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EXPERIMENTAL SUBSTANTIATION OF CONSTANTS IN THE MATHEMATICAL MODEL OF CONCRETE IN STRUCTURES MADE BY 3D PRINTING TECHNOLOGY

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Abstract*:* The paper presents the results of the study of concrete fracture mechanisms in structures made by 3D printing technology using the layer-by-layer extrusion method. It is established that concrete fractures in such structures occur by fundamentally different mechanisms - cohesion and adhesion fracture mechanisms. The type of fracture mechanism is determined by the load direction relative to the direction of concrete extrusion layers. The compressive strength of concrete and the corresponding basic constant (compressive strength of concrete - R_b) is determined, in general, by the cohesive fracture mechanism. But when loaded parallel to the extrusion layers, the influence of the adhesion mechanism of fracture on the overall value of the key constant of the concrete model has been established. Fracture of concrete in structures made by 3D-printing technology by layer-by-layer extrusion is determined by the direction of loading relative to the direction of concrete extrusion layers. Under loading perpendicular to the extrusion layers (direction of tensile stresses is parallel to the extrusion layers), failure occurs by cohesive mechanism. The value of concrete tensile strength (R_{bt}) corresponding to the cohesive fracture mechanism can be used as a key constant of the mathematical model of concrete. When loading parallel to the extrusion layers (direction of tensile stresses is perpendicular to the extrusion layers), the failure occurs by the adhesion mechanism. As a key constant of the mathematical model of concrete can be used the value of adhesive strength of interaction of layers (R_{adh}), corresponding to the adhesive mechanism of fracture. The presented experimentally substantiated key constants of the mathematical model of concrete provide adaptation of such a model for concrete in structures made by layer-by-layer extrusion.

Keywords: 3D Concrete Printing (3DCP), Mechanical Properties, Anisotropy, Orthotropic Material, Stress-Strain Diagram, Mechanisms of destruction

ЭКСПЕРИМЕНТАЛЬНОЕ ОБОСНОВАНИЕ КОНСТАНТ МАТЕМАТИЧЕСКОЙ МОДЕЛИ БЕТОНА В КОНСТРУКЦИЯХ, ВЫПОЛНЕННЫХ ПО ТЕХНОЛОГИИ 3D-ПЕЧАТИ

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Аннотация: В статье представлены результаты исследования механизмов разрушения бетона в конструкциях, выполненных по технологии 3D-печати методом послойной экструзии. Установлено, что разрушения бетона в таких конструкциях происходят по принципиально различным механизмам – когезионный и адгезионный механизмы разрушения. Вид механизма разрушения определяется направлением нагрузки относительно направления слоев экструзии бетона. Прочность бетона на сжатие и соответствующая базовая константа (прочность бетона на сжатие – R_b) определяется, в целом, когезионным механизмом разрушения. Но при нагружении параллельно слоям экструзии установлено влияние адгезионного механизма разрушения на общую величину ключевой константы модели бетона. Разрушение бетона в конструкциях, выполненных по технологии 3D-печати методом послойной экструзии, определяется направлением нагружения относительно направления слоев экструзии бетона. При нагружении перпендикулярно слоям экструзии (направление растягивающих напряжений параллельно слоям экструзии) разрушение происходит по когезионному механизму. В качестве ключевой константы математической модели бетона может быть использована величина прочности бетона на растяжение (R_{bt}), соответствующая когезионному механизму разрушения. При нагружении параллельно слоям экструзии (направление растягивающих напряжений перпендикулярно слоям экструзии) разрушение происходит по адгезионному механизму. В качестве ключевой константы математической модели бетона может быть использована величина адгезионной прочности взаимодействия слоев (R_{adh}), соответствующая адгезионному механизму разрушения. Представленные экспериментально обоснованные ключевые константы математической модели бетона обеспечивают адаптацию такой модели для бетона в конструкциях, изготовленных методом послойной экструзии.

Ключевые слова: технология 3D-печати бетоном (3DCP), механические характеристики, анизотропия механических характеристик, ортотропная модель бетона, диаграмма «напряжения-деформации, механизмы разрушения

1. INTRODUCTION

3D Concrete Printing (3DCP - 3D Concrete Printing) is one of the most promising technological trends, which is part of a vast group of additive technologies, providing increased efficiency of work on the construction of building structures. Additive technologies provide the implementation of the principles of digital approach to construction: on the basis of a 3-dimensional digital model of structures of the bearing system of the building a program of the printer is created. Under the control of such a program the printer layer by layer forms structures using 3D concrete printing technology. The technology of 3D concrete printing provides the possibility of transition to mass construction of houses according to individual designs developed in digital technologies. Thus, 3DCP technology is a modern industrial approach with the production of the necessary structure directly at the place of its further use. In this case, the known limitations on the diversity of architectural appearance of construction objects are removed, which is ensured by the use of individual digital projects of houses built using standard standard standard technology. Construction production based on digital principles realizes the task of digital transformation of the construction industry as a whole and ensures the growth of labor productivity in construction [1-4].

The obvious prospects of 3DCP-technology application in the construction industry are recognized in many countries. Saudi Arabia has adopted a program for the construction of housing with the mass application of 3DCP technology [5]. In the UK, the National Additive Manufacturing Strategy program [6] evaluated the possibility of creating marketable products in the volume of the country's GDP up to 1 billion dollars and creating up to 15,000 jobs in the construction industry. A group of industrial ministries in the People's Republic of China has developed an initiative [7-8] to support industrialized construction methods, including 3DCP technologies, as the main direction for the development of the construction industry.

The possibility of practical realization of 3DCP technology is provided by the achievements of construction science in several main directions: the development of methods and technologies of layer-by-layer structure formation with various effective extrusion mechanisms [9-13]; the development of new types of concrete mixtures with specified characteristics that allow layer-by-layer formation of a structure that retains its shape until the moment of strength gain [14-16].

At present, two directions of realization of the method of 3D printing with concrete using the technology of layer-by-layer horizontal extrusion are actively developing: Direct Digital Fabrication of Concrete (DDFC) / Direct Digital Fabrication of Concrete Structures/ and Digital Fabrication of Formworks (DFF) / Digital Fabrication of Formwork/.

