

STUDY OF THE STRESS-STRAIN STATE OF FLOOR STRUCTURES MANUFACTURED BY CONSTRUCTION 3D PRINTING

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Abstract. This paper presents the results of experimental studies of floor slab structures fabricated using construction 3D printing technology, with an emphasis on the specifics of their manufacturing and reinforcement. The current state of development of construction 3D printing technology is summarized, particularly in terms of materials and research directions. The main scientific approaches in this field are highlighted, the materials used are analyzed, and existing reinforcement concepts applicable to 3D-printed structures are considered. A beam-type structural element in the form of a planar truss is proposed, which improves material efficiency and reduces self-weight.

The paper also describes the manufacturing process of specimens using a gantry-type 3D printer with a concrete mixture and conventional reinforcement with steel bars, which was integrated into the printing process by manual placement between layers. The methodology and results of experimental tests to determine the load-bearing capacity of the specimens are presented. The characteristic stages of structural behavior are identified, including crack initiation, crack propagation, and failure, as well as the zones of crack localization.

The presence of a load-bearing capacity reserve after crack initiation up to ultimate failure is observed, along with the overall stability of the experimental results. The obtained results confirm the effectiveness of the proposed structural solution and the feasibility of using conventional reinforcement methods in structures produced by additive manufacturing technologies.



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Furthermore, the obtained data can be used for further structural calculations and for predicting structural behavior under varying initial design parameters. This work is of practical importance for the development of construction 3D printing technologies and their application in the restoration of structures damaged due to the full-scale aggression of the Russian Federation.

Keywords: construction 3D printing; additive manufacturing; floor structures; reinforcement.

PROBLEM STATEMENT

At the current stage of development, construction 3D printing has reached a relatively high level of technological maturity and is gradually moving beyond the production of small architectural forms and low-responsibility structures.

Implemented projects demonstrate the feasibility of its application for the construction of full-scale buildings and structures, confirming the significant potential of this technology in civil engineering. In this context, interest from both the scientific community and practitioners is increasing, leading to intensified research efforts aimed at improving technological processes.

At the same time, despite the achieved progress, the issue of full automation of the construction process using 3D printing remains unresolved. In practice, most realized projects are limited to the construction of vertical structural elements, such as walls and columns, which primarily operate under compressive loads. Meanwhile, the fabrication of horizontal structural elements, particularly floor and roof systems subjected to bending, is still predominantly carried out using conventional construction methods, including timber, steel, or reinforced concrete solutions.

This approach significantly limits the level of construction automation and reduces the efficiency of utilizing the full potential of additive technologies. The main reasons for this include the difficulty of ensuring reliable performance of structures under bending, as well as the insufficient development of methods for integrating reinforcement into the layer-by-layer fabrication process.

Therefore, there is a need for further research focused on the development and experimental validation of structural solutions for horizontal elements, particularly floor systems, manufactured using construction 3D printing technology. Addressing this issue will contribute to expanding the scope of application of additive technologies and increasing the level of automation in the construction industry.

ANALYSIS OF PREVIOUS STUDIES

In recent years, construction 3D printing technology has demonstrated rapid development and is gradually transitioning from experimental applications to practical implementation in the construction industry. Despite this progress, a significant portion of

research is still primarily focused on issues related to geometric design, material composition, and optimization of printing parameters, while the problems of ensuring load-bearing capacity, especially under bending, remain insufficiently studied.

Considerable attention has been paid to approaches aimed at reducing the role of conventional reinforcement. In study [1], a structural solution is proposed in which horizontal elements primarily work in compression. The paper presents an example of a 3D-printed bridge, where, due to the geometry of the structure and the use of prestressed reinforcement, tensile and bending stresses are minimized. Although this approach is effective, its application in typical building structures, particularly floor systems, is limited.

There are also approaches that involve manufacturing structures as separate elements followed by their assembly into a unified system. In study [2], the formation of lattice structures with subsequent installation of reinforcement is considered, which allows for reducing material consumption and structural weight. However, this approach essentially combines additive manufacturing with conventional construction methods, thereby partially offsetting the advantages of automation.

