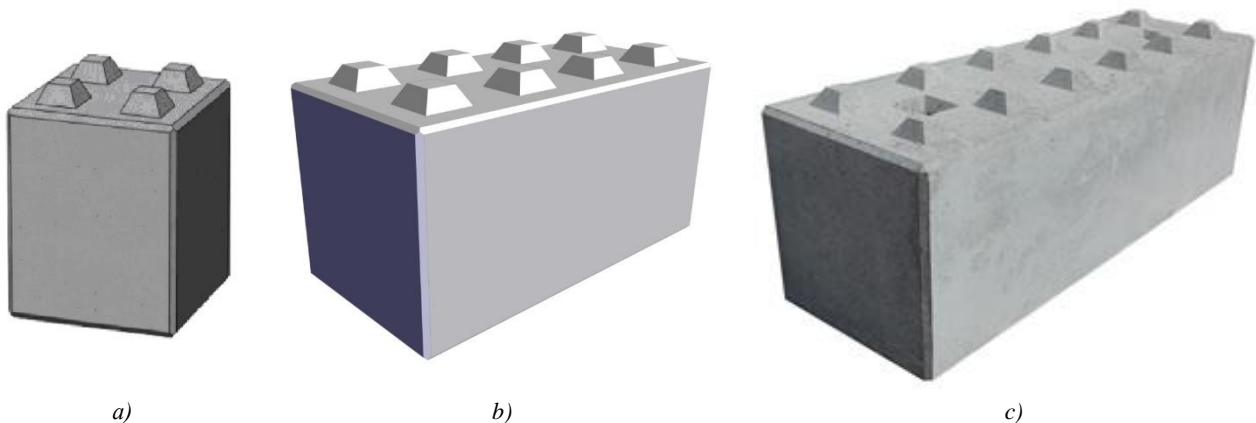


Fig. 4. IS GROUP foundation LEGO blocks [16]: *a* – FBS 6-6-6; *b* – FBS 12-6-6; *c* – FBS 24-6-6 [16]

In the Rostov region, concrete LEGO blocks of different sizes are produced:

- Ferroconetoninvest LLC (Rostov-on-Don) — 21 standard sizes of FBS foundation blocks [17];
- Mineral Trading House LLC (Tselina town) — 10 standard sizes of universal concrete LEGO blocks [18].

In 2025 TD Mineral LLC developed Technical specifications 23.61.12-001-86245892-2025 "Lego-Type Concrete Blocks" according to which blocks are manufactured of heavy concrete according to GOST 26633-2015 "Heavy and Fine-Grained Concretes" with the following characteristics:

- concrete compressive strength class — at least B20;
- water resistant — W4;
- frost resistance — F1 100 according to the 1<sup>st</sup> basic method.

The technical specifications indicate the following areas of application for these blocks:

- zoning of premises (construction of compartments and niches for a separate storage, e.g., of agricultural products within a facility);
- durable, non-removable formwork for monolithic construction;
- construction of walls and basements, internal partitions;
- construction of retaining walls;
- construction of storage and utility rooms.

In 2024-2025, in the territory of JSC Tselinskagrokhimservice (Tselina town, Rostov region), a one-storey warehouse building for storing agricultural products (basement-free, pentagonal according to the plan, with the total dimensions of 96.5×48.5 m) was erected from LEGO blocks of TD Mineral LCC with the following characteristics:

- the maximum height of the building is 14.0 m;
- the level of responsibility is normal (II);
- the degree of durability — II (at least 50 years);
- the degree of fire resistance — II;
- the building area is 4347 m<sup>2</sup>.

Employees and graduate students of the Department of Engineering Geology, Bases and Foundations at the Don State Technical University, commissioned by JSC Tselinskagrokhimservice, were tasked with an inspection of the technical condition of a building (at the stage of incomplete construction) and scientific and technical support for its construction. The major goal of the Contractor was to identify whether walls from LEGO blocks could be loaded with horizontal operational loads from bulk and liquid materials. The general view (individual facades) and structural elements of the warehouse building are in Fig. 5.