The DDFC direction allows, on the basis of the general technological process of 3D printing with concrete, to realize the production of concrete structures of various shapes in conditions of limited possibilities of using reinforcement elements. The DDFC direction can be very effective in the production of small-scale and individual structures, in the operational modes of

which there are no significant tensile or shear forces. Such limitations are determined by the current state of 3D concrete printing technology, in the framework of which the installation of reinforcing elements in the body of the structure to absorb tensile forces is quite complicated, and the technology of installation of reinforcing elements is a foreign (in relation to the 3DCP concrete technology) process. The actual practice of DDFC direction implementation shows that the installation of reinforcement elements into the body of a structure is possible with human intervention in the highly mechanized technology of 3D printing with concrete or in the conditions of using additional equipment [17].
The currently known problems in the field of practical application of 3D concrete printing technology are not critical for manufacturing building structures using the new innovative technology. The characteristics of masonry structures are quite similar, as masonry made of piece materials (bricks, large-sized artificial stones) on masonry mortar is a layered structure with minimal opportunities for installing interlayer reinforcement. But the characteristics of masonry do not prevent the widespread use of masonry structures in construction.
The most significant factor that ensures the wide application of a particular technology in the construction industry, including 3D concrete printing technology, is the availability of methods that allow you to justify the strength, reliability and level of deformability of designed structures by calculation. Such calculation methods are based on a scientifically substantiated model of the material forming the structure and realizing strength properties as part of this structure. The latter circumstance is very important, as the model should correctly reflect the realization of mechanical characteristics of the material, which are formed not only in the frames of local volumes of such material, but also in the conditions of interaction of local volumes in the total volume of the structure. Such local volumes of the material can be formed due to the peculiarities of the manufacturing technology of the structure.

The analysis of 3DCP technology shows that the structure obtained by layer-by-layer extrusion of concrete has significant differences from the traditional technology of manufacturing structures by monolithic concreting technology. The traditional technology of manufacturing of reinforced concrete structures, which includes the procedure of concrete mixture compaction, provides the formation of a sufficiently homogeneous concrete body of the structure with minimal amounts of leaks. The most important quality control procedures in the traditional monolithic concreting technology is the control of concrete mixture homogeneity. Concrete homogeneity ensures the realization of interaction of concrete mixture particles throughout the entire volume of the structure. According to [18], concrete obtained by conventional technology is a composite material consisting of binder particles, aggregate particles of different size and transition zone of interaction between particles, modeled by a set of elastic bonds. In general, the model of interaction of concrete particles in a structure made by traditional technology with concrete compaction procedures is presented in Fig. 2. The homogeneity of the concrete mixture makes it possible to use the characteristics of concrete strength and deformability corresponding to the model of a homogeneous deformable body in the design justification.

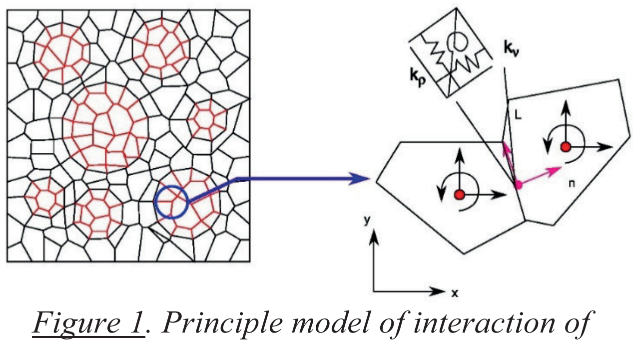
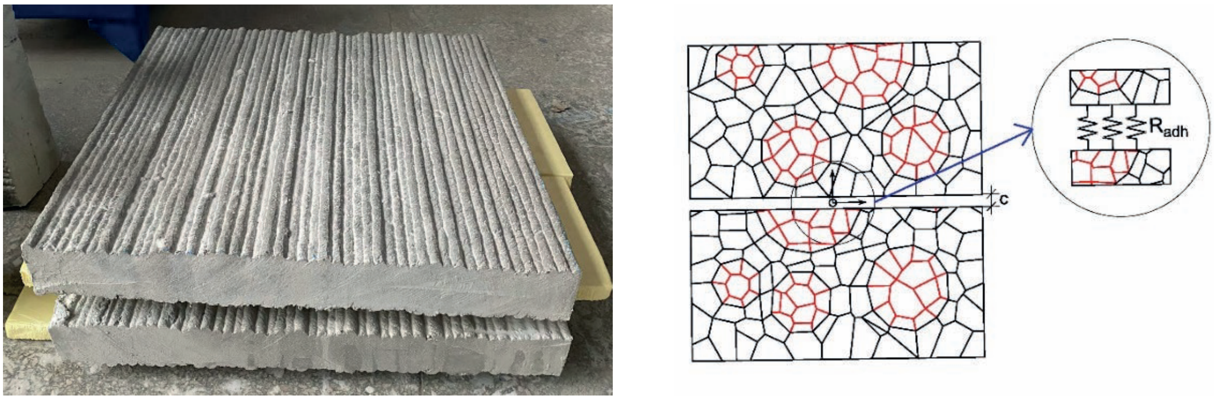


Figure 1. Principle model of interaction of concrete particles in a structure made with the procedure of concrete mixture compaction (by [18])

Contrary to concrete in a structure made by traditional technology with concrete compaction throughout the entire volume of the structure, concrete in a structure made by 3D-printed concrete by layer-by-layer horizontal extrusion has natural zones of concrete layers of a given thickness, each of which is produced separately from other layers with a gap in the time of production. In this way, a layered structure of concrete is technologically formed, and each layer has a mechanism of contact interaction with other layers. Since freshly placed concrete has adhesive properties due to the presence of binder, the interaction of layers is realized by adhesive mechanism (Fig. 2).



(a) *(b)*

Figure 2. Principle model of interaction of local elements of the structure made layer-by-layer by 3DCP technology; a - appearance of the structure at single-row concrete extrusion; b - model of interaction of local elements of the structure; c - zone of contact interaction of local elements of the structure

Differences in the structure of concrete in structures made by the technology of traditional forming of the monolithic concrete body of the structure in comparison with structures made by 3DCP technology have been investigated by many authors, but, in general, this direction is at the initial stage of development.

In [19] the issues of concrete mixes formulation peculiarities suitable for 3DCP method of structural fabrication are investigated. In [20] the influence of 3DCP-technology on changes in the mechanical characteristics of concrete under compression conditions is studied. The issues of variability of mechanical characteristics of concrete in structures made using the 3DCP method are considered in [21-23].

