

СТРОИТЕЛЬНЫЕ МАТЕРИАЛЫ И ИЗДЕЛИЯ CONSTRUCTION MATERIALS AND PRODUCTS

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Determination of Key Quality Indicators of Multilayer Building Structures

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Abstract. The development of layered structures represents a viable and promising avenue in the field of construction, as their utilization has the potential to significantly enhance strength characteristics, resistance against external forces, as well as enhance the thermal and acoustic insulation properties of buildings and structures. The aim of this study is to investigate the diversity and benefits of utilizing multilayer building components as an alternative to conventional structures, as well as to analyze the characteristics of their operation. Based on the findings of the study, it can be inferred that multilayered structures offer enhanced thermal and acoustic insulation characteristics, which contribute to the creation of a more comfortable living and working environment. Additionally, these structures can significantly decrease the weight of buildings, leading to potential savings in foundation and other structural components.

Keywords: multilayer structures, rubber-based concrete, additive technologies, corrugated structures, wall systems

Conflicts of interest. The authors declare that there is no conflict of interest.

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Определение основных показателей качества многослойных строительных конструкций

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Аннотация. Разработка слоистых конструкций — перспективное направление в области строительства. Использование данного типа конструкций имеет потенциал для значительного повышения прочностных характеристик, устойчивости к внешним силовым воздействиям, а также улучшения тепло- и звукоизоляционных свойств зданий и сооружений. Цель работы — исследование разнообразия и преимуществ применения многослойных строительных элементов в качестве альтернативы традиционным конструкциям, а также анализ особенностей их функционирования. На основании полученных результатов исследования можно сделать вывод, что многослойные конструкции обладают улучшенными тепло- и звукоизоляционными характеристиками, что способствует созданию более комфортной среды для эксплуатации. Кроме того, эти конструкции могут значительно снизить вес зданий, что приводит к потенциальной экономии на фундаменте и других конструктивных компонентах.

Ключевые слова: многослойные конструкции, бетон на основе каучука, каутоны, аддитивные технологии, гофрированные конструкции, стеновые системы

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1. Introduction

Today, the development of new load-bearing structural systems and calculation methods is a relevant issue, allowing for more accurate estimations in order to decrease the specific weight of the structure, costs and complexity of construction, enhance the load-bearing capacity, crack resistance, and durability of buildings and structures.

One area of progress in load-bearing systems is the development of composite structures and materials with new properties that are not inherent in the original components and allow creating new architectural solutions, improving the quality of buildings and reducing construction costs [1; 2]. Structural wear has become a critical issue in the modern construction industry worldwide. Article [3] provides a comprehensive view of the complex application of composite materials to improve restoration methods, including applications in the repair, strengthening and modernization of concrete structures in the modern construction industry. In [4–6], an in-depth analysis of modern research and applications of composite materials aimed at developing innovative and environmentally friendly construction solutions was carried out. The article also discusses the mechanical characteristics and possible impact of these composites in the context of sustainable architectural practice. In [7], an analysis of the available experimental and theoretical studies on determining the fire-hazardous properties of polymer composite materials and structures in modern construction was carried out. Components and structures operating in the marine environment are subjected to high loads associated with the action of wind, waves and tides [8]. In addition, they have to deal with adverse and harsh environmental conditions throughout their service life. Composite materials, in most cases fiber-reinforced polymers, are currently used in many applications where low weight and high specific modulus of elasticity and strength are crucial [9]. Composite materials are popular not only in civil engineering, they are also used in shipbuilding. In [10], the authors presented a simple and effective analytical method for calculating the ultimate longitudinal strength and analyzing the reliability of a marine hull made of composite materials.

The creation of composite (or layered) structures is an efficient and promising trend in the construction industry. Composite structures have gained significant popularity due to their ability to significantly enhance strength characteristics [11], resistance to external forces, as well as to improve thermal and acoustic insulation properties of buildings and structures [12]. In [13], structural and morphological characteristics are presented, which show that composite materials are of great importance and represent new materials with special properties, where the concentration and nature of the filler affect the structure of nanomaterials and their conductivity.

Composite materials have been actively used as a substitute for traditional and already familiar materials due to their use in housing construction [14]. In [15], the authors considered and analyzed the problem of maintainability of composite structures, compared the strength characteristics of composite structures before and after damage in order to assess the effectiveness of composite materials in the construction industry. Article [16] collected and analyzed information on the use and main types of polymer composite materials in relation to the decorative design of facades in housing construction. In [17], aspects of the use of corrosion-resistant composite materials in the construction of reinforced concrete structures are analyzed with an assessment of both advantages and disadvantages, confirming the prospects of studying this area.

Composite materials are used not only in housing construction. In [18], the experience of using polymer composite materials in shipbuilding is presented, examples of ship structures made using these materials are given, where the main technological qualities are analyzed, according to which polymer composite materials are tested to select their field of application.

Composite structures can be manufactured from various metals, such as steel and aluminum, and are applicable in various industries, including manufacturing, construction, and transportation. An efficient infrastructure in any country cannot exist without the construction of strong and durable bridges. According to international experience, the actual service life of bridges built from materials common in bridge construction, such as wood, metal and reinforced concrete, is noticeably reduced in modern conditions.

In study [19], a comparative analysis of the use of traditional and synthetic materials in bridge structures was performed.

In the context of the construction of bridge structures, article [20] discusses methods for quality control of reinforcement of reinforced concrete structures with external reinforcement systems made of composite materials as a load-bearing material in bridge structures. In [21], an analysis of the Russian composite materials market was carried out in order to understand the existing problems, advantages and prospects of market development.

Such structures enable the optimization of the manufacturing process. For instance, the utilization of advanced 3D printing techniques can considerably simplify the creation of intricate geometric shapes and enhance the quality of the finished product. In recent years, various countries have seen diverse experiences in the introduction of additive manufacturing in the construction of buildings using 3D printing carried out using robots or automated equipment [22]. In [23; 24], the advantages and disadvantages of using 3D concrete construction printing, the features and the possibility of using this technology for industrial and civil construction in the Russian Federation are substantiated. Article [25] discusses and classifies the advantages, problems and risks associated with 3D printing in construction, as the use of 3D printing technology provides a number of advantages over traditional methods. The analysis of buildings created using 3D printing is also carried out, with an emphasis on their design, dimensions, construction time and the need for additional structural elements. 3D printing is a new method used in the construction sector to increase economic efficiency and reduce environmental impact. In study [26], the results showed that houses built using additive manufacturing and 3D printing materials are more environmentally friendly. Article [27] discusses the use of various additive construction systems with integrated algorithms for building information modeling, as there is a huge potential for changing the way cement materials are manufactured and environmental aspects are considered, especially in complex structures.

Technologies for creating concrete or steel structures with 3D printing are entering the market thanks to the creation of the first printed buildings and bridges [28]. This opens up new opportunities to accelerate construction and reduce costs by minimizing labor and waste materials. In addition, 3D printing makes it possible to implement complex architectural forms that are inaccessible to traditional construction methods.