Here is what the survey concluded. The structural scheme is a frame one: load-bearing combined columns (the lower part is reinforced concrete, the upper one is metal); metal girders and roof trusses. The spatial rigidity of the building is ensured by the joint work of columns of LEGO blocks with monolithic cores, a monolithic reinforced concrete belt at a height of 6.0 m around the entire perimeter of the building and metal roof trusses. Due to the complexity of the building configuration, a large number of elements with different rigidity, and the heterogeneity of the soil base, the finite element method was employed, which had been properly tested in solving similar problems in a three-dimensional formulation [19, 20]. In order to assess the VAT of structures from the effects of combinations of permanent and temporary loads, a three-dimensional finite element model of the building was developed. In order to design the initial geometric model of the building, constructive solutions were adopted with the dimensions of the elements identified during the measurement. The general view of the 3D model of the warehouse building is shown in Fig. 6.

The model accounts for all of the supporting elements: columns, walls, metal frame trusses with the precise purpose of the rod sections according to the survey. At the 1<sup>st</sup> stage of modeling, the geometric variability of the scheme was identified with the existing truss design solution. 4 options for reinforcing structures with additional core elements were thus explored, and the 1<sup>st</sup> reinforcement option was recommended, i.e., installing additional strut rods between the lower girdle of the trusses and the metal column, as well as of additional connections between the trusses in order to increase the overall rigidity of the frame. At the same time, those were only constant loads, snow and wind that were specified.



a)

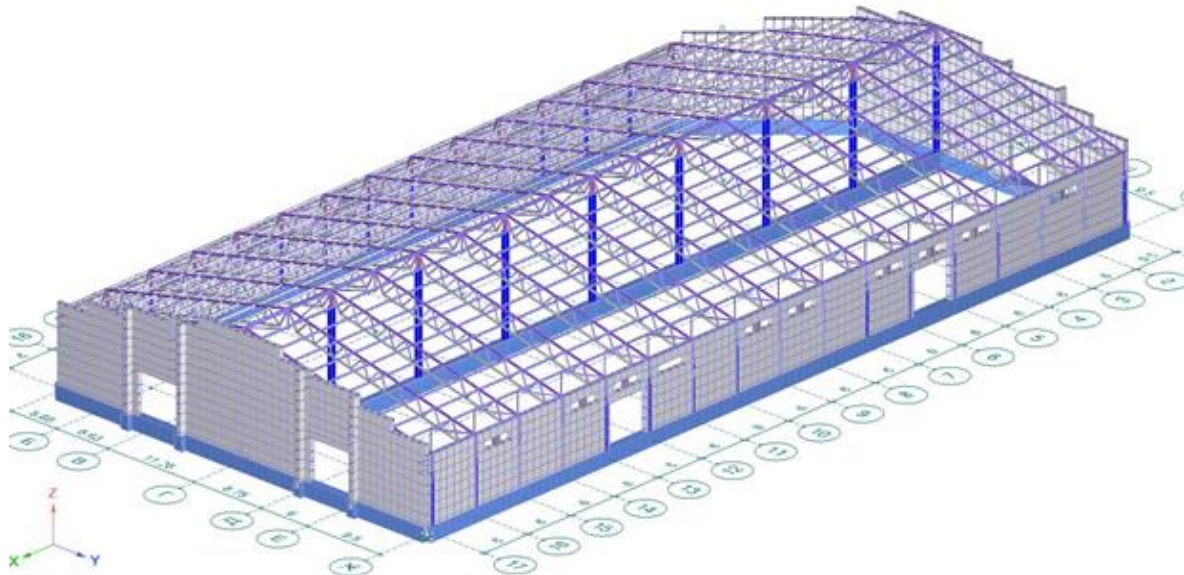


b)