A number of studies have investigated the manifestation of anisotropy properties in concrete, the volume of which is made using 3DCP technology by layer-by-layer extrusion. The results of such studies confirm: concrete in a structure made by 3D printing technology realizes a pronounced anisotropy effect. In [24] the results of the study of the influence of 3DCP-method on the formation of the anisotropy effect of concrete strength characteristics are presented. The results of the study show that the average axial compressive strength of the samples drilled from the massif made by 3D printing technology is 15-27% lower than that of the samples drilled from the massif made by the traditional technology of monolithic concreting. The data on the measured densities of different zones of concrete of the array made by 3D-printing technology are also given. It is shown that 3DCP technology forms the concrete body of the structure with a significantly lower compaction relative to the same indicator of concrete of structures made using traditional technology. In [25], the influence of the layered structure and imperfections in the geometry of the structure, determined by the peculiarities of 3DCP technology, which influence the premature failure of the structure in the manufacturing process, was investigated. In [26, 27], the mechanical properties of concrete at an early age are investigated, which allows predicting the behavior of the structure in the mode of fabrication using 3D printing technology. In [28], a method of modeling concrete deformation in the process of structure fabrication is proposed. The standard method of modeling of the construction with additional functions of activation of layers of the manufactured structure was used, which allows to correct the geometry of the model. In [29] it is noted: in structures made by 3DCP technology, in the process of extrusion in the layer of concrete can be formed zones of looseness, and in some cases - breaks in the body of the concrete layer, which has a negative impact on the cohesion (monolithicity) of the concrete in the structure.

In [30, 31] it was established: the layered structure of concrete in structures made by 3DCP technology with layer-by-layer extrusion of concrete forms a special type of concrete, the mechanical characteristics of which have a pronounced anisotropy, which is a fundamental difference from traditional cast-in-place concrete with compaction of the mixture in the formwork (the mechanical characteristics of traditional concrete are recognized as isotropic).

The reason for the anisotropy of mechanical properties of 3DCP concretes according to [32, 33] is the weak bonds of extruded concrete layers. It is quite obvious that the direction of bond failure between the layers corresponds to the extrusion trajectory of the layers, and this, in turn, determines the anisotropy of the me-mechanical properties of concrete. Studies [34] have established that the anisotropy of 3DCP concrete properties can be correlated with mutually orthogonal directions: properties in the direction perpendicular to the extrusion layers and properties in the direction of the extrusion layers.

Thus, the fact of a significant difference between the mechanical characteristics of concrete in structures with the traditional technology of monolithic concreting with compaction of the mixture over the volume of the structure and the similar characteristics of concrete in structures made with the technology of 3D printing by layer-by-layer extrusion can be considered established and substantiated by scientific research.

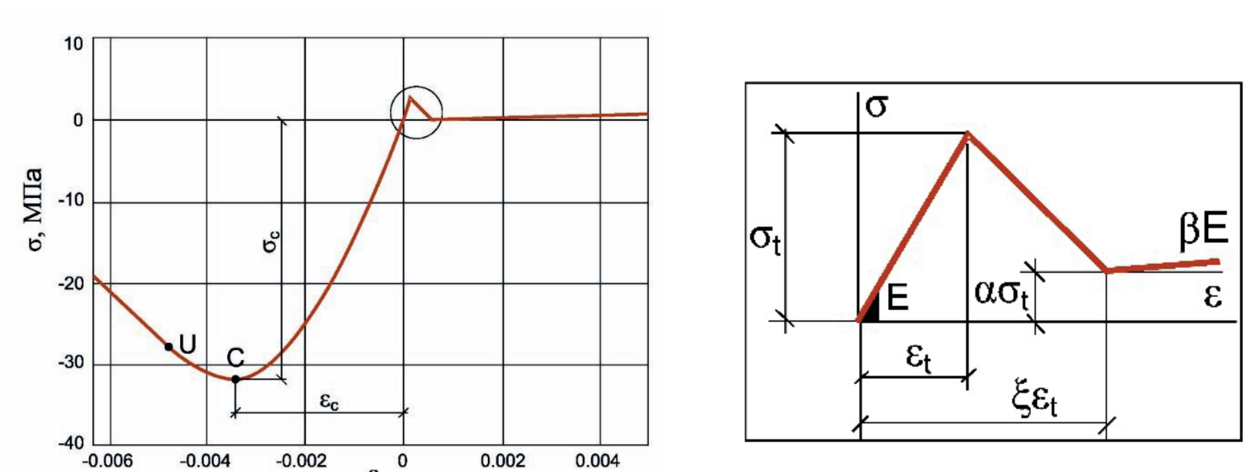
However, it should be emphasized that neither academic reviews on the topic of 3DCP technology nor open publications provide information on the development/adaptation of a mathematical model of 3DCP-concretes, which would take into account the pronounced anisotropic properties of such concretes. Also there is no information about works on correction or improvement of methods of calculation of constructions made by 3DCP technology. The analysis of few published works on the subject of calculation analysis of structures made by 3D printing technology by layer extrusion method shows that traditional concrete models are used with minimal refinements of traditional constants values. Thus, [35] provides only a list of issues that need to be taken into account when calculating the strength of structures made by 3DCP technology, as well as directions for optimizing concrete structures made by layer-by-layer extrusion technology. In [36], a model of concrete structures made by 3DCP technology is proposed in the form of a brittle-plastic material model. The model uses the well-known orthotropic smeared crack model for tension (fracture) and a plasticity-based model for compression (plastic behavior). This material model is extended to take into account the temporal variability of its parameters. The interaction of layers was modeled by weaker (relative to concrete) interface elements. However, the failure of layered materials occurs by significantly different mechanisms (adhesion and cohesion), which must be taken into account in the layered material model. A similar approach was used in [37, 38], where the interaction of layers was modeled by special interfacial elements. For the conditions of the time interval corresponding to the fabrication of the structures, results close to the experimental results were obtained. For the conditions of concrete with design strength, the results of numerical studies have significant differences from the results of physical experiments, which indicates the need to improve the mathematical model of concrete as a layered material.

Thus, the analysis of open publications on the results of studies of mechanical characteristics of 3DCP-concretes made by the technology of layer-by-layer extrusion shows: mechanical characteristics of 3DCP-concretes have pronounced anisotropic properties, which determines the fundamental differences of such concretes from traditional cast concrete. It is obvious that anisotropy of mechanical properties is determined by various factors. The factor of looseness of the layered material, which was not subjected to compaction throughout the entire volume of structures, is an objective consequence of the technology of layer-by-layer extrusion. However, the most significant factor affecting the manifestation of anisotropic properties of concrete in structures made by 3DCP technology is the factor of layer interaction in a multilayer structure, which requires an experimental study to determine the mechanism of layer interaction and the mechanism of destruction of interlayer interaction. The results of the study will allow us to substantiate the characteristic characteristics of the key constants of the mathematical model of concrete in structures made by layer-by-layer extrusion using 3DCP technology.