Polymer concrete, which uses synthetic resins such as rubber as binders (commonly known as caoutchouc), demonstrates outstanding physical, mechanical, and chemical properties. The double-layer structure of concrete and rubber-based concrete effectively exploits the best qualities and advantages of each material [29]. Concrete performs well in compression, whereas rubber possesses high compressive and tensile strength, making it a suitable material for safeguarding products and structures from corrosion in aggressive environments. In study [30], an experimental determination of internal friction in materials such as rubber concretes based on low molecular weight polybutadiene rubber was carried out using the pulse action method. It was found that the addition of steel fiber reduces internal friction in the material, while polymer fiber has the opposite effect. In article [31], rubber concrete was studied as a polymer concrete with high performance characteristics, and a comparative analysis of the three stages of the stress-strain state of polymer concrete structures with and without dispersed reinforcement is carried out, similar to bent elements made of reinforced concrete and fibrocrete.

In the process of constructing small-scale man-made structures such as overpasses, tunnels, and underground pedestrian passages, corrugated metal constructions are frequently employed. Corrugated structures are often used in railway construction. Article [32] analyzes damage to transport structures made of corrugated metal structures located in the body of a railway track or road that occur during operation. A constructive method for restoring the bearing capacity of such structures is proposed, which involves installing an annular rib inside the concave part of the corrugated metal profile. Study [33] considers methods for increasing the load-bearing capacity of corrugated metal structures of transport structures through the use of transverse stiffeners, including additional corrugation and stiffeners. An approach for calculating equivalent loads occurring during rolling stock movement is also presented. It has been established that the use of double corrugation contributes to a significant increase in the bearing

capacity of such structures. These structures may comprise multiple layers of materials and exhibit enhanced operational attributes [34] such as thermal conductivity and resilience to mechanical stress owing to their layered configuration.

Among these structures are multilayered enclosing wall systems that can serve as supporting elements in low-rise structures or as self-sustaining structures in multi-storied buildings. These systems comprise an exterior cladding layer and an interior structural layer that are joined together through specialized connections. A layer of insulation is positioned between these two components, significantly enhancing the rigidity, stability, and durability of the entire structure.

Despite serious efforts to study multilayer structures, their application remains limited, and current design methods are not always ideal. This study aims to eliminate these limitations through a comprehensive analysis of the advantages and effectiveness of using multilayer building components, which will expand their scope of application and contribute to the development of more innovative and efficient construction solutions.

The study aims to investigate the key characteristics of multilayer structures used in the construction of buildings, with an emphasis on assessing their potential as an alternative to traditional structural solutions and analyzing operational properties. The object of research in this article is multilayer structures used in the construction of buildings.

Research objectives:

- based on the analysis of literary sources and the results of previous research, to identify and systematize the advantages inherent in multilayer structures;
- to carry out a comparative analysis of the operational characteristics of various types of multilayer structures with the characteristics of traditional structural solutions;
- to evaluate the economic feasibility of using multilayer structures.

2. Methods

Multilayer structures offer a wide range of possible combinations, depending on the shape of the cross-section, the properties of the materials and the nature of the application, as evidenced by the various examples shown in Figures 1, 2.

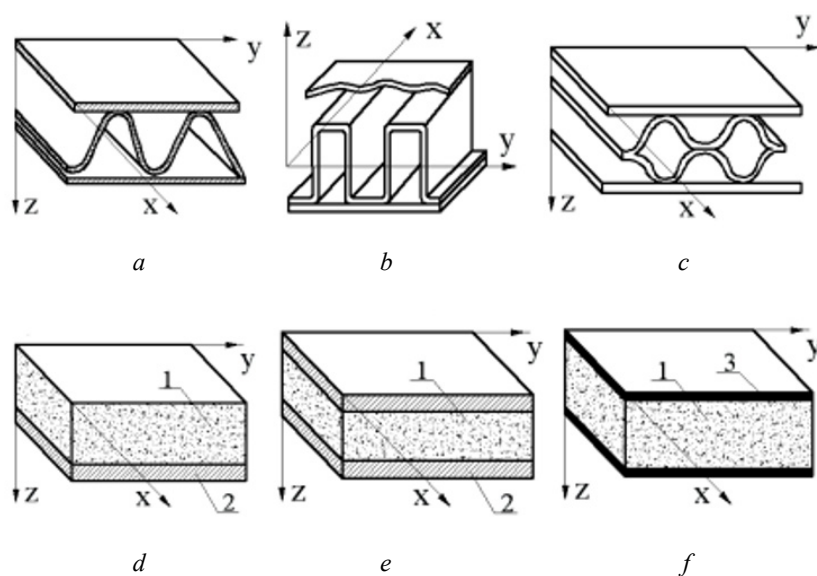


Figure 1. Types of multilayer elements:

a, b, c — corrugated single wave, box-shaped, and double-wave; *d, e, f* — two-layer and three-layer

Source: made by A.A. Morozov

As part of the study aimed at studying the advantages of multilayer structures and their performance characteristics compared to traditional structural solutions, the main types of multilayer structures were analyzed, including three-layer structures created by layer-by-layer printing, elements made of double-layer rubber-based concrete, multilayer metal corrugated structures and multilayer enclosing systems.

The comparison was carried out according to the parameters representing the key factors that are taken into account in the design, construction and operation of building structures:

“*Simplicity and versatility*” are parameters that show how easy the structure should be to manufacture, install and operate, and how suitable the structure can be for a wide range of applications and conditions;

“*Reliability and durability*” — where “Reliability” is the probability of a structure performing its functions flawlessly for a given period of time and under certain operating conditions, and “durability” is the ability of a structure to maintain its performance and functionality under environmental conditions and operating loads;

“Safety” is a criterion that evaluates the degree of protection when using materials or structures, as well as the likelihood of risks such as collapse, injury, or other accidents.;

“Endurance” — the ability of a structure to withstand repeated loads without fatigue failure (for example, flexural and compressive strength tests);

“Material consumption” is a parameter that indicates the amount of material needed to build a structure;

“Cost and labor costs” — the costs related to design, construction, materials, equipment, and the cost of labor required to perform construction work;

“Operating costs” — a description of the possible costs associated with maintenance, repair, heating, cooling, lighting and other aspects of the operation of a facility during its life cycle.

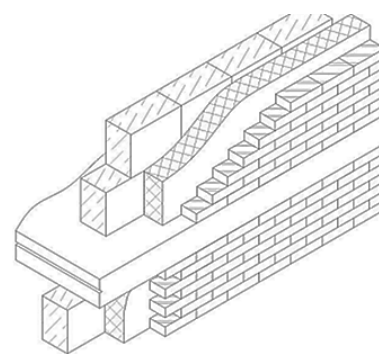


Figure 2. Section of a three-layer wall
Source: made by A.A. Morozov

3. Results and Discussion

3.1. Additive Technologies. Three-Layer Structures Created Using the Process of Layer-by-Layer Printing

Additive manufacturing technologies have the potential to significantly enhance the aesthetic appeal of construction projects, reduce construction times and costs, and minimize the consumption of various resources. However, despite these advantages and proposed solutions, the adoption of 3D printing technologies in both Russia and internationally has not yet achieved a significant level. This can be attributed to several challenges related to facility design, the absence of regulatory framework, and the lack of standardized equipment for construction printing.