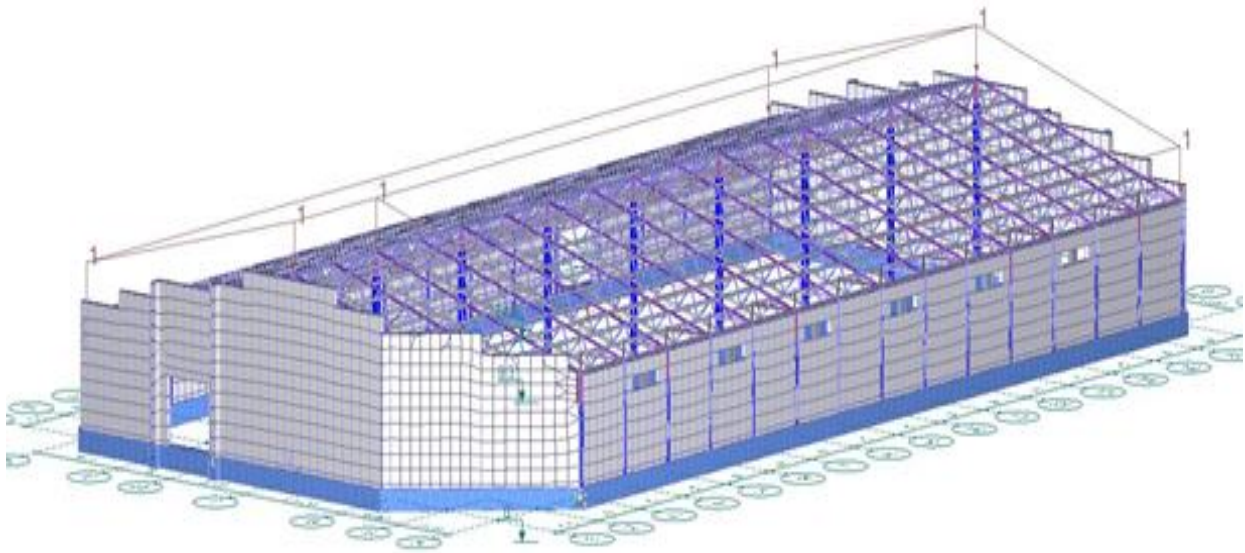


c)

Fig. 5. Examined building of an agricultural warehouse under construction with exterior walls made of LEGO blocks (Tselina town, February 2025): a — facade in axes A–W; b — facade in axes 17–1; c — frame elements



a)



b)

Fig. 6. General view of the 3D model of the building: *a* — view from the facades A–G and 17–1; *b* — view from the facades G–A and 1–17

At the 2<sup>nd</sup> stage of the simulation, the operability and stability of the structure against horizontal operating loads were tested that resulted in the loss of stability of structures of non-reinforced walls made of LEGO blocks being established even with minimal loading of bulk material (with grain). Due to no chance of using non-reinforced walls made of concrete LEGO blocks for perceiving calculated operational loads, scientific and technical cooperation with Tselinskagrokhim-service JSC was commissioned by the employees of the DSTU Department of Engineering Geology, Basements and Foundations, which included:

- examining positive and negative experiences of construction and operation of buildings and structures made of LEGO blocks;
- analyzing the advantages and disadvantages of the well-known LEGO blocks, as well as buildings and structures built from them;
- developing constructive solutions to improve LEGO blocks in order to reinforce the masonry of these blocks;
- analyzing the operational loads acting on load-bearing walls from the storage of various materials and products: liquid fertilizer and grain;
- developing a computer model of a wall made of LEGO blocks in the Lira 10 PC and assessing the stress-strain state under various loads and wall heights;
- developing the recommendations for designing load-bearing reinforced walls made of LEGO blocks.