2. MATERIALS AND METHODS

Concrete in structures made by traditional technology with concrete placement in the formwork of the structure and concrete compaction throughout the volume, which provides an acceptable level of uniformity of the material, is described by a well-known mathematical model, which is approved by the International Federation for Structural Concrete (FIB) and is used in the normative documents of many countries, computing systems, for example, [39], and is given in many publications.

In a generally accepted form, the model of traditional cast-in-place concrete for uniaxial compression-tension conditions is described in the stress-strain axes (“*σ-ε*”) is shown in Fig. 3.



(a) *(b)*

Figure 3. Diagrams “ σ-ε ” for concrete at traditional technology of structural performance: a - full diagram; b - fragment of the diagram for tensile conditions

The diagram is represented by the following ratios:

$$\sigma(\varepsilon)=\begin{cases} E\varepsilon, 0\le\varepsilon\le\varepsilon_t, \\ \alpha\sigma_t+\dfrac{(1-\alpha)E}{1-\xi}(\varepsilon-\xi\varepsilon_t), \varepsilon_t\le\varepsilon\le\xi\varepsilon_t, \xi>1, \\ \alpha\sigma_t+\beta E(\varepsilon-\xi\varepsilon_t), \varepsilon>\xi\varepsilon_t, \\ \dfrac{\frac{E}{E_r}\varepsilon_r\ \sigma_c}{1+A\varepsilon_r\ +B\varepsilon_r^2+C\varepsilon_r^3}, \varepsilon_r\le\varepsilon<0, \end{cases} \tag{1}$$

where the point C(ε_c, σ_c) corresponds to the compressive strength; the point U(ε_u, σ_u) is the limit point, and (according to FIB experts' recommendations) σ_u = 0,85ε_c; ε_u = 1,41ε_c. The other parameters correspond to [40]:

$$\begin{gathered} E_r=\frac{\sigma_c}{\varepsilon_c}, \varepsilon_r=\frac{\varepsilon}{\varepsilon_c}, E_u=\frac{\sigma_u}{\varepsilon_u}, p=\frac{\varepsilon_u}{\varepsilon_c}, \\ A=\frac{\frac{E}{E_u}+(p^3-2p^2)\frac{E}{E_r}-(2p^3-3p^2+1)}{p(p^2-2p+1)}, \\ B=2\frac{E}{E_r}-3-2A, C=2-\frac{E}{E_r}+A. \end{gathered} \tag{2}$$

The descending sections of the diagram simulate the strength reduction during crack formation and opening. The parameter ξ determines the length of the descending section of the diagram, while the parameters α and β determine the residual strength of concrete and secondary strengthening.

The diagram shown in Fig. 3, is based on well known mechanisms of deformation and fracture of concrete under uniaxial stress state, uses natural characteristics of strength and deformability of concrete and allows correct modeling of concrete performance in a structure made by traditional technology with the formation of a monolithic structure of concrete in the structure.

The deformation theory of plasticity of concrete, which is widely used in mathematical modeling of concrete, is based on the following provisions:

- elastic volume change:

$$\Theta = 3K\sigma, \tag{3}$$

where $\Theta = \sigma_x + \sigma_y + \sigma_z$; $\sigma = (\sigma_1 + \sigma_2 + \sigma_3)/3$; $K = (1 - 2\nu)/E$; Θ – volume expansion; σ – average pressure; E – initial strain modulus; ν – Poisson's ratio;

- stress and strain deviators are proportional to:

$$\mathbf{D}_\sigma = 2G'(\mathbf{D}_\varepsilon - \mathbf{D}_\varepsilon^A), \tag{4}$$

where $\mathbf{D}_\sigma$, $\mathbf{D}_\varepsilon$ - stress and strain deviators; $\mathbf{D}_\varepsilon^A$ – residual strain deviator; G' = σ_e / (3 ε_e) – shear modulus; σ_e, ε_e – reduced stresses and strains;

- elastic relief:

$$\mathbf{D}_\sigma = 2G'\mathbf{D}_\varepsilon^P - 2G(\mathbf{D}_\varepsilon - \mathbf{D}_\varepsilon^A), \tag{5}$$

where индекс P – plot point σ_e – ε_e (Fig. 4), corresponding to the beginning of unloading; $G = E / (2(1 + \nu))$ – elastic shear modulus.

In the framework of the deformation theory of plasticity of concrete, let us consider the case shown in Fig. 4, when the deformation process starts in the tensile zone of concrete and active loading is carried out along the *OP* trajectory (described in detail in [41, 42]).

According to [41, 42], at the loading step, at each subsequent time instant the reduced strain exceeds its value at the previous time instant:

$\varepsilon_e^{i+1} > \varepsilon_e^{i}$, where i is the conditional number of the moment (step) of the analysis. If the analysis at the considered step demonstrates $\varepsilon_e > \varepsilon_e^P$, the loading process continues. In the case where $\varepsilon_e \leq \varepsilon_e^P$, elastic unloading occurs, which corresponds to equation (5).

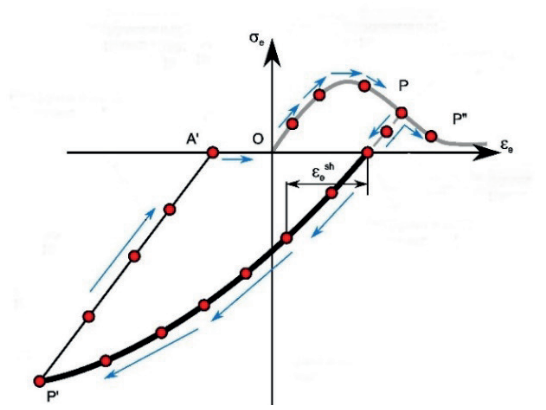
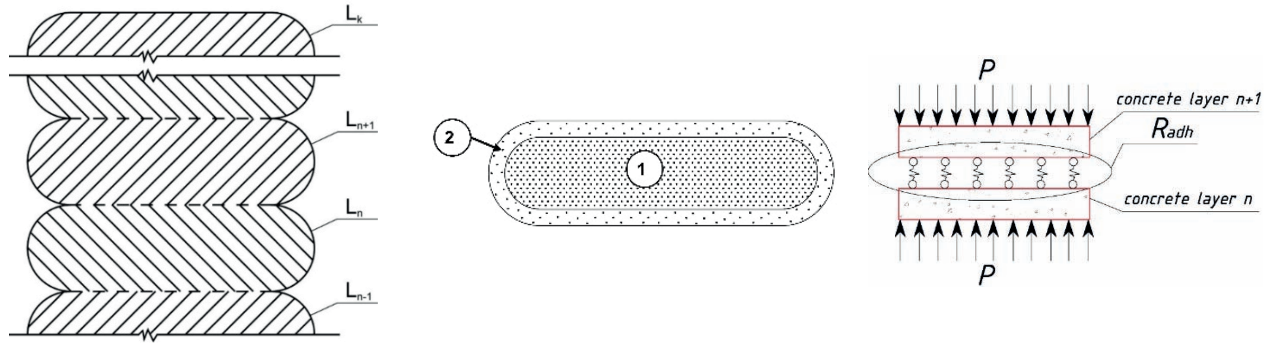


