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QUALITY AND COMPETITIVENESS OF 3D-PRINTED SLABS

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Abstract: *The paper discusses the use of 3D printing for slab construction, focusing on the quality and competitiveness of new structures. An innovative approach to the construction of horizontal load-bearing elements is proposed, using mortar mixes with partial replacement of cement with aleuropelite and the viscosity modifier methocaolin. The main attention is paid to the printing technology, which includes the use of a gantry 3D printer with a "mortar extruder" and the development of the design of rotatable slab segments. The article analyzes existing methods and approaches to 3D printing in construction, identifying the shortcomings of traditional technologies and the need to improve them to increase efficiency. The existing experience of printing beams and flat trusses using concrete mixtures is considered. Methods for calculating and evaluating the quality of 3D printed slabs, including a qualimetric methodology for assessing competitiveness compared to traditional slab types, are proposed as part of this work. The results show that the new technologies can provide higher quality and lower construction costs, making them competitive in the market. In addition, the use of 3D printing can significantly reduce construction time, which is particularly relevant in the context of increasing demand for housing. The use of automated processes reduces dependence on labor, which helps to solve the problem of a shortage of qualified specialists in the construction industry. It is also worth noting that the introduction of eco-friendly materials in 3D printing helps reduce the negative impact on the environment, making construction more sustainable and efficient.*

Keywords: *construction, additive technologies, slab, quality, competitiveness, design, numerical methods*

1. Introduction

Additive technologies in construction represent a significant step forward in the design and erection of buildings. Every year, there is a growing interest in 3D printing, which makes it possible to create structures with high precision and minimal time. In particular, the use of additive technologies for slabs opens up new horizons for architects and engineers, allowing them to realize complex geometric shapes and improve the performance of buildings.

The main directions of the state policy in the sphere of development of the additive technologies industry in the Russian Federation are defined in the Strategy for the Development of Additive Technologies in

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the Russian Federation for the period up to 2030. The strategy is aimed at creating a competitive industry of additive technologies on the basis of development of scientific, technical and personnel potential, optimization of production capacities, their modernization and technical re-equipment, creation of new technological directions and technologies, development of priority industrial additive technologies.

Currently, the main direction of development of 3D-additive construction technologies is extrusion 3D printing - the object is created by layer-by-layer extrusion of a visco-plastic mixture (Tay et al., 2017; Mechtcherine et al., 2020; Lyu et al., 2021) Key advantages of additive technologies in construction: construction of individual and architecturally unique construction projects; reduction of time and cost of construction of buildings and structures; the possibility of rapid production of single and small-series elements and structures; realization of production of single and small-series elements and structures; implementation of production and manufacturing of single and small-series elements and structures; implementation of production and manufacturing of single and small-series elements and structures.

An unresolved problem is that in practice, robotic 3D printing in construction projects is currently used only to build the shell of vertical structures, mainly walls, which are reinforced and finished using traditional manual methods. With the exception of walls, the remaining structures of these objects (slabs, beams, stairs, etc.) are usually also manufactured using traditional concrete casting technology. As a result of this scientific and practical approach, the labor and time costs and the cost of 3D-printed objects remain at the level of traditional construction technologies. This contradicts the idea of construction 3D printing as a robotic intelligent technology and leads to its vulgarization. It is recognized that this situation is an obstacle to the development and implementation of 3D printing in construction practice.

A key aspect of successful implementation of additive technologies is the standardization of processes and materials. At the moment, there are no clear national and international standards for 3D-printed structures, which creates obstacles to their widespread use. However, recent changes in the legislation of the Russian Federation concerning technical regulation of the safety of buildings and structures open up new opportunities for the application of innovative technologies in construction. This allows designers to use alternative methods to justify design solutions, which can significantly accelerate the process of implementing additive technologies.

The analysis of scientific papers on the arrangement of bending load-bearing elements in 3d printing of buildings and structures shows that the information is mainly of a review nature. For example, in (Fayzollin & Chernavin, 2022) the authors point out the possibility of printing slabs in a vertical position with subsequent installation by crane, but this idea for a structure with a large dead weight is difficult to realize, as there is a danger of its destruction during rotation and installation in the design position. Authors in the articles (Swiss scientists) and (Anton et al., 2020) offer to print slabs with a complex system of beams and install the product with a crane, but the process of the device of this structure is very labor-intensive. The works Luneva et al. (2017) and Krainkov (2024) contain a perspective model of a building that is printed on a 3d printer, including the slab structure, but there is no information about the methods of erecting horizontal elements. The source (Additive technologies) contains information on the construction of beams for bridge structures printed sectionally and then joined together using a complex system of external reinforcement. The paper (Maitenaz et al., 2021) proposes a variant of the slab device for which the formwork is first printed using a 3D printer and then the cavities are filled with mortar. This method is very difficult to produce and does not differ much in labor intensity from the traditional monolithic slab.

A similar solution for the rotation of the supporting element was proposed by scientists from the University of Southern California (Gorbach et al., 2016, Figure 1a), but there is no information on the reinforcement and materials of the product. In (Figure 1b) an image of a similar structure with external reinforcement, the data on the manufacturing location and materials are not known. In (Figure 1c) is a photograph of a variant of a similar segment proposed in (Breseghello & Naboni, 2022), in the form of a beam with parallel girders connected by a tortuous network of elements arranged according to the position of the main stresses. This design was calculated using computer programs and the element was fabricated and tested for 3-point bending.

(a) Published in (Gorbach, 2016)

(b) Published in (O'Neal, 2015)

(c) Published in (Breseghello & Naboni,,2022)

Figure 1. Examples of manufactured pivoting structures

At the University of Viçosa, Brazil, a pivoting structure was fabricated and tested with the beam, and the calculation was performed as for a structure consisting of rectilinear rods connected hingedly (Veloso et al., 2022). This type of calculation does not allow to fully cover the real operation of the structure, as it does not take into account the operation of the mating elements in the hinge joints. The reinforcement was selected based on the tensile behavior of the rod, and the reinforcement was installed manually (Figure 2).