The major aim of the study is scientific substantiation and development of technical solutions to allow the use of concrete LEGO blocks in load-bearing structures that accept horizontal operational loads. Due to a possibility of storing liquid and bulk materials with different densities of  $\rho$ ,  $t/m^3$  inside the premises (containers) made of LEGO blocks, the calculation and selection of reinforcement of masonry made of LEGO blocks was performed for walls up to 15 m high at operating loads up to 13 m high for 2 different options:

- depending on the weight of the fertilizer-32 ( $\rho = 1.32 t/m^3$ );
- from the weight of the grain ( $\rho = 0,8 t/m^3$ ) accounting for the dynamic loads from the loader.

As a result of the analysis of domestic [15–18, 23] and overseas [21, 22, 24–26] experiences in designing and constructing buildings and structures made of LEGO blocks, including those designed using 3D printing [24], it was found that the major disadvantage of masonry made of such blocks is its low resistance to horizontal (shear and tipping) loads that might occur during the operation of buildings and structures for storing bulk and liquid materials.

In this case, there are tensile stresses in the masonry causing excessive deformations and even complete destruction of such structures, which has been confirmed by some negative experiences of operating them.

Reinforcement of individual blocks would increase the strength of each block rather than the strength of their connection to each other. The main direction of improving the masonry of concrete LEGO blocks is thus its reinforcement with vertical reinforcing rods connecting a few concrete blocks in height. This solution serves to significantly increase the strength of the masonry and creates favorable conditions for perceiving horizontal operational loads from the weight of bulk or liquid materials.

In order to enable reinforcement of masonry in LEGO blocks, solid vertical holes are to be provided during their manufacture that can be formed by placing them in the form of removable rods or pipes of a specified diameter. While designing LEGO blocks that enable their vertical reinforcement, an essential engineering task is to select the rational placement of holes in the block. While solving the problem at hand, the following factors were accounted for:

- geometric parameters of the blocks and the distance in a row between the axes of adjacent spike-groove joints (250 mm);
- a protective layer of concrete to the operating reinforcement as specified in Table 2 of GOST 13015-2015 "Concrete and Reinforced Concrete Products for Construction", from 15 to 35 mm, depending on the operating conditions of the building structures;
- stress distribution in the masonry under horizontal operational loads.

As the maximum tensile stresses in the masonry from horizontal operational loads will be in the upper blocks from the side of the load (from inside the building or structure), the reinforcement and thereby the vertical holes in the blocks under it must be shifted towards the side of the load.

Given all of the above, the suggested design of the improved LEGO block provides for vertical holes with a diameter of 50 mm located at a distance of 250 mm from each other. The distance from the axis of the holes to the inner side of the block is 125 mm, so the protective layer of concrete will be  $100 \text{ mm} \pm 15 \text{ mm}$ . An example of the design of such an improved LEGO block for the standard size  $500 \times 1500 \times 600 \text{ mm}$  is in Fig. 7.

Vertical holes for reinforcing masonry in blocks of other standard sizes are formed in a similar way to the above drawing.

For the developed LEGO blocks, the VAT of wall structures was calculated and the required reinforcement was selected. Two impacts are perceived by the wall structures: net weight and lateral pressure from the useful load. The useful load is represented by the hydrostatic pressure of the liquid fertilizer KAS-32 or the pressure of the bulk medium, i.e., grain (wheat). The walls are made of masonry concrete LEGO blocks on a cement-sand mortar. The thickness of the blocks is 500 mm. The concrete class accepted for calculation is B25.

Table 1 shows the physical and mechanical characteristics of the grain used for load modeling and calculation. As the load from wheat is the most disadvantageous one, it was decided to calculate the impact of this type of bulk medium.

The lateral pressure on the wall from the bulk medium is given by the formula:

$$P = \gamma \cdot h \cdot \text{tg}^2(45^\circ - \varphi/2),$$

where  $\gamma$  is the specific gravity of wheat,  $\text{kN/m}^3$ ;  $h$  is the height of the filling, m;  $\varphi$  is the angle of internal friction, degrees.

The results of calculating the pressure on the wall from the weight of the grain depending on the height of the filling are summarized in Table 2.