Figure 4. Unsymmetrical "σ-ε" diagram for concrete

The analysis of the considered situation shows that the mathematical model of concrete, developed for the traditional technology of manufacturing of structures, corresponds to the conditions of realization of the elastic unloading phase in the mode of tensile stresses. The realization of the elastic unloading phase is ensured by the homogeneous structure of concrete throughout the entire volume of the structure under cohesion failure conditions.

The cohesive mechanism of tensile fracture adopted in the traditional mathematical model of concrete is substantiated by numerous experimental studies and corresponds to a key constant in the form of concrete tensile strength (R_{bt}). A number of methods for modeling the process of crack development in monolithic concrete, including the method of distributed ("smeared") cracks, have been developed based on the use of this constant (R_{bt}).

The 3DCP technology of layer-by-layer horizontal concrete extrusion has fundamental differences from the traditional technology, which is that the volume of concrete in the structure is formed layer by layer. The concrete structure made by the method of layer-by-layer concrete extrusion consists of concrete layers formed during the passage of the extrusion head of the 3D printer, and contact zones of such layers (Fig. 5). The concrete of the layers is heterogeneous (Fig. 5b): the main part of the layer volume (estimated up to 80%) has a structure close to the traditional concrete structure; the volume of concrete forming the outer part of the layer (estimated up to 20%) has a more loose structure with increased porosity, which is confirmed by studies [21]. The interaction of concrete layers is determined by the mechanism of adhesion of layers with a certain level of adhesion strength (R_{adh}), which is determined by the composition of concrete mixtures including binders, such as cement. In general, at the micro level, the assumed scheme of interaction of structural elements (layers) is presented in Fig. 5c, which requires experimental confirmation.



(a) (b) (c)

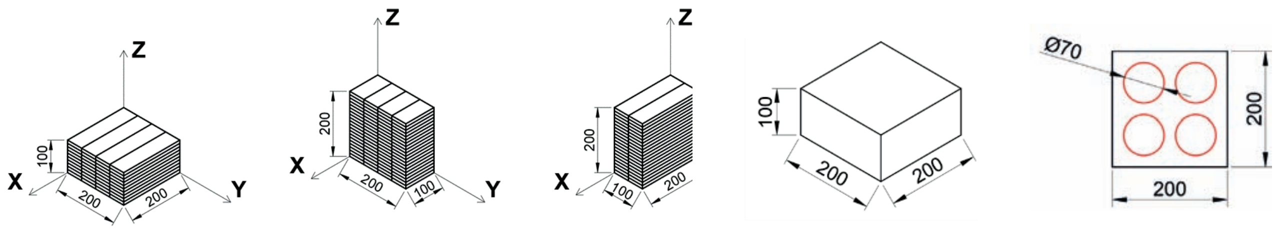
Figure 5. Peculiarities of the structure of the concrete structure made by the technology of layer-by-layer extrusion of concrete: a) - scheme of layers of the structure (L_i - layers of concrete); b) - scheme of the layer structure (1 - central area of the layer; 2 - outer area of the layer); c) - assumed scheme of interaction of the layers of the structure

Taking into account these features of concrete structure in the structure made by layer-by-layer extrusion by 3DCP-method, the model of concrete of such a structure, including basic constants based on cohesive fracture mechanism, should be adapted to the fabrication technology on the basis of taking into account the actual characteristics and fracture mechanisms that are realized by concrete. Thus, to substantiate the parameters of the adapted model of concrete, correctly reflecting the specific features and influence of the manufacturing technology, it is necessary to perform experimental studies to determine the mechanisms of fracture and mechanical characteristics of concrete in the structure made by the method of layer-by-layer horizontal concrete ex-trusion.

For experimental studies of concrete compressive strength (R_b), fragments of the structure made by layer-by-layer extrusion by 3DCP method (Fig. 6a) and control specimens made by traditional technology (Fig. 6b) were made.

Fragments of the structure for 3DCP-concrete samples were made by layer-by-layer extrusion using a 3D printer with an extrusion head, which provides the formation of a layer of concrete with a width of 50 mm and a thickness of 20 mm. The structure for making 3DCP-concrete specimens is a rectangular slab of 200x200 mm size with a thickness of 100 mm (Fig. 6a). Multilayer 3D printing was applied in the fabrication of the fragments. For 3DCP-concrete samples, a special mixture for 3D printing produced by the building materials industry of the Russian Federation was used. Control samples were made of this mixture using the traditional technology, including concrete compaction in the formwork.

Cylinder specimens with a diameter of 70 mm (Fig. 6c) were selected from the fragments of structures for testing. From the fragments of the structure made by layer-by-layer extrusion using the 3DCP method, cylinder specimens were selected by drilling parallel and perpendicular to the layers of extrusion.



(a) (b) (c)

Figure 6. Geometric dimensions of concrete fragments for determining the compressive strength of concrete (R_b) a - samples made of fragments by the method of layer-by-layer horizontal extrusion of concrete; b - samples made by the traditional technology with compaction of concrete mixture; c - scheme of drilling out cylinder samples from concrete fragments for determining the compressive strength of concrete (R_b)

Compression testing of the specimens was performed according to the method recommended by FIB on a laboratory press machine MEGA 6-3000-100 (Form+Test, Germany) with a maximum compression force of 3000 kN. The loading of the specimen was carried out at a constant rate of 0.6 MPa/s.

For testing, the specimen ends were machined to obtain a plane perpendicular to the longitudinal axis of the specimens. Before the tests the specimens were prepared to standard humidity (55%). The tests were carried out within 30-36 days after fabrication of fragments for 3DCP-concrete specimens and control specimens.