Currently, there are no national, international and regional standards for building structures made by 3D printing based on cement composites. There is no mention of 3D-printed structures of buildings and structures in the Code of Regulations (CoR). In accordance with the Federal Law No. 653-FZ dated December 25, 2023 "On Amendments to the Federal Law "Technical Regulations on the Safety of Buildings and Structures", the ways of justification of design solutions to ensure the safety of buildings and structures at all stages of the life cycle have been expanded. The list of documents, as a result of the application of which ensures compliance with the requirements of the Federal Law "Technical Regulations on the Safety of Buildings and Structures" includes the results of the application of methods of substantiation (part 6 of Article 15) of compliance of architectural, functional-technological, structural, engineering and other solutions to ensure the safety of buildings and structures.

The regulation, which came into force on September 1, 2024, allows, in a simplified format, to promptly introduce innovative materials into design and construction and to apply non-standardized non-ordinary design solutions by providing designers with the opportunity to choose alternative options to justify their technical solutions by establishing requirements.

Figure 2. Manufacturing and testing of a rotary structure (Veloso et al., 2022)

The efficiency of slabs of different designs is determined by the required level of quality and an acceptable market price. The point is that it is necessary to assess the price-quality ratio, or in other words, the potential competitiveness of 3D-printed slabs in comparison with traditional types of slabs. It should be noted that building products and structures characterized by minimum costs for obtaining the required functional properties (heat and sound insulation, strength, etc.), relatively low price and high quality level should be considered competitive (Ortiz et al., 2009).

In this paper we consider the technology of slabs made of rotary segments, which are printed using a 3D printer, structural calculation and selection of reinforcement for the rotary segment of the slab.

The effectiveness of the proposed approach to slab construction is proved by the qualimetric method developed by the authors to evaluate the quality and competitiveness of 3D printed slab in comparison with traditional solid monolithic and hollow prefabricated slabs.

The problem of objective measurement and quantitative assessment of product quality is currently one of the key problems: the competitiveness of domestic manufacturers depends on its solution. Quantitative assessment of aggregate quality indicators of reinforced concrete floor slabs, differing in design features and production technologies, makes it possible for designers and manufacturers to solve many problems of product quality at the stage of design, manufacturing and installation.

The authors of this paper present calculations and research results as part of the evidence base to justify the safe use of pivoting slab segments in multilayer construction in building construction.

The use of qualimetry in construction provides a scientifically based transition from intuitive assessments to quantitative quality management (Azgaldov et al., 1989). This approach is particularly relevant for new technologies, such as 3D concrete printing, where traditional standards have not yet been fully developed. The integration of qualimetric methods with digital design and manufacturing tools creates the foundation for improving the competitiveness of construction products (Lielgaidina & Geipele, 2011).

2. Methods

2.1 Slab installation technology

On the example of an individual residential house, which is planned to be printed with a 3D printer, let's consider the technology of the slab device.

The printer gantry structure (Figure 3) was chosen for the erection of this facility.

The overlap has been proposed to be divided into rotatable segments that are printed on a turntable provided in the printer design (Figure 4).

The segment is printed in a horizontal position, and when it gains the necessary strength, it is installed in the design position using the same platform, as shown in Figure 4. The weight of the slab segments in this case does not exceed 400 kg, (for spans up to 5.0 meters), so it does not require additional lifting and transport mechanisms. After the slab disk is formed from the "turning segments", the upper joints between them are caulked with mortar mixture, uniting the structure into a single whole.

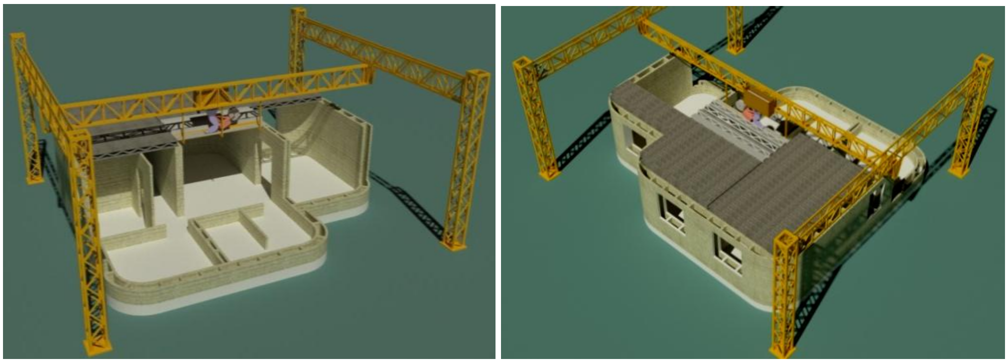

Figure 3. Printing of the overlap segment on the turntable of the portal printer

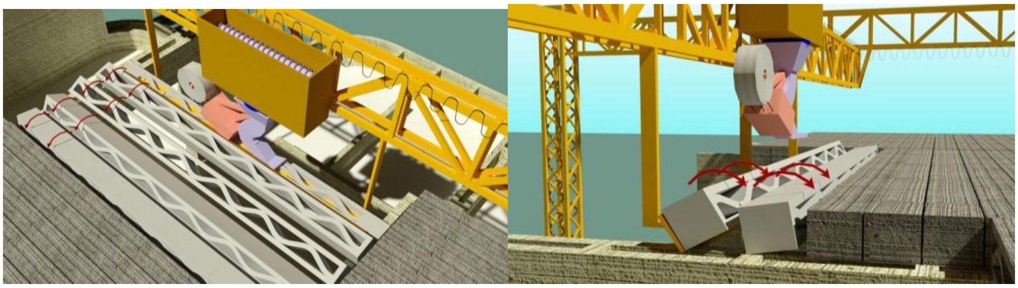

Figure 4. Printing of the overlap segment on the turntable of the portal printer

The design is made using an extruder, which involves 3 nozzles that feed the mortar mixture. Water flooding and mixing of the 3D printing mixture is carried out in the hopper of the mortar extruder just before the mixture is fed to the nozzles. Behind the extruder there is a device for laying the reinforcement, stepper motors of which ensure the feeding of reinforcement wire from the coil. This method of reinforcement is described in the work (Bos et al., 2017). The required geometric position of the reinforcement wire is additionally ensured by the design of the mortar nozzles. The extruder and reinforcing device together with the wire coil can be rotated through 360 degrees in the horizontal plane relative to the hopper. The mortar hopper also has the ability to move vertically relative to the printer's support truss to allow unobstructed operation of the turntable. After gaining strength of not less than 70% of the grades, the platform on which the structural element is printed, rotates the element by 90 degrees with its installation in the design position. The turntable is designed to be removable, and the printer itself is used to print walls or other building elements after the turntable is removed.