The fundamental principle of additive manufacturing is that a 3D FDM printer deposits molten material, typically based on base polymers or combinations thereof, in the form of a solid filament, through an extruder nozzle, and selectively applies it onto a work platform, thereby creating a part with a specific shape and desired properties.

3D printing techniques can be classified into several categories, presented below.

- Layer-by-layer deposition techniques (FDM and FFF), which involve sequential deposition of layers of a thermoplastic material. While the material is in the printhead, it is subjected to high temperatures, after which it is deposited onto the substrate in a molten state.

- Photopolymer-based printing methods (SLA, LCD, and DLP), which utilize photopolymer as the consumable material in its liquid form. This material is ideal for subsequent bonding, painting, and other processing techniques.

- Selective laser sintering techniques (SLS), which use a powder-based raw material that is evenly spread over the surface of a substrate. During the laser treatment process, the material begins to fuse in specific areas. This process allows for the production of parts with a rough surface that can subsequently be polished.

■ Selective laser melting (SLM) is a process that is similar to the two previous methods. During this process, a laser beam melts metal powder, and then the melted layer is re-applied and further processed. This technique allows for the production of parts with complex shapes and non-standard dimensions, which cannot be achieved through injection molding or machining.

■ Multi-jet molding (MJM) uses photopolymer, plastic, or wax as consumables, which are fed onto a smooth surface using a special head equipped with micro-nozzles.

The ability to produce functional end products in small and medium quantities offers a significant time advantage compared to traditional manufacturing methods. 3D printing, also known as additive manufacturing, provides several significant advantages over conventional production techniques such as casting, machining, and stamping:

■ 3D printing enables the creation of complex geometric shapes, including polyhedra, cylinders, and circles, which are often difficult to achieve using traditional methods.

■ When used for small batch production, the average cost of 3D printed parts can be 30–50% lower compared to traditional techniques.

■ The process time from concept to final product can be reduced by 70–90% using 3D printing compared to conventional methods, reducing lead times from days to hours.

■ Less manual labor is required in the 3D manufacturing process compared to classical fabrication methods.

In traditional manufacturing methods, the quantity of material used can often exceed 50%, particularly during machining processes. In contrast, 3D printing techniques utilize only the exact amount of material required, resulting in a close to 100% material utilization rate.

The key advantages of 3D printing lie in its economic efficiency. It reduces production costs by minimizing waste, accelerates product launch to market, and saves on equipment and consumable costs. Table 1 presents a comparative analysis of the characteristics of three-layer structures created using 3D printing technology and traditional construction methods, in particular brickwork.

Each method has its own set of advantages and disadvantages. Three-dimensional (3D) printing, for example, can reduce construction time and waste, as it creates the structure directly from a given model without the need for significant amounts of materials or labor.

Table 1

A comparative analysis of the characteristics of three-layer structures constructed using the technique of layer-by-layer 3D printing and conventional methods for constructing structures (brick masonry)

№	Parameter	Three-layer structures constructed using the method of layer-by-layer printing	Traditional construction method (brickwork)
1	Simplicity and versatility	The process is automated and can be utilized to generate various shapes and architectural designs	This method is more time-consuming and requires skilled labor
2	Reliability and durability	It depends on the specific materials and technologies used. Although some 3D printed structures have shown promising results in terms of reliability, durability still requires further study, as special additives or protective coatings are needed to ensure sufficient durability	Brickwork has time-tested reliability, but it can be subject to defects related to the quality of the masonry and the mortar used, brickwork can collapse under the influence of freeze-thaw cycles and aggressive environments
3	Safety	The materials used in 3D printing can be less fire resistant or subject to other hazards	Dense, stable structures that have been tested over time ensure high safety
4	Endurance	The durability of a product depends on the material used and the printing technology employed	They provide traditional strength and are resistant to loads
5	Material consumption	It can significantly reduce material waste due to its high accuracy and the ability to utilize recycled materials	Less opportunity for optimizing material use and often leads to excessive waste
6	Cost and labor costs	The initial investment in equipment can be significant, but over the long term, especially for large-scale operations, it may result in reduced overall costs through automation and the need for fewer workers	Although the initial cost of the traditional method may be lower, it requires more time and highly skilled workers
7	Operating costs	Potentially more energy-efficient structures.	Well-insulated structures can lead to lower heating and cooling costs

Source: made by A.A. Morozov

3.2. Double-Layer Rubberized Concrete Flexural Elements

Double-layered rubber-concrete flexural elements are a combination of materials containing rubber and concrete, which provide certain advantages in terms of construction and architecture. These double-layered elements are used in both Russia and other countries in various areas of construction.

Rubber concrete has favorable physical and mechanical properties (high strength, resistance to cracking), high chemical resistance, and, along with various types of polymer concretes, can be used to solve the problem of protecting various products and structures from corrosion in aggressive environments.

It is emphasized in [35] that one of the fundamental principles of creating double-layer rubber concrete structures is an increased ratio of tensile strength (in the stretched zone — rubber concrete) to compressive strength (in the compressed zone — regular concrete): $R_{kt}/R_b = 0.5 \dots 1$, compared with single-layer reinforced concrete structures ($R_{bt}/R_b = 0.05 \dots 0.09$) or rubber concrete structures ($R_{kt}/R_k = 0.1 \dots 0.15$).

The key difference in the composition of rubber-based concrete and rubber-fiber concrete (fibrocement) lies in the addition of fiber from scrap metal cord. Nevertheless, among the benefits of utilizing these materials, it is noteworthy that both types of material are insulators with good thermal insulation properties, as well as having a porous structure that contributes to their insulation capabilities.

It has been noted in [36] that rubber-fiber concrete comprises industrial waste products, such as fly ash, metal cord fibers, and industrial sulfur, which indicates the potential of this polymer concrete to help address the issue of large-scale industrial waste recycling.

In order to increase the elasticity of concrete, some studies [37] have suggested adding crushed rubber from recycled tires to the concrete mix. The results showed that such modified concrete has significantly greater elasticity than traditional concrete and also promotes the recycling of car tires. Article [38] presents results demonstrating the superiority of hybrid rubber-based concrete beams over traditional designs. The use of the hybrid approach resulted in improved failure patterns, increased ultimate load and stiffness, and increased modulus of rupture and stress. These results stimulate the development and implementation of innovative solutions in the field of sustainable civil engineering. A comparative analysis of the characteristics of flexural elements made of double-layer concrete based on rubber and a traditional solution is presented in Table 2.