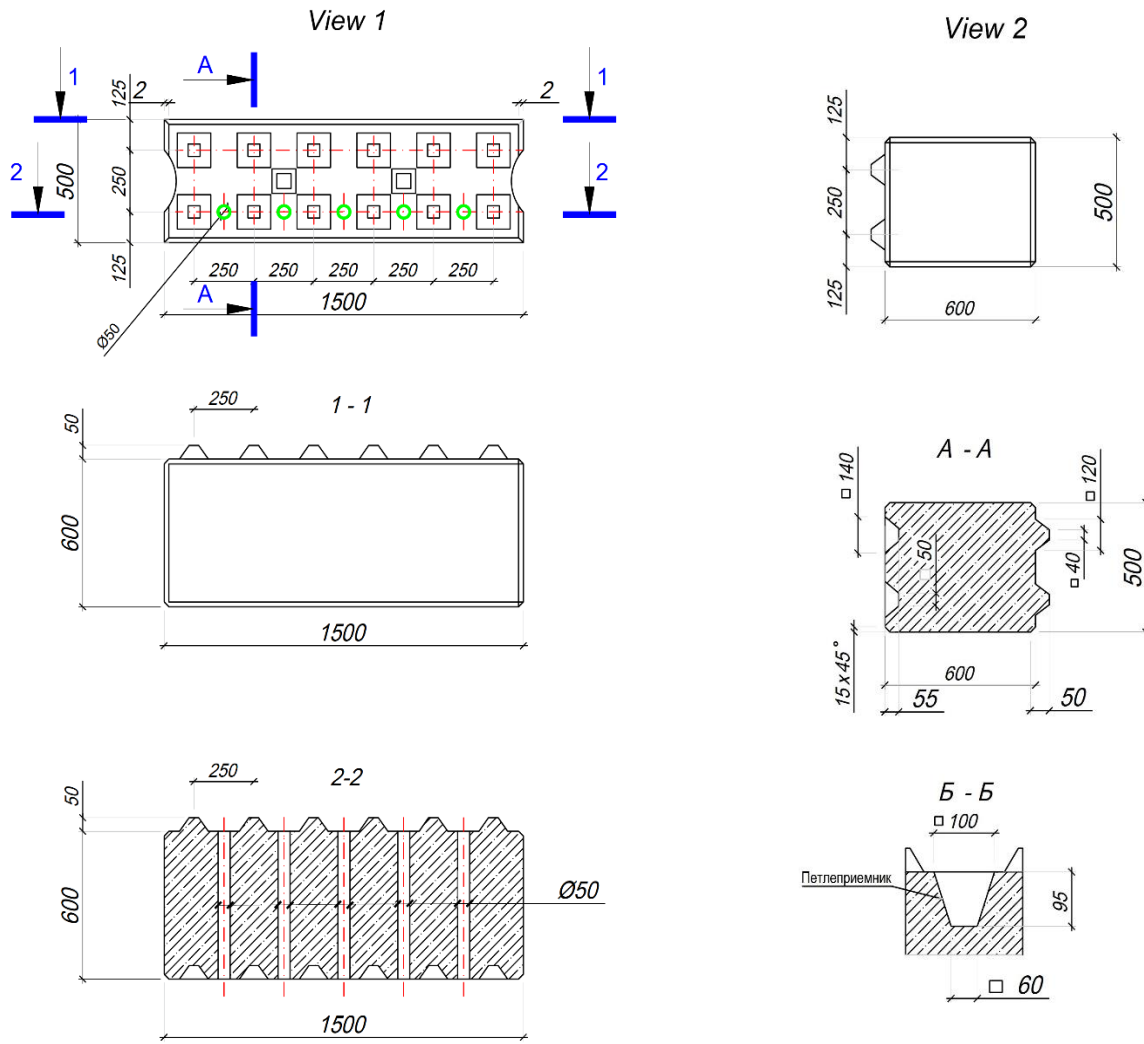


Fig. 7. Design of an improved LEGO block for the formation of reinforced masonry

Table 1

Physical and mechanical characteristics of the grain

Grain material	Average grain diameter $d$ , mm	External friction angle $\psi$ , °	Internal friction angle $\varphi$ , °	Humidity, %	Density $\rho$ , kg/m <sup>3</sup>
Wheat	3.8	22.1	17.5	14.4	808
Sunflower	5.0	26.6	16.7	14.7	450
Corn	7.1	22.4	18.4	16.6	783
Millet	2.2	20.2	15.1	15.0	770