Another variant of the proposed methodology can be considered as printing the slab directly on the ground. In this case, the pivoting segments are provided in the form of structures that make it possible to form the pitched roof of the building (Figure 5). After gaining strength, these structures are placed in the design position by means of a crane. The weight of the segments for the example building does not exceed 800 kilograms, so if the load-carrying equipment is available in the gantry printer design, the assembly can be carried out without the use of a crane.

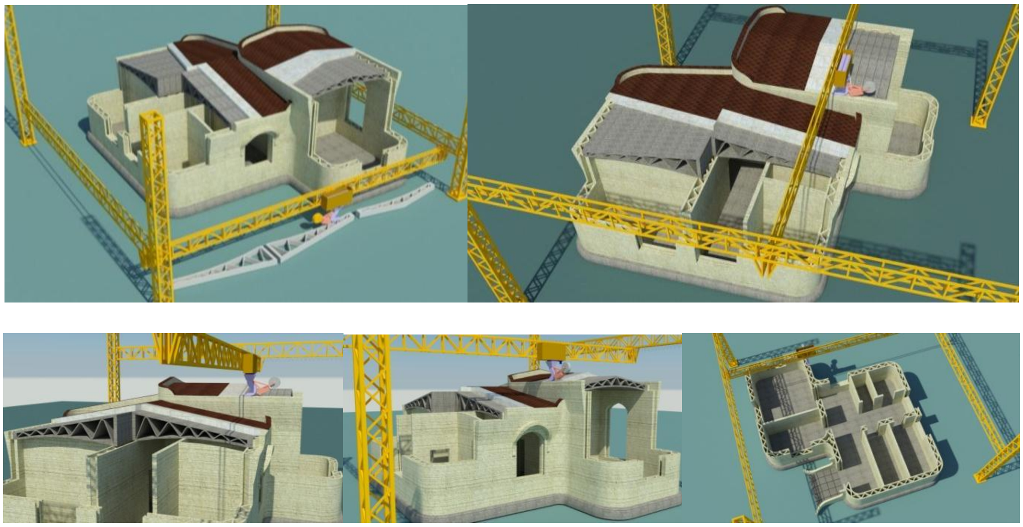

Figure 5. Printing of the slope-forming overlap segment on the ground

2.2 Calculation method of the rotary segment

Structural calculation of the rotating segment and selection of the necessary reinforcement is proposed to be performed using the Lira Sapr (Gubchenko, 2017) software package or similar programs such as Lira Soft, Scad Office, Stark ES. These programs are based on the finite element method, which have good convergence of the calculation results in comparison with the experimental results, as indicated in Lapina (2019), Vodopianov (2019), Popov et al. (2013), Klovanich & Mironenko (2007).

As an object of research the turning segment with a span of 4.8 m, segment height 250mm, segment width 250mm with different configuration of connecting elements between the lower and upper belt of the turning segment, which are shown in Figure 6.

The finite element models were formed in two ways:

1) volumetric bodies (finite element type-36), with element dimensions of 0.05×0.05×0.05 meters;

2) with the finite element "Type 42/44", then "plates" with dimensions of 0.05×0.05 meters, and for the correctness of the calculation scheme, when modeling "plates", to ensure the joint operation of differently shaped elements at the point of contact of the wave-shaped and rectilinear element, the

association of linear and angular displacements was introduced with the help of absolutely rigid bodies (ARB). When formed at the point of contact between the wave and the belt, a number of nodes are created, located exactly along the contour of the cross-section, then, these nodes are combined in the ARB, with the leading node assigned to the center at the top, the other nodes of the joint were slave.

The type of fixing at the ends of the structure under consideration is assumed to be hinged and fixed.

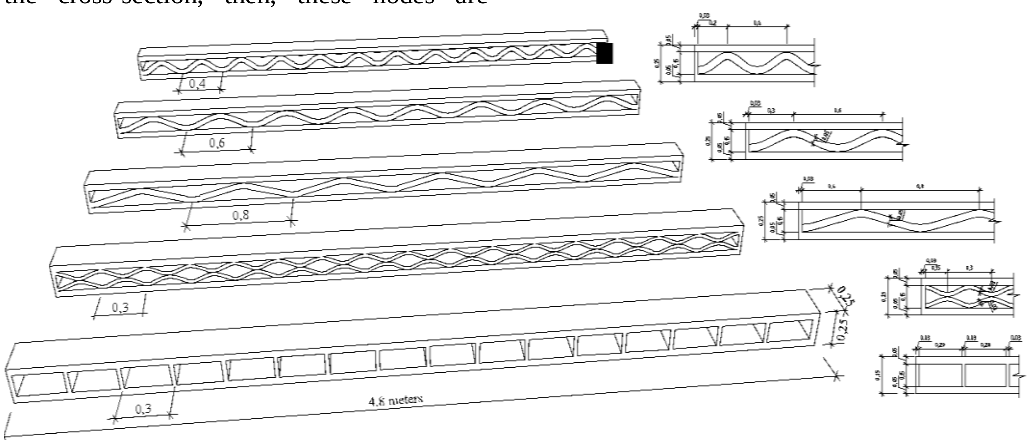

Figure 6. Variants of swivel segments with different configurations of connecting elements between the lower and upper girdle

When selecting the reinforcement for the elements, the protective layer was set up to the center of gravity of the reinforcement and is 25 millimeters, based on the condition that the reinforcement is located in the center of the printed layer with a thickness of 50 millimeters. The required reinforcement was calculated without taking into account the physical nonlinearity of the materials.

The following parameters were used as calculated material characteristics for the rotary segment: mix material Eb=22000.0 MPa, Rbn=22.0 MPa, Rbtn=1.75 MPa, Rb=17.0 MPa, Rbt=1.15 MPa; reinforcement Es=200000.0 MPa, Rsn= 1500.0 MPa, Rs= 1300.0 MPa, Rsw=300 MPa, Rsc=500.0 MPa.

As a load the following is taken into account: dead weight of the product γ=2,5 t/m^3 ; useful load with intensity P=1,0 t/m^2 applied to the upper chord of the element. For the first case of modeling the application of the payload was carried out to the upper edge of the volume element.

The main criteria for evaluating the optimal design option were:

- Minimum Z-axis movements (vertical);
- Minimum stresses Nx-tensile/compression along the span direction;
- Maximize print manufacturability.