Table 2

A comparative analysis of the characteristics of double-layered rubber-based concrete flexural elements and a conventional solution (prestressed, reinforced concrete flexural elements)

№	Parameter	Double-layered rubber-based concrete flexural elements	Traditional solution (prestressed reinforced concrete flexural elements)
1	Simplicity and versatility	Good versatility due to a variety of shapes and sizes	More sophisticated technologies for invention and production require specialized equipment and expertise, and are commonly utilized in large-scale construction projects due to their dependability and adherence to standards
2	Reliability and durability	They exhibit good resistance to external influences, including corrosion. The durability of rubber-based concrete depends on the rubber's resistance to aging and environmental influences	These technologies demonstrate a high level of reliability and effectively resist dynamic loads, but the susceptibility of reinforced concrete to reinforcement corrosion negatively affects its durability
3	Safety	They demonstrate good safety indicators	They also provide a high degree of safety, being able to withstand heavy loads and maintain functionality even in the event of cracks
4	Endurance	A smaller crack opening width is achieved due to the high tensile strength of the material	Their high flexural and compressive strengths make them well-suited for large spans and structural applications
5	Material consumption	The use of modern composite materials can lead to lower material consumption, resulting in a reduced overall weight of the structure	However, they often necessitate the use of more materials
6	Cost and labor costs	It is often more cost-effective to manufacture and install, as it can reduce overall costs by reducing the weight of the product.	Due to the complexity of their manufacturing processes and the requirement for specialized equipment, these technologies can be more expensive. Additionally, labor costs may be higher, particularly during the installation phase
7	Operating costs	Additionally, they may require lower maintenance costs, due to their resistance to corrosion and environmental factors.	Despite these higher initial costs, load-resistant technologies may result in lower maintenance expenses in the long term

Source: made by A.A. Morozov

Regarding the potential for research into the impact of fiber reinforcement on the strength properties of polymer concrete, regulatory documents provide developed recommendations for considering fiber reinforcement in calculations for building structures made from cement concrete:

- The National Standard of the Russian Federation, GOST R 57345-2016 / EN 206-1: “Concrete — Part 1: Specification, performance, production and conformity, IDT”, which establishes requirements for cement-fiber reinforced concrete.
- SP 52-104-2006. “Steel fibre reinforced concrete structures design”.
- SP 297.1325800.2017 “Fiber reinforced concrete structures and precast products with non-steel fibers. Design rules”, which establishes the requirements for the design of structures made of fiber-reinforced concrete with non-metallic fibers.

3.3. Laminated Metal Corrugated Structures

Concrete and reinforced concrete structures have a relatively high dead weight, making the installation process time-consuming and requiring significant financial resources for material transportation. Recently, laminated metal corrugated structures have been increasingly introduced into construction practices in Russia. The types of sections of metal corrugated structures are shown in Table 3.

Table 3

Types of sections of metal corrugated structures

Type of cross-section	Specifications	Type of cross-section	Specifications
 <i>circle</i>	Span, m: 1.5–7.0	 <i>vertical ellipse</i>	Span, m: 1.5–6.5
 <i>arch</i>	Span, m: 2.0–13.0	 <i>pipe of reduced height</i>	Span, m: 1.5–2.0
 <i>flat-bottomed pipe</i>	Span, m: 1.9–8.0	 <i>horizontal ellipse</i>	Span, m: 2.6–9.0
 <i>high profile arch</i>	Span, m: 6.0–15.0	 <i>low profile arch</i>	Span, m: 6.0–15.0
 <i>pear-shaped</i>	Span, m: 2.6–9.0	 <i>square</i>	Span, m: 3.6–8.0

Source: made by A.A. Morozov

Laminated metal corrugated structures are building elements consisting of several layers of metal sheets having a corrugated (wavy) shape. These layers are interconnected in various ways, forming a strong and rigid structure.

By using this type of structures, it is possible to span up to 30 meters, erecting structures for road and railway crossings at different levels, underground transport tunnels for industrial enterprises, and structures to protect roadways from rockslides and other hazards. At the same time, the cost of building structures made from corrugated metal is considerably lower than that of structures with similar applications. Currently, corrugated structures, in particular beams with a corrugated wall, are widely used in construction. They are used as floor beams for multi-storey residential buildings [39], large-span roof beams for industrial buildings, as well as in dome structures of administrative buildings. A comparative analysis of the characteristics of metal corrugated systems and conventional solutions is given in Table 4.

The key advantages of using corrugated metal structures include:

- applicability in various soil-hydrologic and climatic conditions;
- optimal balance between load-bearing capacity and structural weight;
- use of light-weight construction equipment;
- reduction of construction and installation costs.

Laminated metal corrugated structures have versatile properties, which is why they have found application in various fields, depending on the specific section.

Table 4

A comparative analysis of the characteristics of metal corrugated systems and conventional solutions (reinforced concrete structures)

№	Parameter	Metal corrugated structures	Traditional solution (reinforced concrete structures)
1	Simplicity and versatility	Easy installation due to the lightness and modular nature of the product	A more complex manufacturing and installation process is required. There are fewer opportunities for quick adaptation to changes
2	Reliability and durability	The products are resistant to corrosion when using special coatings. With proper care, their durability can reach 50 years or more	Generally, they have a high level of reliability and durability, but they can crack and corrode the reinforcement
3	Safety	When designed and operated correctly, the products are safe	These products are usually more fire-resistant and better protected against external influences
4	Endurance	They possess high compressive strength and flexural strength, with high relative strength values and low weight	Although they typically have very high compressive strength, they may have lower tensile strength compared to metal
5	Material consumption	It is possible to design products that are lighter by using less material for supporting elements, due to their high strength	There is high material consumption due to the need for large volumes of concrete and reinforcement
6	Cost and labor costs	While the materials may be more expensive, installation time can be shorter, reducing labor costs	The cost of materials is lower, but there are higher labor costs for production and installation
7	Operating costs	Maintenance costs are lower with good corrosion protection, as the products require less maintenance	Maintenance costs are low, although periodic maintenance may be required

Source: made by A.A. Morozov

Metal corrugated structures offer advantages in terms of faster construction and lower installation costs. Reinforced concrete structures, on the other hand, provide greater durability and fire resistance.

3.4. Multilayer Enclosing Wall Systems

Currently, there is a significant shift in the design and materials used in building structures with the aim of enhancing energy efficiency and improving the appearance and durability of buildings. Enveloping structures, which are the most critical component of any building, play a vital role in maintaining the required sanitary, hygienic conditions, and comfortable indoor environment.

The thermal performance of a multi-layer (at least three-layer) structural system is primarily determined by the appropriate selection of the type, dimension, and placement of thermal connections, rather than by increasing the thickness of insulation. In [40] the author emphasizes that multilayer composite sandwich panels with a corrugated core represent a promising material for structural applications whose characteristics require rigidity and strength while minimizing weight. When designing flexible connections in wall structures, it is essential to minimize the diameter of metallic connections in order to reduce heat loss. This is not only beneficial for metal conservation but also crucial to minimize unnecessary heat loss resulting from the presence of these connections. In [41], the authors present numerical modeling and experimental verification of axially loaded thin sandwich panels with soft core and different rib configurations and obtained the result that the axial stiffness and strength also increased as the skins or ribs became thicker, or their Young's modulus increased, or the shear modulus of the core increased.

The main advantages of multi-layer walls include:

- high resistance to heat transfer through external walls;
- excellent thermal insulation properties;
- aesthetic appearance;
- reduced material consumption.