Table 2

Calculated pressure on the wall depending on the weight of the grain

Filling height, m	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum pressure at the lower face, kPa	13	17	22	26	30	34	39	43	47	52	56	60	65

The formula for calculating the pressure from liquid fertilizer CAS-32 is as follows:

$$P = \gamma \cdot h,$$

where  $\gamma$  is the specific gravity of liquid fertilizer CAS-32, kN/m<sup>3</sup>;  $h$  is the height of the hydrostatic column, m.

The results of calculating the pressure on the wall from the liquid fertilizer CAS-32 depending on the height of the hydrostatic column are summarized in Table 3.

Table 3

Pressure on the wall from CAS-32

Height of the hydrostatic column, m	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum pressure at the lower face, kPa	39.6	52.8	66.0	79.2	92.4	105.6	118.8	132.0	145.2	158.4	171.6	184.8	198.0

The reinforcement pitch in the block is 250 mm with a connection to the outer face is 100 mm.

The loads on the walls from the hydrostatic pressure of the fertilizer CAS-32 with a column height of 3 to 7 m for walls with a height of 3 to 15 m were calculated. The summary of the maximum wall movements under operational loads in comparison with the maximum permissible movements, mm (according to Table L2 SP 20.13330.2016 "Loads and Impacts") is shown in Table 4.

According to Table 4, the height of the hydrostatic column of liquid (CAS-32) should not be over 6 m. With a higher fluid height, structural deformations are above those allowed for any wall height (7–15 m). In Table 4 and 5, the values of horizontal displacements that are unacceptable according to SP 20.13330.2016 are highlighted in red.

Table 4

Summary of horizontal movements of wall structures under the liquid fertilizer CAS-32

		Maximum horizontal movement, mm												
		at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Height of the hydrostatic column CAS-32, m	3	0.37	0.52	0.67	0.83	0.98	1.13	1.29	1.44	1.59	1.75	1.9	2.05	2.21
	4		1.55	2.04	2.52	3.01	3.49	3.98	4.47	4.95	5.44	5.92	6.41	6.89
	5			4.74	5.93	7.12	8.3	9.49	10.7	11.9	13.1	14.3	15.4	16.6
	6				11.8	14.3	16.7	19.2	21.7	24.1	26.6	29.1	31.5	34
	7					25.6	30.1	34.7	39.3	43.9	48.4	52	57.4	62.2
Maximum permissible horizontal movement, mm (SP 20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

The loads on the walls from the lateral pressure of the grain mound with a height of 3 to 9 m for walls with a height of 3 to 15 m were calculated. The summary of the maximum wall movements due to operational loads in comparison with the maximum permissible movements, mm (according to Table L2 SP 20.13330.2016) is shown in Table 5.

Table 5

Summary of horizontal movements of wall structures under the action of the grain

		Maximum horizontal movement, mm												
		at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Grain filling height, m	3	0.15	0.21	0.27	0.33	0.39	0.45	0.51	0.59	0.63	0.69	0.75	0.81	0.87
	4		0.6	0.79	0.97	1.16	1.35	1.54	1.73	1.91	2.1	2.29	2.48	2.66
	5			1.9	2.4	2.9	3.3	3.8	4.3	4.8	5.2	5.7	6.2	6.7
	6				4.7	5.6	6.6	7.6	8.5	9.5	10.5	11.5	12.4	13.4
	7					9.96	11.7	13.5	15.3	17.1	18.9	20.7	22.4	24.2
	8						19.3	22.3	25.3	28.3	31.3	34.4	37.4	40.4
	9								35.4	40.4	45.3	50.2	55.2	60.1
Maximum permissible horizontal movement, mm (according to SP20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

According to Table 5, the height of the grain filling should not be over 8 m. With a higher height of the grain filling, structural deformations exceed those allowed for any wall height (9–15 m).