2.3 Methodology for assessing the competitiveness of slab structures

The author's methodology was developed on the basis of qualimetric expert method of product quality assessment (Azgaldov et al., 2014) based on the use of complex quality indicators (Akulova, 2007; Akulova & Slavcheva, 2021; Akulova et al., 2021). The methodology was previously tested on the example of a number of building materials and products (Akulova et al., 2017; Akulova et al., 2024; Slavcheva et al., 2017).

This approach is particularly useful in situations where other assessment methods (e.g., instrumental or computational) cannot be applied. Key characteristics of the expert method include:

- selection of an expert group of at least 20 specialists;
- independence and anonymity when conducting the questionnaire;
- statistical processing of questionnaire results with calculation of consistency of expert opinions by the concordance coefficient.

The methodology of competitiveness assessment included the following steps:

Stage 1 - selection of the list of properties, assessment of their importance for the consumer. The method of expert evaluations realized on the basis of questionnaires was used. In the course of selecting the nomenclature of quality indicators, the group to which the constructions of the considered floor slabs belong was taken into account, destination indicators and production-technological indicators were singled out.

The questionnaire proposed to the expert, in addition to the list of consumer properties of the product, contained the parameters of the scale of expert assessment of their importance for the consumer. A point scale was used, increasing from one to a higher point, which coincides with the number of highlighted properties. And the number of points in the evaluation of different properties should not be repeated. The most significant property for the consumer, in the expert's opinion, is assigned the highest score.

Calculation of property weighting coefficients was carried out in tabular form (Table 1). The following condition must be fulfilled

$$\sum_{i=1}^{n} M_{ni} = 1 \quad (1)$$

where n is the number of consumer properties; M_{ni} is the value of the weighting coefficient of I – that consumer property.

Observance of equality (1) ensures comparability of the calculations performed regardless of the number of properties considered

Table. 1 Calculation of the weighting coefficient of indicators of consumer properties of the product

Name indicators properties	The meaning of the ballpark estimates (M) by experts (r)					Medium weighting factor $M' = \sum M / r$	Total sum of average coefficients weights $\sum M'$	Coefficient weights for each indicator $M_i = M' / \sum M'$
	1	…	rg	…	r			
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…

Step 2 – calculation of a single competitiveness indicator for each attribute and product. Initially, it is necessary to make a transition from properties to relevant indicators and select a comparison base. The abstract product with the best values of indicators among all the compared products is taken as the base of comparison, which acts as a reference product in subsequent calculations.

Table. 2 Comparison of indicators of consumer properties of products of different manufacturers

Name indicators properties	Value of product indicatorscompetitors (P_{ij}) by type				Significance indicators reference product
	…	…	…	…	
…	…	…	…	…	…

Then for each j – that product of Table 2 for all indicators (P_{ij}) a single indicator of competitiveness (k_{ij}) is calculated according to the ratios:

$$k_{ij} = P_{ij} / P_i^{эт} \quad (2)$$

$$k_{ij} = P_i^{эт} / P_{ij} \quad (3)$$

where $P_i^{эт}$ is the value of i - that index of the benchmark product, and P_{ij} is the value of i - that index of the product of j - that manufacturer.

Ratio 2 applies to the case when an increase in the value of an indicator is reflected in an increase in the quality of the product; Ratio 3 applies to the case when the quality of the product is improved when the value of an indicator is reduced (e.g. thermal conductivity coefficient).

Stage 3 - Calculation of indices and relative indicators of competitiveness of competing products. To determine the competitiveness index characterizing the quality of the product, the scheme is used

$$Q_{nj} = \sum_{i=1}^{n} k_{ij}^{n} \cdot M_{ni} \quad (4)$$

where $Q_{пj}$ - competitiveness index by consumer properties; k_{ij}^{n} - unit competitiveness index of i - that consumer property of j - that product.

Finally, a relative competitiveness index ($P_{кj}$) is calculated for each product of different manufacturers:

$$П_{кj} = \frac{Q_{nj}}{Ц_{oj}} \quad (5)$$

where $Price_{oj}$ is a relative indicator of the selling price of the product of j-th producer. In turn

$$Ц_{oj} = \frac{Ц_j}{Ц^{эт}} \quad (6)$$

where $Price_j$ - selling price of j - that product, p.; $Price_{эт}$ - selling price of the reference product, i.e. the lowest price.

Obviously, the closer the value of $P_{кj}$ is to one, the more competitive is the product of a particular manufacturer on the market.

3. Results

3.1 Results of numerical calculations

Analysis of the results of the calculation, which is made by the first method using finite elements Type 36, for structures of 3 variants with different type of "lattice" shows:

1) Maximum positive (tensile) stresses Nx (Figure 7) occurring in the volume elements of the connecting grid are characteristic for variant 1, and positive stresses Nx in the lower belt are minimal for this variant. For variants 2 and 3, the positive stresses Nx in the lower belt are commensurate with each other, but greater than for variant 1, and no maximum stresses occur in the grid elements;

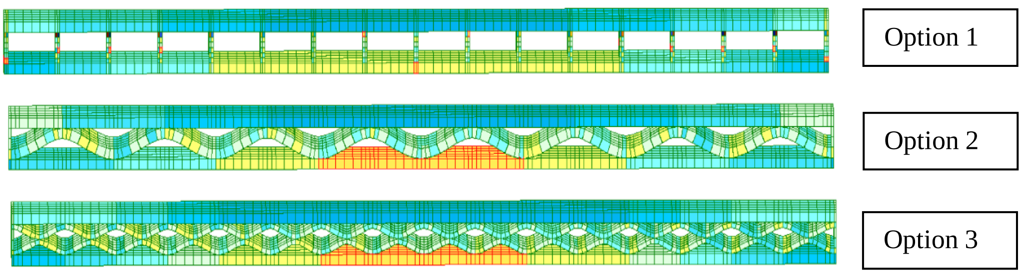

Figure 7. Voltages Nx

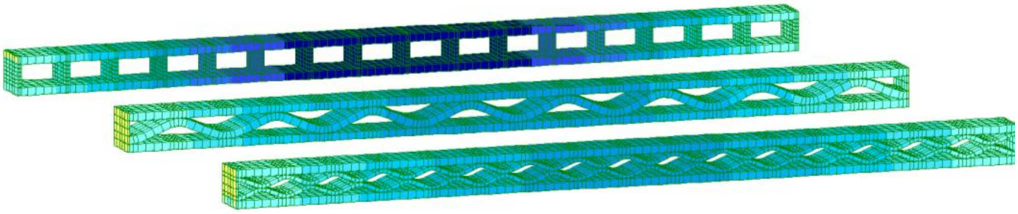

Figure 8. Movements along the Z axis

2) According to the results of the calculated displacements (Figure 8), it can be concluded that option 1 is more deformable than the other options. Variants 2 and 3 are commensurate with each other in terms of deformability;
3) According to a set of criteria, of the proposed variants of the rotating slab segments shown in Figure 7, the most optimal configuration can be considered to be variant 2, the belts of which are connected by means of a wave-shaped element. This conclusion is based on the fact that the stresses occurring in the element are minimal, and in terms of printing technology using a 3 D printer, this configuration is the most suitable.