In buildings with enhanced thermal protection, the outer layers of the wall (known as “shells”) are made from a durable and heat-conductive material that can carry a load. The middle layer is composed of effective insulation material. For single-story houses, chipboard can be used, while concrete is used for multi-story buildings and industrial structures, and metal is used for industrial buildings.

The experience of using multi-layer masonry around the world has been evaluated for decades. However, their active introduction into the Russian market, without taking into account the specific features of our country, climate, and lack of construction experience, leaves its mark. Multi-layer structures have advantages that are highly appreciated in terms of energy conservation policies, as well as disadvantages that are largely manageable.

Table 5

The parameters of the estimated performance indicators for multilayer and single-layer envelope wall systems

№	Parameter	Single-layer enclosing wall systems	Multi-layer enclosing wall systems
1	Simplicity and versatility	The installation time for a single — layer system is 20–30% less than for a multi-layer system. They are universal for most cases, but may not be suitable for specific conditions	They are versatile, as each layer can be adapted to different climatic and operational conditions
2	Reliability and durability	Less resistance to mechanical damage and environmental influences, the durability of single-layer systems is limited by the durability of the material used	Multilayer systems provide increased reliability due to functional differentiation of layers (for example, thermal insulation and hydraulic protection) and extended service life due to mutual protection of layers and effective moisture removal
3	Safety	Less protection from external factors and impacts (fires, break-ins)	Better thermal and acoustic insulation, as well as protection from system damage. The fire resistance of the multilayer system is 40% higher
4	Endurance	The strength depends on the specific material, often insufficient for harsh conditions	By combining different materials, high strength and stability can be achieved
5	Material consumption	They usually require fewer materials, since homogeneous materials are used	A multilayer system can exceed the material consumption of a single-layer system by 30–50%
6	Cost and labor costs	The initial cost of a single-layer system can be 20–40% lower than for a multi-layer system	High cost of materials and more time for installation
7	Operating costs	They may require more energy saving and maintenance costs	The cost of operating a multilayer system may be lower by 15–25% due to better thermal insulation

Source: made by A.A. Morozov

Wall panels are used as vertical and inclined enclosure structures in the construction of industrial, warehouse, and agricultural buildings, public and commercial structures, refrigeration facilities, and low-rise residential buildings of rural and suburban types. These structures can have either vertical or horizontal

joints. Table 5 shows the parameters of calculated performance indicators for multilayer and single-layer enclosing wall systems.

A comparison of multi-layer and single-layer enclosure wall systems can be conducted based on several key factors.

4. Conclusion

After analyzing these multilayer building components as an alternative to conventional structures, it has been noted that each has specific values and characteristics. These materials are utilized in the construction of smaller architectural forms, bridges, fences, buildings, and engineering structures.

As a result of the conducted research, the following should be noted.

1. According to the analysis in Tables 1, 2, 4, 5, it was found that the use of multilayer systems can significantly reduce the weight of structures, potentially saving money on foundations and other elements.

2. Double-layer rubber-based concrete components have excellent mechanical properties and durability, and laminated metal corrugated structures are highly durable with relatively low weight.

3. The use of 3D layer-by-layer printing technologies opens up opportunities for more flexible and customized design in construction, which is not available with traditional methods, as well as reducing production costs by minimizing waste, since with traditional production methods the amount of material used can often exceed 50%, especially during machining.

4. Multilayer building components, which are an alternative to traditional structures, have unique characteristics and are used in various construction projects.

5. Multilayer systems provide improved heat and sound insulation properties, contributing to comfortable living and working conditions.

The presented results confirm the advantages of multilayer structures, opening up prospects for further research in the field of development and optimization of these materials. A comparative analysis of the characteristics of multilayer and traditional structures, as well as an analysis of the possibilities of layered 3D printing, is of considerable scientific interest and may contribute to the development of innovative approaches in construction.

References

1. Annamuradova A., Bayramdurdyev A., Nazarov A.T. Use of lightweight and durable composite materials in construction. *Science Bulletin*. 2024;3(6):1658–1661. (In Russ.) EDN: FZCOMU
2. Jonnala S.N., Gogoi D., Devi S., Kumar M., Kumar C.H. A comprehensive study of building materials and bricks for residential construction. *Construction and Building Materials*. 2024;425:135931. <https://doi.org/10.1016/j.conbuildmat.2024.135931> EDN: NSLDOL
3. Mugahed Amran Y.H., Alyousef R., Alabduljabbar H., Rashid R.S.M., Hung C.C. Properties and applications of FRP in strengthening RC structures: A review. *Structures*. 2018;16:208–238. <https://doi.org/10.1016/j.istruc.2018.09.008> EDN: MOLRME
4. Nasr Y., El Zakhem H., Hamami A.E.A., El Bachawati M., Belarbi R. Comprehensive review of innovative materials for sustainable buildings' energy performance. *Energies*. 2023;16(21):7440. <https://doi.org/10.3390/en16217440> EDN: CYCYPO
5. Elfaleh I., Abbassi F., Habibi M., Ahmad F., Guedri M., Nasri M., Garnier Ch. A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. *Results in Engineering*. 2023;19:101271. <https://doi.org/10.1016/j.rineng.2023.101271> EDN: GNJFKH
6. Voutetaki M.E., Mpalaskas A.C. Natural fiber-reinforced mycelium composite for innovative and sustainable construction materials. *Fibers*. 2024;12(7):57. <https://doi.org/10.3390/fib12070057> EDN: DAEHJ
7. Kudryashov V.A., Drobysh A.S. Features of application of polymer composite materials and structures in construction. *Journal of Civil Protection*. 2024;8(4):398–410. (In Russ.) <https://doi.org/10.33408/2519-237X.2024.8-4.398> EDN: FEUIRY
8. Rubino F., Nisticò A., Tucci F., Carlone P. Marine application of fiber reinforced composites: A review. *Journal of Marine Science and Engineering*. 2020;8(1):26. <https://doi.org/10.3390/jmse8010026> EDN: ZMHSQA
9. Friedrich K., Almajid A.A. Manufacturing aspects of advanced polymer composites for automotive applications. *Applied Composite Materials*. 2013;20(2):107–128. <https://doi.org/10.1007/s10443-012-9258-7> EDN LKCXQX