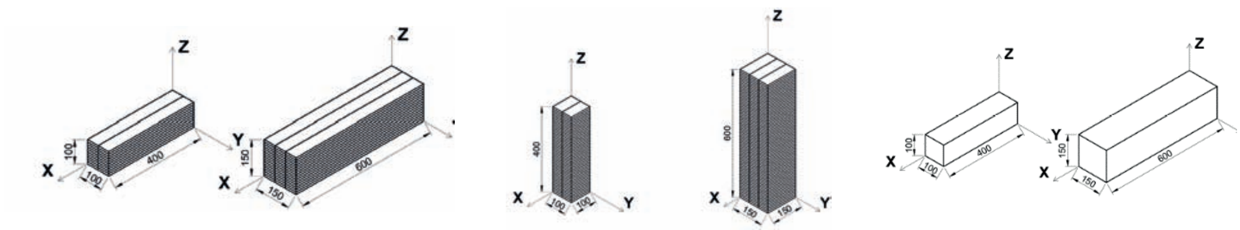
The values of compressive strength were determined by loading the specimen-cylinders with compressive loads in the press equipment (Fig. 7).

(a) *(b)*

Figure 7. Test of cylinder specimens for determining the compressive strength of concrete (R_b) a - test with loading perpendicular to the extrusion layers; b - test with loading parallel to the extrusion layers

For experimental investigations of concrete tensile strength (R_{bt}), beam specimens of two types of sizes (*bxhxl*) were fabricated (Fig. 8) using 3DCP technology: 100x100x400 mm (series 1); 150x150x600 mm (series 2). The control beam specimens with similar dimensions were manufactured using conventional technology with concrete mix compaction.

3DCP-concrete specimens were produced by layer-by-layer extrusion using a 3D printer with an extrusion head, which ensures the formation of a layer of concrete with a width of 50 mm and thickness of 20 mm. Multilayer 3D-printing was used in the fabrication of the fragments. For 3DCP-concrete samples a special mixture for 3D-printing, produced by the building materials industry of the Russian Federation, was used. Control samples were made of this mixture according to the traditional technology, including concrete compaction in the formwork.



(a) *(b)* *(c)*

Figure 8. Geometric dimensions of concrete fragments for determining the tensile strength of concrete (R_{bt}), made fragments by layer-by-layer horizontal extrusion of concrete: a) - specimens for flexural tensile tests under loading perpendicular to the layers of the seal; b) - specimens for flexural tensile tests under loading parallel to the layers of the seal; c - control specimens made by traditional technology

Flexural tensile testing of specimens was performed according to the method recommended by FIB on a laboratory press machine MEGA 6-3000-100 (Form+Test, Germany) with a maximum force of 100 kN. The loading of the specimen was carried out at a constant rate of 0.05 MPa/s.

Tensile strength (R_{bt}) testing of concrete specimens was performed on the press with loading at two points (Fig. 9).

(a) (b) (c)

Figure 9. Testing of concrete tensile strength (R_{bt}) specimens (a) specimens for flexural tensile tests when loaded perpendicular to the extrusion layers; (b) - specimens for flexural tensile tests when loaded parallel to the extrusion layers; (c) tests of control specimens

3. RESULTS AND DISCUSSION

The results of the concrete compressive strength (R_b) tests are presented in Table 1.

Table 1. Results of concrete compressive strength studies (R_b)

№	Type of characterization	Cylinder specimens made by 3DCP method in compression along the X-axis (parallel to the extrusion layers) / % of control values	Cylinder specimens made by 3DCP method in compression along the Y-axis (perpendicular to the extrusion layers) / % of control values	Control samples
1	Average value	17,0 / 68,8%	19,7/ 79,8%	24,7
2	RMS deviation	1,2	1,8	-
3	Coefficient of variation (%)	7,1	9,26	-

The analysis of the results of concrete compressive strength (R_b) studies demonstrates failures by traditional cohesive mechanisms. At the same time, the reduction of concrete strength characteristics by ≈20-30%, which is determined by the presence of the outer area of the concrete layer with higher porosity compared to the central area of the layer. To the greatest extent, the influence of the outer region of the concrete layer is realized when the specimen is loaded parallel to the extrusion layers: the tangential stresses destroying the specimen form cracks confined to the contact areas of the layers. The interaction of concrete layers is determined by a complex mechanism, including, among others, the adhesive interaction of layers subjected to tensile tangential stresses. It should be taken into account that the value of adhesive strength (R_{adh}) is significantly lower than the concrete tensile strength (R_{bt}), which corresponds to the cohesive failure mechanism. The combination of dissimilar fracture mechanisms (adhesive and cohesive) leads to a 31.2% decrease in the concrete compressive strength (R_b) when the specimen is loaded parallel to the extrusion layers in relation to the control specimens made of monolithic concrete.

The values of the coefficients of variation of the compression test results of the specimens indicate insignificant deviations from the average values of the test results, which correctly reflects the peculiarities of the structure of 3DCP-concretes for compression conditions.

The results of the concrete tensile strength (R_{bt}) tests are presented in Table 2.

Table 2. Results of tensile strength of concrete specimens (R_{bt})

№	Type of characteristic	Specimens for flexural tensile tests when loaded perpendicular to the extrusion layers / % of control specimen		Samples for flexural tensile tests when loaded parallel to the extrusion layers / % of reference sample		Beam test specimens for bending tensile tests	
		100×100×400 mm	150×150×600 mm	100×100×400 mm	150×150×600 mm	100×100×400 mm	150×150×600 mm
1	Average value	2,23 / 69,25	2,08 / 78,49	0,19 / 5,90	0,22 / 8,30	3.22	2,65
2	RMS deviation	0,32	0,25	0,12	0,11	0,22	0,29
3	Coefficient of variation (%)	14,45	11,89	-	53,16	6,70	10,88

The analysis of the results of concrete tensile strength (R_{bt}) studies demonstrates a pronounced anisotropy of the concrete structure material made by the technology of layer-by-layer extrusion.

Under the action of external loads perpendicular to the layers of extrusion (direction of tensile stresses is parallel to the extrusion layers), the destruction of samples by cohesive mechanism is observed. The reduction of concrete strength characteristics by ≈20-30% was recorded. The magnitude of strength reduction depends on the size of experimental samples and is determined by the presence of the outer area of the concrete layer with higher porosity in comparison with the central area of the layer and, accordingly, the reduced strength of the concrete of the outer area. The presence of the concrete area with reduced density leads to a decrease in the resistance of the compression zone of the experimental specimen, which determines the reduction of the failure load level and, consequently, to a decrease in the tensile strength of concrete (R_{bt}).