Further, we compared the calculation results with different approaches to creating a finite element model. This comparison was made in order to determine the optimal approach for creating a calculation scheme in software packages based on the finite element method for structures printed with a 3D printer. For clarity, Figure 9 shows a fragment of a rotating segment created in two different ways. The upper image in this figure is modeled by "bodies", the lower one by "plates" + ARB.

The results of strain calculations for different approaches to element modeling (bodies and plates) shown in Figure 10 show that the deformations of the element when modeled with "bodies" and "plates" are not very different from each other.

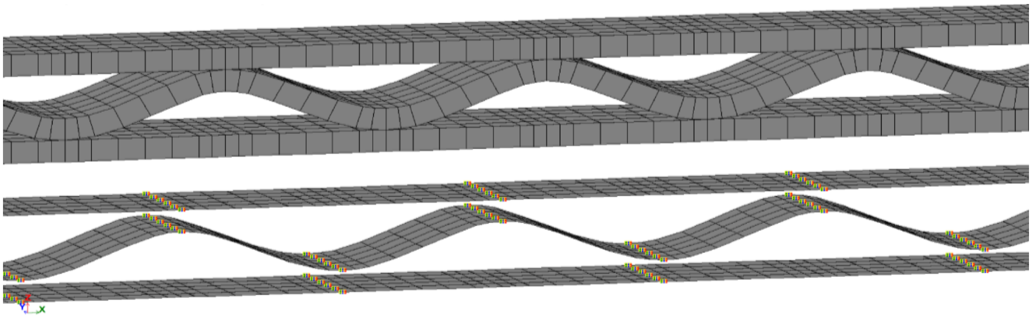

Figure 9. Fragment of the calculation scheme. Modeled with "bodies" at the top and "plates "+AJT at the bottom

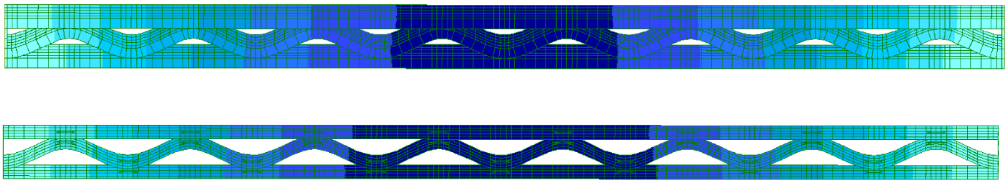

Figure 10. Comparison of displacements along Z direction with different modeling method

The results of stress calculation (Figure 11) also showed minimal discrepancies, therefore, in order to reduce the labor intensity of the calculation model creation and to take into account loads of various kinds, it is necessary to use universal three-angled/four-angled QE Type 42/44 + ARB in the appropriate places, which allows minimizing the labor input for the finite element model creation without compromising the correctness of the results. In addition, when creating a calculation scheme using "plates" (Type 42/44 elements), it is easy to determine the reinforcement in the structure, but for Type 36 elements it is not possible to select the reinforcement in Lira Sapr, Lira Soft, Scad Office, Stark ES.

Further, all the calculation results given below in this paper are computed using the second approach.

Using the second approach to create the computational scheme, the optimal configuration of 3 types of connection grating for the rotary segment, which are shown in Figure 12 with different half-wave lengths (0.4m, 0.6m and 0.8m), is analyzed and identified.

The results of deformation calculations based on the Lira PC (Figure 13) show that the most deformable variant is Type 3 with a half-wave length of 0.8m. The highest stiffness of the structure belongs to the Type 1 variant.

The stress analysis N_x (Figure 14) shows that the minimum number of elements with maximum tensile forces contains the slab structural element of type 2. Since the reinforcement of elements in 3D printing is a complex procedure, in this case we should strive to minimize the elements subject to maximum reinforcement, so the variant of the slab structural element type 2 is of the greatest interest from this point of view.