10. Chen N.Z., Sun H.H., Soares C.G. Reliability analysis of a ship hull in composite material. *Composite Structures*. 2003;62(1):59–66. [https://doi.org/10.1016/S0263-8223\(03\)00084-9](https://doi.org/10.1016/S0263-8223(03)00084-9) EDN: KJLVAI
11. Shorstov R., Suleymanova L., Kara K. Technology of obtaining multilayer structures variational structure. *Bulletin of BSTU Named After V.G. Shukhov*. 2019;4:32–39. (In Russ.) https://doi.org/10.34031/article_5cb1e65fe51130.63177531 EDN: ZDDGGD
12. Zaborova D., Musorina T., Petrichenko M. Thermal stability and thermal resistance of a multilayer wall construction: assessment of parameters. *St. Petersburg Polytechnic University Journal: Physics and Mathematics*. 2017;23(1):18–26. (In Russ.) <https://doi.org/10.18721/JEST.230102> EDN: WAKRSO
13. Tudose I.V., Mouratis K., Ionescu O.N., Romanitan C., Pachiu C., Tutunaru-Brincoveanu O., Suchea M.P., Koudoumas E. Comparative study of graphene nanoplatelets and multiwall carbon nanotubes-polypropylene composite materials for electromagnetic shielding. *Nanomaterials*. 2022;12(14):2411. <https://doi.org/10.3390/nano12142411> EDN: QFCLKJ
14. Vasilyeva E.Yu. Innovative materials and technologies in housing construction: Importance and prospects. *Vestnik MGSU [Monthly Journal on Construction and Architecture]*. 2022;17(11):1586–1593. (In Russ.) <https://doi.org/10.22227/1997-0935.2022.11.1586-1593>
15. Odintsov M.A., Davydova S.O., Pavlova S.A. Investigation of maintainability of fiberglass and carbon fiber plastics during tensile testing. *Proceedings of Young Scientists and Specialists of Samara University*. 2022;2(21):27–32. EDN: HEREMK
16. Ivanova M.S., Korobchuk M.V. The application of polymer composites in residential buildings. *Modern Construction and Architecture*. 2023;5(36):2. (In Russ.) <https://doi.org/10.18454/mca.2023.36.2> EDN: MTCBUJ
17. Bakholdin D.G. Application of composite materials in construction. *International Journal of Humanities and Natural Sciences*. 2024;5-1(92):189–192. (In Russ.) <https://doi.org/10.24412/2500-1000-2024-5-1-189-192> EDN: AVSWVS
18. Meleshin M.A., Salameh A., Alsaid M. Experience in application of composite materials in shipbuilding. *Vestnik of Astrakhan State Technical University. Series: Marine Engineering and Technologies*. 2022;(2):44–50. (In Russ.) <https://doi.org/10.24143/2073-1574-2022-2-44-50> EDN: UXSRLV
19. Kokoreva K.A., Belyaev N.D. Effectiveness of using composite materials in bridge construction. *Interdisciplinarity in Theory and Practice*. 2015;(7):153–158. EDN: UKTIGV
20. Morozova Y.A., Okolnikova G.E. The quality control of concrete structures reinforced with external composite reinforcement. *Bulletin of SUSU. Series: Construction Engineering and Architecture*. 2024;24(3):15–23. (In Russ.) <https://doi.org/10.14529/build240302> EDN: KAAMGK
21. Shirtanov A.A. The potential of composite materials market in the RU. *Science Bulletin*. 2023;3(11):189–194. (In Russ.) EDN: JMIEON
22. Guamán-Rivera R., Martínez-Rocamora A., García-Alvarado R., Muñoz-Sanguinetti C., González-Böhme L.F., Auat-Cheein F. Recent developments and challenges of 3D-printed construction: A review of research fronts. *Buildings*. 2022;12(2):229. <https://doi.org/10.3390/buildings12020229> EDN: XWXSEY
23. Tsarenko A.A., Shaburova N.A. The possibility of using construction 3D printing with concrete in the construction of buildings and structures in Russia. *Construction Economics*. 2024;(4):389–392. (In Russ.) <https://doi.org/10.24412/0131-7768-2024-4-389-392> EDN: GALAVA
24. Krotov O.M., Ptukhina I.S. Evaluation of the effectiveness of 3D printing for wall structures. *Construction Economics*. 2023;(5):73–79. (In Russ.) EDN: UOCGBF
25. El-Sayegh S., Romdhane L., Manjikian S. A critical review of 3D printing in construction: benefits, challenges, and risks. *Archives of Civil and Mechanical Engineering*. 2020;20(2):1–25. <https://doi.org/10.1007/s43452-020-00038-w> EDN: ASRTBA
26. Abdalla H., Fattah K.P., Abdallah M., Tamimi A.K. Environmental footprint and economics of a full-scale 3D-printed house. *Sustainability*. 2021;13(21):11978. <https://doi.org/10.3390/su132111978> EDN: ZNMUFP
27. Al-Tamimi A.K., Alqamish H.H., Khaldoune A., Alhaidary H., Shirvanimoghaddam K. Framework of 3D concrete printing potential and challenges. *Buildings*. 2023;13(3):827. <https://doi.org/10.3390/buildings13030827> EDN: INCTIS
28. Wolf A., Rosendahl Ph.L., Knaack U. Additive manufacturing of clay and ceramic building components. *Automation in Construction*. 2022;133:103956. <https://doi.org/10.1016/j.autcon.2021.103956> EDN: KROOVS
29. Figovsky O.L., Potapov Y.B., Polikutin A.E., Nguyen Z.F. Strength of normal sections of two-layer rubcon-concrete bending elements of building structures. *Eastern-European Journal of Enterprise Technologies*. 2014;11(72):14–20. (In Russ.) <https://doi.org/10.15587/1729-4061.2014.30120> EDN: TCSMSZ
30. Popov I., Levchenko A. Experimental investigation of internal friction in rubber concrete and fiber-reinforced rubber concrete. *Russian Journal of Building Construction and Architecture*. 2021;4:53–62. <https://doi.org/10.36622/VSTU.2021.52.4.005> EDN: JINMHO
31. Polikutin A.E., Potapov Yu.B., Levchenko A., Perekalsky O. The stress-strain foreign state of normal sections of rubkon bends elements with mixed reinforcement. *International scientific conference on energy management of municipal facilities and Sustainable Energy technologies EMMFT 2018 : Series: achievements in intelligent systems and computing*.

Voronezh and Samara, Russia, December 10–13, 2018. Vol. 2. Cham: Springer, 2019;983:586–599. https://doi.org/10.1007/978-3-030-19868-8_56 EDN RWARUH

32. Kovalchuk V., Onyshchenko A., Sysyn M., Hnativ Y., Tiutkin O., Koval M., Parneta M. Restoration of the bearing capacity of damaged transport constructions made of corrugated metal structures. *The Baltic Journal of Road and Bridge Engineering*. 2021;16(2):90–109. <https://doi.org/10.7250/bjrbe.2021-16.529> EDN NGTPIH

33. Kovalchuk V., Sysyn M., Movahedi Rad M., Fischer S. Investigation of the bearing capacity of transport constructions made of corrugated metal structures reinforced with transversal stiffening ribs. *Infrastructures*. 2023;8(9):131. <https://doi.org/10.3390/infrastructures8090131> EDN UWUXSH

34. Osterman E.D., Shutova O.A. Analysis of the types of constructions made of corrugated metal structures. *Bulletin of PNRPU. Construction and architecture*. 2016;7(1):18–29. (In Russ.) <https://doi.org/10.15593/2224-9826/2016.1.03> EDN: VPZUTJ

35. Brooks H., Lupeanu M., Piorkowski B. Research towards high speed extrusion freeforming. *International Journal of Rapid Manufacturing*. 2013;3:154–171. <https://doi.org/10.1504/IJRAPIDM.2013.053686>

36. Polikutin A., Konstantinov I., Nguyen Z., Truong Z. Strength analysis of oblique sections of two-layer rubber concrete flexural elements with varying relative shear span. *Structural Mechanics and Structures*. 2014;1(8):107–116. (In Russ.) EDN: SYRZTV