At action of external loads parallel to layers of extrusion (direction of tensile stresses is perpendicular to the extrusion layers) the destruction of samples on adhesive mechanism is observed - destruction occurs on planes of contact of layers without presence of damages of a surface of concrete of layers in a zone of the destroyed contact. At the same time, a multiple (≈90-95%) decrease in the tensile strength of the specimen was recorded.

Such a significant reduction of mechanical characteristics is determined by a fundamentally different structure of concrete in the structure: concrete has a pronounced layered structure. The layers of the structure are made with a break in time and (in the absence of special structural measures) interact by the mechanism of adhesion. Under the conditions of tensile stresses per-perpendicular to the layers of extrusion, destruction is realized by the weakest mechanism of mutual interaction of concrete elements of the structure - by the mechanism of destruction of adhesive interaction of layers with adhesive strength (R_{adh}), the value of which is many times lower than the tensile strength of concrete (R_{bt}), corresponding to monolithic compacted concrete.

An important feature of the fracture mechanism of adhesive interaction is its brittle character: the unloading phase is practically absent, fracture occurs within a short time. For detailed studies of the unloading phase with adhesive fracture mechanism, it is necessary to perform additional studies.

The values of the coefficients of variation of the tensile test results indicate acceptable deviations from the average values of the test results when loading perpendicular to the extrusion layers. For loading conditions along the extrusion layers, the values of variation coefficients show high heterogeneity of the results, which corresponds to the high variability of the key indicator of monolithicity of the tested structure - adhesion strength of contact interaction between

the layers (R_{adh}). The analysis of experimental results shows that the tests demonstrate fundamental differences in the mechanical characteristics of 3DCP-concretes from the analogous parameters of traditional cast-in-place concrete.
Thus, when external loads are applied perpendicularly to the extrusion layers (direction of tensile stresses is parallel to the extrusion layers), the specimen fracture is realized by the mechanism of cohesive failure of concrete of extrusion layers with reduced tensile strength (R_{bt}). When external loads are applied parallel to the extrusion layers (direction of tensile stresses is perpendicular to the extrusion layers), the specimen fracture is realized by the mechanism of adhesive interaction failure of layers with adhesive strength (R_{adh}). Such different fracture mechanisms determine a pronounced anisotropy of the material of the concrete structure made by the technology of layer-by-layer extrusion. The presence of different fracture mechanisms should be taken into account in the mathematical model of concrete: for the conditions of loading parallel to the extrusion layers, the value of adhesive strength (R_{adh}) should be used as a key constant of the model.
The analysis of the experimental results shows that in compression mode the deformation of the samples qualitatively coincides with the known diagrams of concrete deformations of structures made by traditional technology. The diagrams of deformation diagrams of concrete structures made by 3D-printing technology are similar to the traditional diagrams of concrete deformation. As a key constant of the mathematical model of concrete can be used the value of concrete compressive strength (R_b), corresponding to the cohesive failure mechanism, but corrected on the basis of experimental studies, corresponding to the type of construction made by 3D-printing technology. Differences are observed only in the value of ultimate compression stresses (σ_c) corresponding to the point C(ε_c,σ_c) and some difference in the value of ε_c. To determine more precisely the differences in the limit values of relative strains (ε_c), it is necessary to conduct additional studies. In view of the above, it seems reasonable to adopt the scheme of the diagram "σ-ε" in the compression mode of concrete structures made by 3D-printing technology similar to the scheme of deformation of concrete structures made by traditional technology (the proposals are presented in Fig. 10).

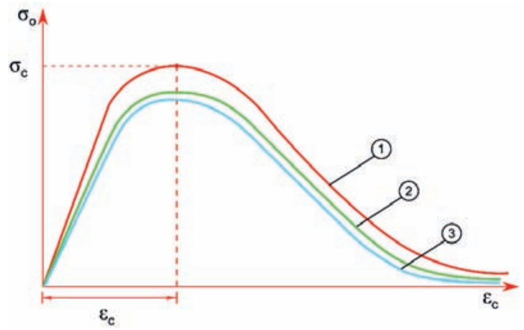


Figure 10. Fragment of the diagram of the "σ-ε" diagram for concrete in compression mode: 1 - concrete in structures made by traditional technology; 2 - concrete in structures made by 3D-printing technology (compression perpendicular to the printing layers); 3 - concrete in structures made by 3D-printing technology (compression parallel to the printing layers)

The analysis of experimental results shows that the deformation of specimens in the tensile mode has significant differences.
When the specimens are loaded perpendicularly to the extrusion layers (direction of tensile stresses is parallel to the extrusion layers), the deformation of the specimens coincides qualitatively with the known diagrams of concrete diagrams of structures made by traditional technology. The coincidence of deformation diagrams is determined by the same cohesive failure mechanisms. As a key constant of the mathematical model of concrete can be used the value of concrete tensile strength (R_{bt}), corresponding to the cohesive fracture mechanism, but corrected on the basis of experimental studies, corresponding to the type of structure made by 3D printing technology. The diagrams of concrete deformation diagrams of the 3D-printed structure are similar to the traditional concrete deformation diagrams. Differences are observed only in the value of ultimate compressive stresses (σ_0) and some difference in the value of ultimate

relative strains (ε_t). For more precise determination of differences in the limit values of relative strains (ε_t) it is necessary to carry out additional studies. In view of the above, it is reasonable to consider the scheme of the σ-ε diagram in the tensile mode of concrete structures made by 3D-printing technology under loading perpendicular to the extrusion layers to be similar to the scheme of deformation of concrete structures made by traditional technology (the proposals are presented in Fig. 11, line 2).

When the specimens are loaded parallel to the extrusion layers (direction of tensile stresses is perpendicular to the extrusion layers), the deformation of the specimens has a prin- tially different character. This is determined by adhesive mechanisms of specimen fracture with the destruction of adhesive interaction between the layers. As a key constant of the mathematical model of concrete should be used the value of adhesion strength of contact interaction of layers (R_{adh}), corresponding to the adhesion failure mechanism Adhesion strength (R_{adh}) is many times lower than the tensile strength of concrete (R_{bt}), which limits the tensile strength of the specimen to the value of adhesion strength. The adhesive failure is brittle in nature (Fig. 12, line 3) and the angle of inclination of the unloading line to the vertical (α) tends to 0. The value of the limit value of relative strain in the adhesive fracture mechanism ($\varepsilon_{t,adh}$) is significantly lower than the analogous value for concrete in structures made by conventional technology (ε_t). To determine the exact values of α and $\varepsilon_{t,adh}$ it is necessary to perform additional studies.