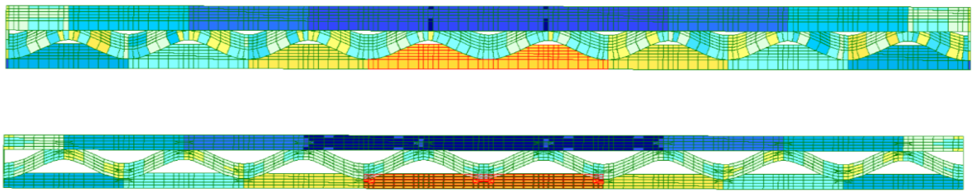

Figure 11. Comparison of Nx stresses with different modeling method

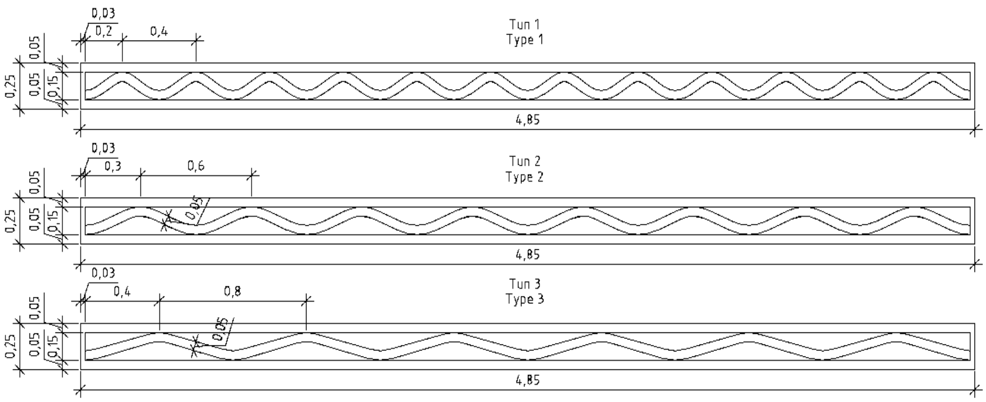

Figure 12. Variants of grid types

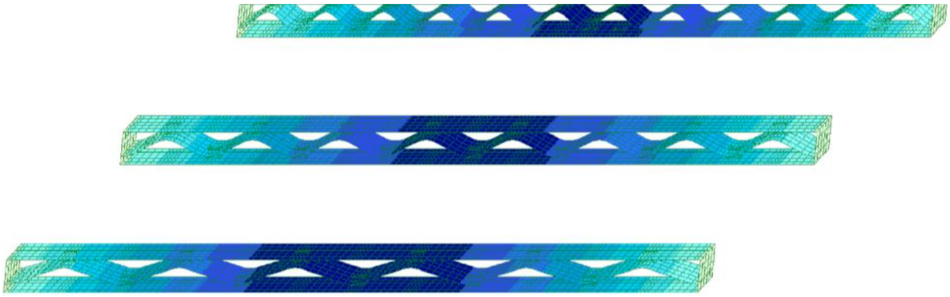

Figure 13. Comparison of displacements in the Z direction for different types of Lira PC grids

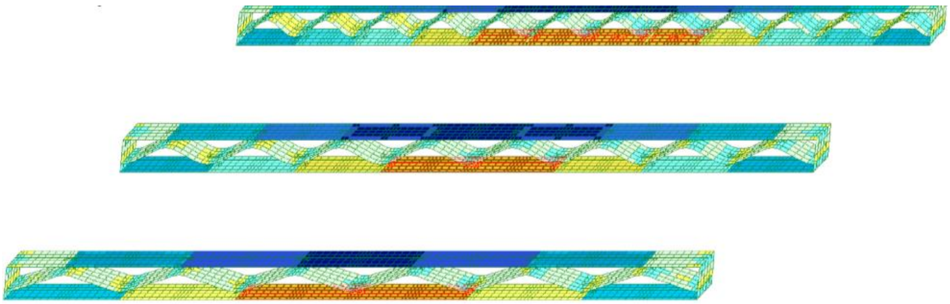

Figure 14. Comparison of Nx stresses for different lattice types

In general, according to the data obtained, it can be concluded that the option with a half-wave length of 0.6m or a grid configuration oriented at an angle of 27 degrees is optimal. Also on the basis of the proposed methodology, calculations and analysis of the stress-strain state for rotary segments of different configurations, which are shown in Figure 15, the purpose of the study is to determine the design, which contains a minimum of tensile elements.

The analysis of the results shown in Figure 16 showed that the structures labeled f and g, whose lower belt has an arched shape and whose lattice structure for connecting the upper and lower belt is oriented at an angle of 27 degrees, are the most prioritized.

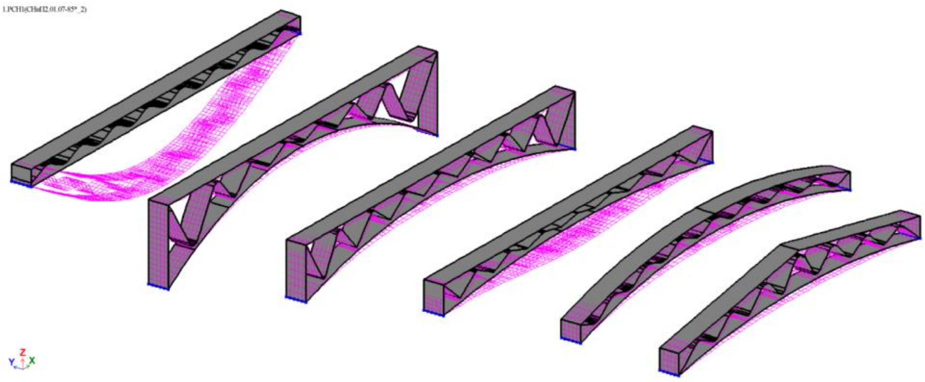

Figure 15. Investigated types of pivoting segments and their deflections obtained by calculation

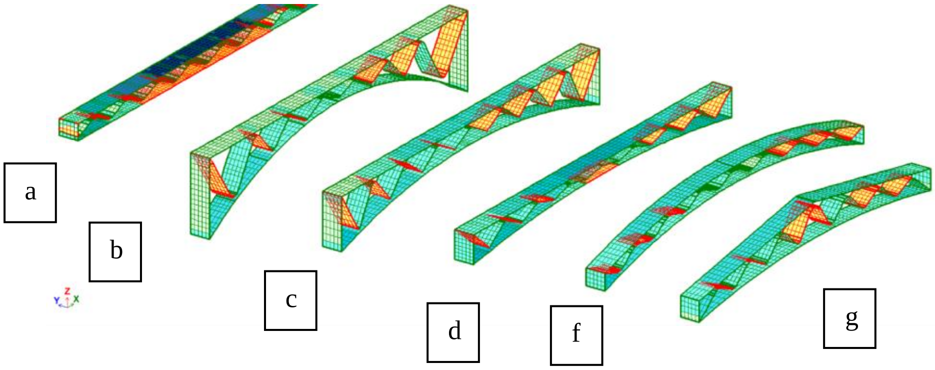

Figure 16. Result of the Nx stress calculation (elements subject to tension are highlighted in red)

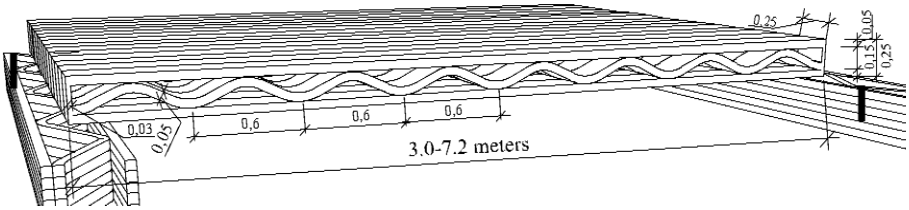

Figure 17. Geometric dimensions of the rotating overlap segment

Also of interest is the variant with a horizontal bottom belt a, in which the grid configuration is oriented at an angle of 27 degrees.