37. Khaloo A., Darabad P.Y. Investigation of flexural capacity of concrete containing liquid silicone rubber. *Shock and Vibration*. 2021;2021(1):668283. <https://doi.org/10.1155/2021/668283> EDN: AZRGZQ

38. Alasmari H.A., Abu Bakar B.H., Noaman A.T. A comparative study on the flexural behaviour of rubberized and hybrid rubberized reinforced concrete beams. *Civil Engineering Journal*. 2019;5(5):1052–1067. <https://doi.org/10.28991/cej-2019-03091311>

39. Zaborova D. Advantages and special aspects of using corrugated beams in construction. *Construction of Unique Buildings and Structures*. 2014;7(22):36–53. (In Russ.) EDN: SKDYAJ

40. Vahidimanesh B., Farrokhabadi A., Shahvari R., Gazor M., Mahdiabadi M. Experimental and numerical investigation of damage in multilayer sandwich panels with square and trapezoidal corrugated cores under quasi-static three-point bending. *Engineering Structures*. 2024;318:118715. <https://doi.org/10.1016/j.engstruct.2024.118715> EDN: GBDYFM

41. Mathieson H., Fam A. Numerical modeling and experimental validation of axially loaded slender sandwich panels with soft core and various rib configurations. *Engineering Structures*. 2016;118:195–209. <https://doi.org/10.1016/j.engstruct.2016.03.044>

Список литературы

1. Аннамырадова А., Байрамдурдыев А., Назаров А. Использование легких и прочных композитных материалов в строительстве // Вестник науки. 2024. Т. 3. № 6. С. 1658–1661. EDN: FZCOMU

2. Jonnala S.N., Gogoi D., Devi S., Kumar M., Kumar C.H. A comprehensive study of building materials and bricks for residential construction // Construction and Building Materials. 2024. Vol. 425. Article no. 135931. <https://doi.org/10.1016/j.conbuildmat.2024.135931> EDN: NSLDOL

3. Mugahed Amran Y.H., Alyousef R., Alabduljabbar H., Rashid R.S.M., Hung C.C. Properties and applications of FRP in strengthening RC structures: A review // Structures. 2018. Vol. 16. P. 208–238. <https://doi.org/10.1016/j.istruc.2018.09.008> EDN: MOLRME

4. Nasr Y., El Zakhem H., Hamami A.E.A., El Bachawati M., Belarbi R. Comprehensive review of innovative materials for sustainable building' energy performance // Energies. 2023. Vol. 16. No. 21. Article no. 7440. <https://doi.org/10.3390/en16217440> EDN: CYCYPO

5. Elfaleh I., Abbassi F., Habibi M., Ahmad F., Guedri M., Nasri M., Garnier Ch. A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials // Results in Engineering. 2023. Vol. 19. Article no. 101271. <https://doi.org/10.1016/j.rineng.2023.101271> EDN: GNJFKH

6. Voutetaki M.E., Mpalaskas A.C. Natural Fiber-Reinforced Mycelium composite for innovative and sustainable construction materials // Fibers. 2024. Vol. 12. No. 7. Article no. 57. <https://doi.org/10.3390/fib12070057> EDN: DAEHJ

7. Кудряшов В.А., Дробыш А.С. Особенности применения полимерных композитных материалов и конструкций в строительстве // Вестник Университета гражданской защиты МЧС Беларуси. 2024. Т. 8. № 4. С. 398–410. <https://doi.org/10.33408/2519-237X.2024.8-4.398> EDN: FEUIRY

8. Rubino F., Nisticò A., Tucci F., Carlone P. Marine application of fiber reinforced composites: A review // Journal of Marine Science and Engineering. 2020. Vol. 8. No. 1. Article no. 26. <https://doi.org/10.3390/jmse8010026> EDN: ZMHSGA

9. Friedrich K., Almajid A.A. Manufacturing aspects of advanced polymer composites for automotive applications // Applied Composite Materials. 2013. Vol. 20. No. 2. P. 107–128. <https://doi.org/10.1007/s10443-012-9258-7> EDN: LKCXQX

10. Chen N.Z., Sun H.H., Soares C.G. Reliability analysis of a ship hull in composite material // Composite Structures. 2003. Vol. 62. No. 1. P. 59–66. [https://doi.org/10.1016/S0263-8223\(03\)00084-9](https://doi.org/10.1016/S0263-8223(03)00084-9) EDN: KJLVAI