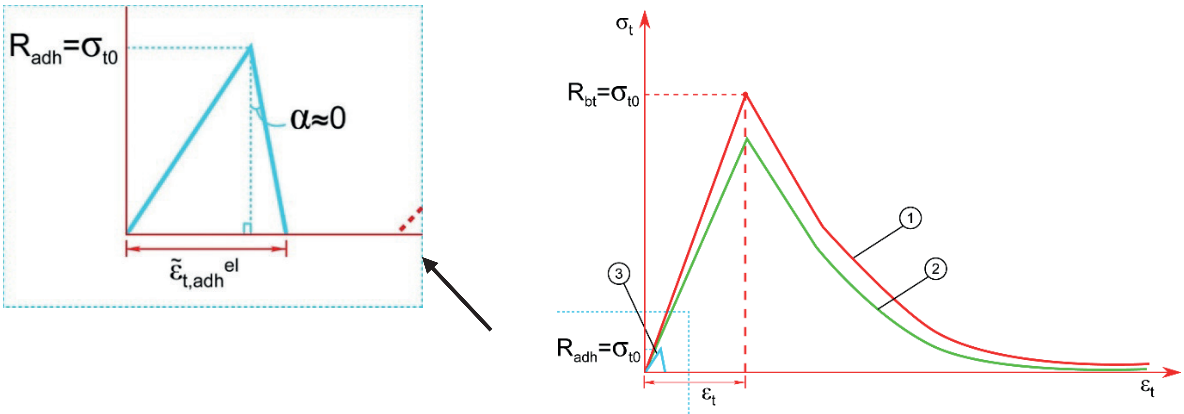


Figure 11. Fragment of the diagram of σ-ε diagram for concrete in the tensile mode: 1 - concrete in structures made by traditional technology; 2 - concrete in structures made by 3D-printing technology (stretching along the printing layers); 3 - concrete in structures made by 3D-printing technology (stretching perpendicular to the printing layers)

The presented stress-strain dependence ("σ-ε") for 3DCP-concretes has prin- cipal differences from similar dependences for traditional cast-in-place concretes. First, the "σ-ε" dependence shows a pronounced anisotropy: the stress limits have significant differences for different directions (along the seal layers/perpendicular to the seal layers). Secondly, the mode of unloading is also fundamentally different: when tensile along the print layers, the concrete demonstrates a smooth mode of fracture, close to the fracture patterns of monolithic concrete made by traditional technologies. When stretching perpendicular to the seal layers, the unloading corresponds to the brittle fracture mechanism.

It should be emphasized that the currently used engineering methods of calculation of concrete and reinforced concrete structures, as well as methods of physically nonlinear calculation cannot realize such significant differences in mechanical characteristics in different directions of concrete in the structure. Traditional mathematical models of concrete, based on isotropic properties of concrete and cohesive failure mechanisms, do not allow to justify by calculation the level of bearing capacity and reliability of structures made of 3DCP-concrete, which essentially restrains the development of promising innovative technology. Consequently, the existing calculation methods need to be finalized and improved (on the basis of an adapted mathematical model of concrete for the conditions of structural fabrication by layer-by-layer extrusion, taking into account fundamentally different failure mechanisms), which will allow the use of such methods for calculations of structures made by 3D printing technology.

4. CONCLUSIONS

The analysis of the performed research allows us to formulate conclusions:

1. The structure of concrete in structures made by the method of layer-by-layer horizontal extrusion of concrete (3DCP) has a layered piecewise homogeneous structure, which forms fundamental differences from the structure of concrete in structures made by the traditional technology of cast-in-place concrete with compaction over the volume of the structure.

2. The results of experimental studies of concrete samples in structures made by the 3DCP method testify to the pronounced anisotropy of concrete properties of such a structure. In a simplified form (with limitations determined by the technology of layer-by-layer extrusion), it is acceptable to define concrete in structures made by the 3DCP method as a piecewise homogeneous layered orthotropic material having different values of mechanical characteristics along mutually orthogonal axes.

3. The results of the research substantiate that fractures in compression mode of concrete structures made by the 3DCP method occur by complex mechanisms. Under loading perpendicular to the extrusion layers, failure occurs by cohesive mechanism. When loading parallel to the extrusion layers, fracture is determined by a complex mechanism, including, among others, adhesive interaction of layers subjected to tensile tangential stresses. As a key constant of the mathematical model of concrete can be used the value of concrete compressive strength (R_b), corresponding to the cohesive mechanism of fracture, but corrected on the basis of experimental studies corresponding to the type of structure made by 3D printing technology. The scheme of “stress-strain” diagram (“σ-ε”) in the compression mode of concrete of structures made by 3DCP method can be accepted as similar to the scheme of deformation of concrete of structures made by traditional technology.

4. The results of the research substantiate that tensile failure of concrete structures made by the 3DCP method under loading perpendicular to the extrusion layers (direction of tensile stresses is parallel to the extrusion layers) occurs by the cohesive mechanism. As a key constant of the mathematical model of concrete can be used the value of concrete tensile strength (R_{bt}), corresponding to the cohesive mechanism of failure, but corrected on the basis of experimental studies corresponding to the type of construction made by 3D printing technology. The stress-strain diagram (“σ-ε”) in the tensile mode under loading perpendicular to the extrusion layers can be assumed to be similar to the deformation diagram of concrete structures made by traditional technology.

5. The results of the research substantiate that the fracture in the tensile mode under loading parallel to the extrusion layers (direction of tensile stresses is perpendicular to the extrusion layers) occurs by the adhesion mechanism. The value of adhesion strength of layer interaction (R_{adh}), corresponding to the adhesive mechanism of fracture, can be used as a key constant of the mathematical model of concrete. The stress-strain diagram (“σ-ε”) in the tensile mode under loading parallel to the extrusion layers in the ascending section can be approximated by a straight line with a constraint determined by the value of the adhesion strength (R_{adh}). The adhesive failure has a brittle character and the angle of inclination of the unloading line to the vertical (α) tends to 0.

6. The presented experimentally substantiated key constants of the mathematical model of concrete provide adaptation of such a model for concrete in structures made by layer-by-layer extrusion. The proposed adapted mathematical model and new types of key constants serve as a basis for the development of engineering methods of calculation of structural elements made of 3DCP-concrete, as well as for the development of numerical methods of calculation of structures made of 3DCP-concrete in the finite element formulation taking into account the physical nonlinearity and anisotropy of the structural material. The creation of methods for the calculation of 3DCP-concrete structures will allow to remove restrictions on the mass application of 3DCP technology in the construction of buildings and structures.

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