Next, the required reinforcement of the slab segment was calculated for different spans in the range of 3.0-7.2 m (Figure 17) for varying values of payloads (600, 800 and 1000 kgf/m^2). Increasing the span size was envisaged in steps of 0.6 m. The results of the calculation for determining the reinforcement are summarized in Tabl. 3 and shown on the graph (Figure 18.

Table 3. Required reinforcement of the top and bottom chord of the pivoting slab segment

Span length	Required reinforcement cm /m^2	Required reinforcement (pcs) of the swivel segment				Required reinforcement cm /m^2	Required reinforcement (pcs) of the swivel segment				Required reinforcement cm /m^2	Required reinforcement (pcs) of the swivel segment			
		⌀2	⌀3	⌀4	⌀5		⌀2	⌀3	⌀4	⌀5		⌀2	⌀3	⌀4	⌀5
Payload on swivel segment 600 kgf/m^2						Payload on swivel segment 800 kgf/m^2					Payload on swivel segment 1000 kgf/m^2				
3,0	0,50	4	2	1	1	0,50	4	2	1	1	0,50	4	2	1	1
3,6	0,50	5	2	1	1	0,50	4	2	1	1	0,55	5	2	1	1
4,2	0,50	5	2	1	1	0,56	5	2	2	1	0,77	7	3	2	1
4,8	0,70	6	3	2	1	0,82	7	3	2	2	0,95	8	4	2	2
5,4	0,96	8	4	2	2	1,13	10	5	3	2	1,30	11	5	3	2
6,0	1,12	10	4	3	2	1,34	12	5	3	2	1,54	13	6	4	2
6,6	1,39	12	5	3	2	1,48	13	6	4	2	1,71	15	7	4	3
7,2	1,61	14	6	4	3	1,69	15	7	4	3	1,93	17	7	5	3

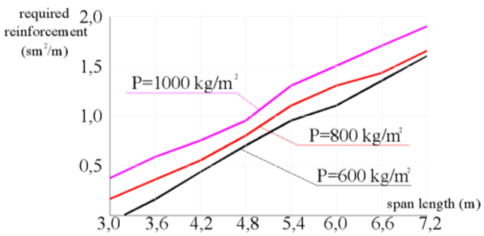

Figure 18. Graphs of the dependence of the change in the cross-sectional area of the reinforcement in the rotary segment depending on the size of the span of the structure

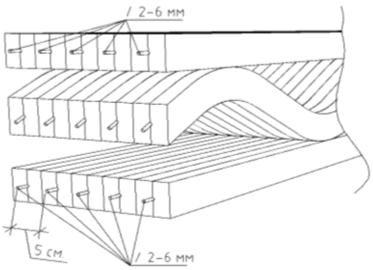

Figure 19. Reinforcement of the floor with wire

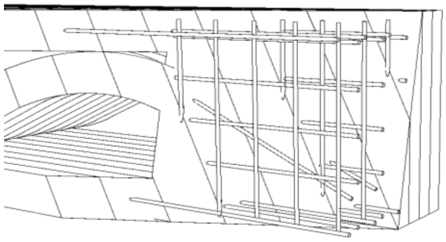

Figure 20. Reinforcement of the supporting area with grids

a. Results of quality and competitiveness assessment of slabs

To assess the quality and competitiveness of the developed 3D-printed slabs, a solid slab manufactured by monolithic method and a hollow-core slab were selected as competitor products.

Geometric dimensions (in meters) of the considered objects are shown in Figure 21.

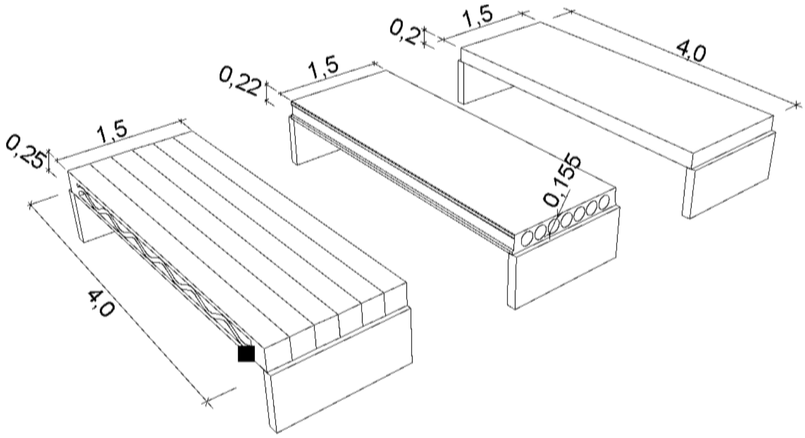

Figure 21. Slab diagrams: (a) prefabricated slab made of rotatable 3D printed segments, (b) hollow core slab, (c) solid slab

Selection of the list of properties, assessment of their importance for the consumer was realized on the basis of questionnaire survey of 110 respondents-experts working in the construction industry of Russia.

Based on the conducted expert evaluation with a concordance coefficient of 0.7 (shows the degree of consistency of experts' opinions), weight coefficients of importance for the consumer of slab properties were obtained, divided into two groups: destination indicators and production and technological indicators Figure 22.

As a result of processing by statistical methods of the received answers regarding the importance of groups of indicators in the competitiveness of slabs it was revealed that the most important for builders with a weight coefficient of 0.59 are production and technological indicators that determine the speed and resource intensity of construction processes.

The obtained weighting coefficients of the indicators of each individual property are involved in further research in the evaluation of the competitiveness of slabs, involving the use of numerical values (Ovcharov et al. 2021).

At the same time, the values of designation indicators for monolithic solid and prefabricated hollow core slabs were determined in accordance with the current normative documents. Since there are no standardized technical requirements for 3D printed slabs, the values of these indicators were determined on the basis of the above calculations. The values of production and technological indicators for monolithic solid and prefabricated hollow core slabs were also determined in accordance with the current normative documents, while for 3D-printed slabs the values of these indicators were determined on the basis of previously conducted studies (Akulova et al., 2020).

The results of the competitiveness assessment of 3D printed slabs, performed according to the methodology proposed by the authors, are presented in Table 4.