11. Шорстов Р.А., Сулейманова Л.А., Кара К. Технологии получения многослойных конструкций вариатронной структуры // Вестник Белгородского государственного технологического университета им. В.Г. Шухова. 2019. № 4. С. 32–39. https://doi.org/10.34031/article_5cb1e65fe51130.63177531 EDN: ZDDGGD
12. Заборова Д.Д., Мусорина Т.А., Петриченко М.Р. Теплотехническая работоспособность многослойной стеновой конструкции // Научно-технические ведомости Санкт-Петербургского государственного политехнического университета. 2017. Т. 23. № 1. С. 18–26. <https://doi.org/10.18721/JEST.230102> EDN: WAKRSO
13. Tudose I.V., Mouratis K., Ionescu O.N., Romanitan C., Pachiu C., Tutunaru-Brincoveanu O., Sucheа M.P., Koudoumas E. Comparative study of graphene nanoplatelets and multiwall carbon nanotubes-polypropylene composite materials for electromagnetic shielding // *Nanomaterials*. 2022. Vol. 12. No. 14. Article no. 2411. <https://doi.org/10.3390/nano12142411> EDN: QFCLKJ
14. Васильева Е.Ю. Значение и перспективы применения инновационных материалов и технологий в жилищном строительстве // Вестник МГСУ. 2022. Т. 1. № 11. С. 1586–1593. <https://doi.org/10.22227/1997-0935.2022.11.1586-1593> EDN: CJCLIZ
15. Odintsov M.A., Davydova S.O., Pavlova S.A. Investigation of maintainability of fiberglass and carbon fiber plastics during tensile testing // *Proceedings of Young Scientists and Specialists of Samara University*. 2022. No. 2 (21). P. 27–32. EDN: HEREMK
16. Иванова М.С., Коробчук М.В. Применение полимерных композиционных материалов в объектах жилищного строительства // Современное строительство и архитектура. 2023. № 5 (36). С. 2. <https://doi.org/10.18454/mca.2023.36.2> EDN: MTCBUJ
17. Бахолдин Д.Г. Применение композитных материалов в строительстве // Международный журнал гуманитарных и естественных наук. 2024. Вып. 5–1 (92). С. 189–192. <https://doi.org/10.24412/2500-1000-2024-5-1-189-192>
18. Мелешин М.А., Саламех А., Алсаид М. Опыт применения композитных материалов в судостроении // Вестник Астраханского государственного технического университета. Серия: Морская техника и технология. 2022. № 2. С. 44–50. <https://doi.org/10.24143/2073-1574-2022-2-44-50>
19. Kokoreva K.A., Belyaev N.D. Effectiveness of using composite materials in bridge construction // *Interdisciplinarity in Theory and Practice*. 2015. No. 7. P. 153–158. EDN: UKTIGV
20. Морозова Ю.А., Окольников Г.Э. Методы контроля качества усиления железобетонных конструкций системами внешнего армирования из композитных материалов // Вестник Южно-Уральского государственного университета. Серия: Строительство и архитектура. 2024. Т. 24. № 3. С. 15–23. <https://doi.org/10.14529/build240302> EDN: KAAMGK
21. Ширтанов А.А. Потенциал рынка композитных материалов в Российской Федерации // Вестник науки. 2023. Т. 3. № 11. С. 189–194. EDN: JMIEON
22. Guamán-Rivera R., Martínez-Rocamora A., García-Alvarado R., Muñoz-Sanguinetti C., González-Böhme L.F., Auat-Cheein F. Recent developments and challenges of 3D-printed construction: A review of research fronts // *Buildings*. 2022. Vol. 12. No. 2. Article no. 229. <https://doi.org/10.3390/buildings12020229> EDN: XWXSEY
23. Царенко А.А., Шапурова Н.А. Возможность использования строительной 3D-печати бетоном при возведении зданий и сооружений в России // Экономика строительства. 2024. № 4. С. 389–392 <https://doi.org/10.24412/0131-7768-2024-4-389-392> EDN: GALAVA
24. Кротов О.М., Птухина И.С. Оценка эффективности применения 3D-печати для стеновых конструкций // Экономика строительства. 2023. № 5. С. 73–79. EDN: UOCGBF
25. El-Sayegh S., Romdhane L., Manjikian S. A critical review of 3D printing in construction: benefits, challenges, and risks // *Archives of Civil and Mechanical Engineering*. 2020. Vol. 20. No. 2. P. 1–25. <https://doi.org/10.1007/s43452-020-00038-w> EDN: ASRTBA
26. Abdalla H., Fattah K.P., Abdallah M., Tamimi A.K. Environmental Footprint and Economics of a Full-Scale 3D-Printed House // *Sustainability*. 2021. Vol. 13. No. 21. Article no. 11978. <https://doi.org/10.3390/su132111978> EDN: ZNMUFP
27. Al-Tamimi A.K., Alqamish H.H., Khaldoune A., Alhaidary H., Shirvanimoghaddam K. Framework of 3D Concrete Printing Potential and Challenges // *Buildings*. 2023. Vol. 13. No. 3. Article no. 827. <https://doi.org/10.3390/buildings13030827> EDN: INCTIS
28. Wolf A., Rosendahl Ph.L., Knaack U. Additive manufacturing of clay and ceramic building components // *Automation in Construction*. 2022. Vol. 133. Article no. 103956. <https://doi.org/10.1016/j.autcon.2021.103956> EDN: KROOVS
29. Фиговский О.Л., Потанов Ю.Б., Поликутин А.Э., Неуен З.Ф. Прочность нормальных сечений двухслойных каутоно-бетонных изгибаемых элементов строительных конструкций // Восточно-Европейский журнал передовых технологий. 2014. № 11 (72). С. 14–20. <https://doi.org/10.15587/1729-4061.2014.30120> EDN: TCSMSZ
30. Попов И.И., Левченко А.В. Экспериментальное исследование внутреннего трения в каутоне и фиброкаутоне // Научный журнал строительства и архитектуры. 2021. № 4 (64). С. 83–92. <https://doi.org/10.36622/VSTU.2021.64.4.008> EDN: QHDDDE
31. Polikutin A.E., Potapov Yu.B., Levchenko A., Perekal'skiy O. The stress-strain state of normal sections rubcon bending elements with mixed reinforcement // *International Scientific Conference Energy Management of Municipal Facilities*

and Sustainable Energy Technologies EMMFT 2018 : Серия: Advances in Intelligent Systems and Computing Voronezh and Samara, Russia, 10–13 декабря 2018 года. Vol. 2. Cham: Springer, 2019. Vol. 983. P. 586–599. https://doi.org/10.1007/978-3-030-19868-8_56 EDN: RWARUH

32. Kovalchuk V., Onyshchenko A., Sysyn M., Hnativ Y., Tiutkin O., Koval M., Parneta M. Restoration of the bearing capacity of damaged transport constructions made of corrugated metal structures // The Baltic Journal of Road and Bridge Engineering. 2021. Vol. 16. No. 2. P. 90–109. <https://doi.org/10.7250/bjrbe.2021-16.529> EDN: NGTPIH

33. Kovalchuk V., Sysyn M., Movahedi Rad M., Fischer S. Investigation of the bearing capacity of transport constructions made of corrugated metal structures reinforced with transversal stiffening ribs // Infrastructures. 2023. Vol. 8. No. 9. Article no. 131. <https://doi.org/10.3390/infrastructures8090131> EDN: UWUXSH

34. Остерман Е.Д., ШUTOва О.А. Анализ типов сооружений из металлических гофрированных конструкций // Вестник ПНИПУ. Строительство и архитектура. 2016. Т. 7. № 1. С. 18–29. <https://doi.org/10.15593/2224-9826/2016.1.03> EDN: VPZUTJ

35. Brooks H., Lupeanu M.E., Piorkowski B. Research towards high speed extrusion freeforming // International Journal of Rapid Manufacturing. 2013. Vol. 3. No. 2–3. P. 154–171. <https://doi.org/10.1504/IJRAPIDM.2013.053686>

36. Поликутин А.Э., Константинов И.А., Нгуен З.Ф., Чыонг З.Х. Исследование прочности наклонных сечений двухслойных каутоно-бетонных изгибаемых элементов при изменении величины относительного пролета среза // Строительная механика и конструкции. 2014. № 1 (8). С. 107–116. EDN: SYRZTV

37. Khaloo A., Darabad P.Y. Investigation of flexural capacity of concrete containing liquid silicone rubber // Shock and Vibration. 2021. No. 2021. Article no. 6668283. <https://doi.org/10.1155/2021/6668283>

38. Alasmari H.A., Abu Bakar B.H., Noaman A.T. A comparative study on the flexural behaviour of rubberized and hybrid rubberized reinforced concrete beams // Civil Engineering Journal. 2019. Vol. 5. No. 5. P. 1052–1067. <https://doi.org/10.28991/cej-2019-03091311>

39. Заборова Д.Д., Дунаевская Ю.П. Преимущества и особенности применения гофро-балки в строительстве // Строительство уникальных зданий и сооружений. 2014. № 7 (22). С. 36–53. EDN: SKDYAJ

40. Vahidimanesh B., Farrokhhabadi A., Shahvari R., Gazor M., Mahdiabadi M. Experimental and numerical investigation of damage in multilayer sandwich panels with square and trapezoidal corrugated cores under quasi-static three-point bending // Engineering Structures. 2024. Vol. 318. Article no. 118715. <https://doi.org/10.1016/j.engstruct.2024.118715>

41. Mathieson H., Fam A. Numerical modeling and experimental validation of axially loaded slender sandwich panels with soft core and various rib configurations // Engineering Structures. 2016. Vol. 118. P. 195–209. <https://doi.org/10.1016/j.engstruct.2016.03.044>