As a result of modeling all the possible combinations of wall height and load height from liquid fertilizer CAS-32 and grain filling, the recommended masonry reinforcement parameters are calculated as shown in Table 6 and 7, respectively. The tables show both the values of the total reinforcement area per 1 square meter of the wall structure and the specific diameters of the reinforcement rods calculated based on the reinforcement pitch of 250 mm (i.e., 4 rods per 1 square meter).

Table 6

Summary of the required reinforcement at the stretched face of the wall structures under the liquid fertilizer CAS-32, cm<sup>2</sup> per 1 p. m. (at a pitch of 250 mm)

		Required reinforcement area, cm <sup>2</sup> , and reinforcement diameter, mm												
		at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Height of the hydrostatic column CAS-32, m	3	2.60 Ø10	2.39 Ø10	2.14 Ø10	1.96 Ø8	1.78 Ø8	1.59 Ø8	1.41 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	
	4		7.49 Ø16	7.57 Ø16	7.29 Ø16	7.02 Ø16	6.78 Ø16	6.87 Ø16	6.63 Ø16	6.21 Ø16	6.09 Ø14	5.91 Ø14	5.73 Ø14	5.57 Ø14
	5			17.1 Ø25	16.7 Ø25	17.0 Ø25	16.6 Ø25	16.9 Ø25	16.5 Ø25	16.1 Ø25	16.5 Ø25	16.1 Ø25	15.7 Ø25	15.3 Ø25
	6				35.1 Ø36	33.9 Ø36	35.0 Ø36	34.3 Ø36	33.7 Ø36	34.8 Ø36	34.2 Ø36	33.5 Ø36	34.6 Ø36	34.0 Ø36
	7					<b>62.0</b>	<b>60.9</b>	<b>62.9</b>	<b>61.8</b>	<b>60.7</b>	<b>62.5</b>	<b>61.2</b>	<b>59.9</b>	<b>61.4</b>
Maximum permissible horizontal movement, mm (according to SP20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

Note: based on the minimum percentage of reinforcement, it is recommended that rods with a diameter of at least 14 mm are used.

Table 7

Summary of the required reinforcement at the stretched face of the wall structures from the action of grain, cm<sup>2</sup> per 1 p. m. (at a pitch of 250 mm)

		Required reinforcement area, cm <sup>2</sup> , and reinforcement diameter, mm												
		at the wall structure height, m:												
		3	4	5	6	7	8	9	10	11	12	13	14	15
Grain filling height, m	3	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8
	4		2.21 Ø10	1.94 Ø8	1.76 Ø8	1.57 Ø8	1.4 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8	1.25 Ø8
	5			5.53 Ø14	5.32 Ø14	5.11 Ø14	4.92 Ø14	4.74 Ø14	4.56 Ø14	4.38 Ø12	4.21 Ø12	4.04 Ø12	3.89 Ø12	3.70 Ø12
	6				10.6 Ø20	10.6 Ø20	10.4 Ø20	10.1 Ø18	10.3 Ø20	9.94 Ø18	9.65 Ø18	9.83 Ø18	9.55 Ø18	9.06 Ø18
	7					18.8 Ø25	18.3 Ø25	18.7 Ø25	18.3 Ø25	17.8 Ø25	18.3 Ø25	17.8 Ø25	17.4 Ø25	17.9 Ø25
	8						32.1 Ø32	31.5 Ø32	30.9 Ø32	30.3 Ø32	31.2 Ø32	30.7 Ø32	30.0 Ø32	31.0 Ø32
	9								<b>52.3</b>	<b>51.0</b>	<b>52.3</b>	<b>50.8</b>	<b>52.1</b>	<b>51.4</b>
Maximum permissible horizontal movement, mm (according to SP20.13330.2016)		10	13.3	16.7	20	23.3	26.7	30	33.3	36.7	40	43.3	46.7	50

Note: based on the minimum percentage of reinforcement, it is recommended that rods with a diameter of at least 14 mm are used.