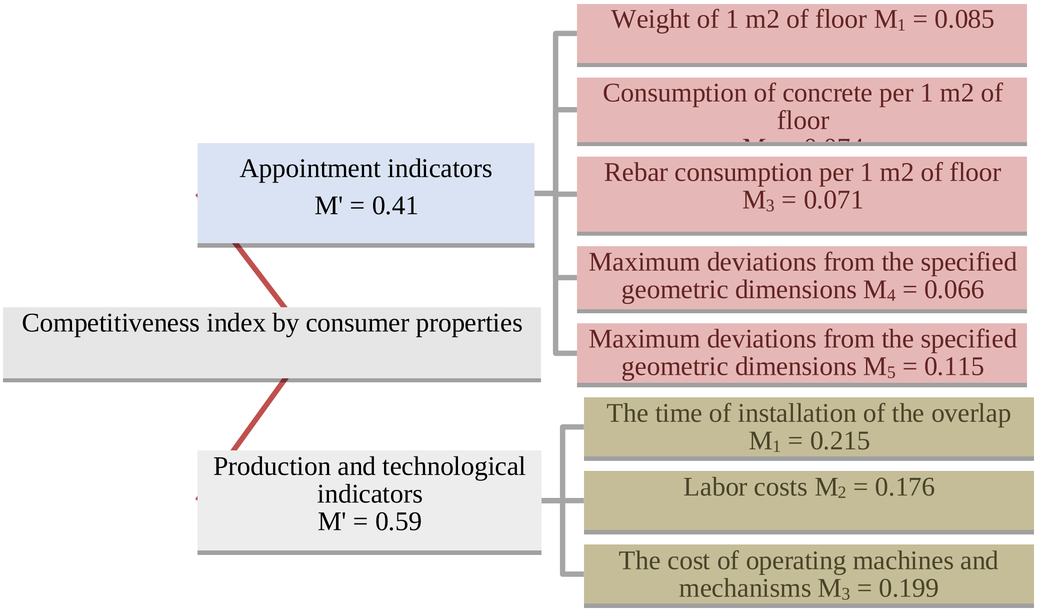

Figure 22. "Tree" of indicators determining the competitiveness of slabs: M' - weighting coefficient of the group of indicators; M_i - weighting coefficient of the i-th indicator in the group

According to calculations, 3D printed slabs have been proven to be highly competitive compared to traditional monolithic solid and prefabricated hollow core slabs. This is due, firstly, to its lowest price. Secondly, the competitive advantages of 3D-printed slabs include low material intensity and minimal labor costs. At the same time, the weak competitive position of 3D-printed slabs in terms of the cost of operating machinery and mechanisms becomes obvious.

Table 4. Competitiveness assessment results of 3D printed slabs

Name indicators comparisons	Indicators for 3D printed slabs	Values for multi-hollow core slab	Indices for monolithic slab	Benchmark
Assignment indicators				
Weight of 1 m^2 of slab, kg	250	273	500	250
Concrete consumption per 1 m^2 slab, kg	0,12	0,11	0,22	0,11
Reinforcement consumption per 1 m^2 slab, kg	1,54	3,44	21,33	1,54
Limit deviations from specified geometrical dimensions, mm	5	3	10	3
Bearing capacity, units. kPa	8	8	8	8
Production and technological indicators				
Slab installation time, min/m^2	90	5	2160	5
Labor Costs, man-h/m^2	0,115	0,195	0,979	0,115
Costs for operation of machinery and mechanisms, p./m^2	1442	930	270	270
Price, p/m^2	1950	3150	3422	1950
Competitiveness index of consumer properties (comprehensive quality index), Q_{nj}	0,60	0,74	0,44	1
A relative measure of product competitiveness, Π^{o}_{kj}	0,60	0,46	0,25	1

The theory of organization of the subject of expertise reveals the main factors of the organization of expert procedures for assessing the quality of floor slabs and thereby realizes the activity aspect of expert qualimetry (Klochkov et al., 2020).

3. Conclusion

As a result of the research, for the first time a method of slab printing without the use of panel formwork with simultaneous reinforcement arrangement was proposed. The essence of the method is to divide the slab disk into smaller "pivot segments", which are printed on a pivot pad, and then with the help of this pad are set in the design position, forming a rigid disk.

According to a set of criteria, the most optimal configuration of the proposed variants of the rotating slab segments is the one whose belts are connected by a wave-shaped element. Since for this design the stresses arising in the element are minimal, and according to the technology of printing with a 3 D printer, this configuration is the highest priority.

To create a finite element model in the calculation programs it is necessary to use the universal three-angled/four-angled QE Type 42/44 + ATT(AJT) in the appropriate places, which allows minimizing the labor input for creating a finite element model without compromising the correctness of the calculation results.

The results of the study of different half-wave lengths for the pivoting segment with parallel belts show that the variant with a half-wave length of 0.6 m is optimal.

For pivoting segments with non-parallel belts all shapes with a lower arched belt showed a high degree of deformability compared to the structure with straight belts. The slight curvature of the lower chord of the pivot segment significantly affects the internal forces and reduces the proportion of tensile members by a factor of 3. Increasing the height of the pivoting segment does not give significant results in reducing the share of tensile elements in the structure, but only reduces the deformability. Changing the configuration of the connecting lattice has little effect on the overall stress-strain state of the rotary segment.

The analysis of the results of the calculation results for determining the reinforcement in the pivoting segments shows that at span sizes from 3.0 m to 7.2 m, a linear relationship is observed for different payloads, hence at such spans it is possible to predict the reinforcement of the structure, without performing calculations, using the data from the graphs. The prediction can be carried out provided that the design of the pivoting segment corresponds to the geometric dimensions given in the corresponding figure. In order to prevent the formation of cracks in the supported areas of the slab pivoting segment from the action of shear forces, this structure should be made continuous by installing mesh reinforcement in this area.

As a result of the analysis of geometric characteristics of the compared slab variants, it can be noted that the 3D printed variant has comparable strength characteristics with the monolithic slab, but has a lower material intensity (0.11 vs. 0.22 kg), requires less reinforcement (1.54 vs. 21.33 kg/m^2) and has a significantly lower amount of human labor input (0.115 vs. 0.979 man-hours/m^2). The printed slab has a lower manufacturing cost and, as a consequence, with regard to mass and dimensional characteristics, a consumer properties competitiveness index (a comprehensive quality index) of 0.60.

The effectiveness of the proposed approach to slab construction is proved by the results of quality assessment and competitiveness of 3D-printed slabs in comparison with traditional solid monolithic and hollow prefabricated slabs. The competitive advantages of 3D-printed slabs include low material intensity, minimal labor input at the construction site and the lowest price compared to competing slabs.

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