The following possible connections are recommended for reinforcing bars in the masonry of LEGO blocks (according to SP 63:13330.2018 "Concrete and Reinforced Concrete Structures"): threaded coupling; crimped coupling; lap-welded according to GOST 14098-2014 "Joints of Welded Fittings and Embedded Products of Reinforced Concrete Structures" (type C23). The length of the reinforcement joint must be accepted in compliance with SP 63.13330.2018 and the recommendations of the coupling manufacturer.

**Conclusion.** Based on the analysis of spatial planning and architectural solutions of warehouse and storage buildings and structures of the agroindustrial complex, single-storey frame-type warehouses, bunker (storage) and silo (tower) tanks have been found to be primarily used in both domestic and overseas practice. The major feature of the operation of such facilities is the time-varying horizontal operating loads from the weight of liquids or bulk materials. The analysis of the advantages and disadvantages of the existing agricultural storage facilities has revealed the relevance of developing new highly effective, prefabricated, reliable and safe throughout the life cycle of constructive and technological solutions for such facilities. Using the example of an agricultural warehouse building under construction in Tselina town of the Rostov region, its technical condition, measurement work were examined, the engineering and geological conditions were investigated, and a mathematical 3D model was developed using which the VAT of structures for operating loads was studied. As a result of the simulation, it was found that the masonry of non-reinforced LEGO blocks does not provide structural strength even with a minimum loading height of bulk or liquid material.

The major direction of improving the masonry of LEGO concrete blocks is its reinforcement with vertical reinforcing rods connecting a few concrete blocks in height. The solution serves to significantly increase the strength of the masonry and creates favorable conditions for perceiving horizontal operational loads from the weight of bulk or liquid materials. The authors have thus improved the design of concrete LEGO blocks produced by TD Mineral LLC according to TU 23.61.12-001-86245892-2025 "Concrete Blocks of the Lego Type". The suggested design of the improved LEGO block provides for vertical holes with a diameter of 50 mm located at a distance of 250 mm from each other. The distance from the axis of the holes to the inner side of the block is 125 mm, so the protective layer of concrete will be  $100 \text{ mm} \pm 15 \text{ mm}$ . The blocks in the masonry must be oriented with the reinforced side in the direction of the horizontal operating load from the side of the bulk or liquid material. Mathematical models have been employed in order to select rational reinforcement parameters for LEGO block masonry for various combinations of warehouse height and height of bulk material (grain) or dense liquid (fertilizer CAS-32).

The results presented in the article can be routinely used in design and construction of warehouse and storage facilities of the agro-industrial complex, while the major advantages of implementing the suggested structural solutions of reinforced masonry from LEGO blocks are high construction rates, adaptability, possibility of increasing horizontal loads from bulk or liquid materials on external load-bearing walls, a more rational use of the internal volume of the premises, etc.

The new design solution enables one to reinforce LEGO blocks and build warehouses up to 10–15 m high while filling with grain up to 8 m or filling with fertilizer KAS-32 up to a height of 6 m. This greatly expands the scope and technical and economic indicators of such facilities. The recommended schemes for reinforcing masonry made of LEGO blocks with rational combinations of the specified maximum wall height and the height of loading warehouses with products will optimize storage costs while maintaining the operational reliability of a facility throughout its life cycle.

As a follow-up, it is planned to develop curved LEGO blocks for forming round objects (silos, bunkers) as well as a system for monitoring the stress-strain state of such structures throughout their entire operation period.

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**AYu Prokopov:** formation of the basic concept, aims of the study, modeling and calculations, analysis of the research results, revision of the manuscript, correction of the conclusions.

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