A separate group of studies is devoted to the use of 3D-printed elements as auxiliary structures, particularly permanent formwork. Studies [3–6] demonstrate that the use of printed shells makes it possible to optimize the shape of elements and improve their performance within reinforced concrete systems. While this approach offers greater technological flexibility, it does not fully address the challenge of creating independent load-bearing elements manufactured entirely by 3D printing.

It is also worth noting the results obtained by Ukrainian researchers, particularly in the works [7, 8], which investigate the possibilities of manufacturing floor structures and shells with complex geometries using 3D printing technology. The results obtained demonstrate the relevance of developing this area of research and the advisability of further refining

structural solutions to ensure the performance of elements under bending forces.

Thus, the analysis of previous research indicates that, despite the considerable number of scientific contributions, the problem of developing efficient horizontal structures capable of resisting bending loads while remaining suitable for fabrication using 3D printing without significant technological complexity is still not fully resolved. This determines the need for further research in this field.

MAIN STUDY

In the era of rapid technological advancement and digitalization, the construction industry is also undergoing significant transformations and requires the implementation of innovative solutions. One of the key directions of modernization is the use of Building Information Modeling (BIM), which is already widely applied at the stages of design, planning, and organization of construction processes.

Alongside this, construction 3D printing technology is becoming increasingly widespread. Construction 3D printing is an innovative method for erecting buildings and structures, as well as for manufacturing individual structural elements, based on the layer-by-layer formation of an object according to a pre-developed digital model.

The core technological process of this method is the extrusion of a building mixture through a printing nozzle, followed by the sequential deposition of material layers and the formation of the structure [9-11]. This approach makes it possible to reduce labor intensity, optimize material consumption, and ensure high accuracy in reproducing the geometric parameters of structures.

A widespread and relatively successful application of construction 3D printing is the production of small architectural forms of varying complexity, such as fences, gazebos, and landscape design elements. These structures are well suited for the implementation of new technologies due to

relatively simple service conditions and the absence of significant loads.

Significant progress has also been achieved in the printing of vertical structural elements capable of withstanding substantial compressive forces, particularly walls and columns of buildings [12, 13]. This indicates a gradual transition of the technology from an experimental stage to practical application in civil engineering.

Among the well-known examples of construction 3D printing implementation are an administrative building in Dubai (UAE), a two-story residential building printed in Beckum (Germany), as well as low-rise residential structures constructed in China, among others. These examples demonstrate the strong potential of this technology for modern construction applications.

The primary materials used in construction 3D printing are concrete and cement-sand mixtures, as well as their modified variants adapted for extrusion-based processes [14-18]. The high compressive strength of concrete, even without additional reinforcement, makes this technology particularly effective for constructing elements that predominantly operate under compressive loads.

At the same time, the implementation of a complete construction cycle requires the fabrication of horizontal structural elements, such as floor and roof systems, which are subjected to bending loads. It is well known that concrete has relatively low tensile strength, which necessitates the use of reinforcement to ensure reliable structural performance.

One of the key challenges in the application of construction 3D printing is the integration of reinforcement into the continuous material extrusion process, as well as ensuring adequate bond between the reinforcement and the concrete matrix. To date, several approaches to reinforcing printed structures have been proposed. These include the placement of steel reinforcing bars during the printing process or into pre-formed cavities followed by filling with concrete; the use of dispersed reinforcement by incorporating steel fibers; and the integration of thin steel wires or impregnated carbon filaments directly during

printing [19-24]. The latter two approaches contribute to a higher level of automation but require specialized equipment and materials, which may increase construction costs.

The use of conventional steel reinforcing bars, in turn, is more consistent with existing construction practices and does not require complex materials; however, it disrupts the concept of full automation of the construction process.

In order to evaluate the load-bearing capacity and structural behavior of horizontal elements manufactured using construction 3D printing technology, experimental testing of beam specimens was conducted.

The design of the beam specimens was chosen to be a flat truss, due to the specific behavior of its components, which primarily experience axial forces-tension and compression. This approach enables more efficient material utilization, as bending in individual elements is minimized, thereby reducing the need for a significant amount of reinforcement. In addition, the use of such a structural system contributes to a reduction in self-weight.

At the same time, the increased overall depth of the floor structure, which is typical for such solutions, may have certain disadvantages, including an increase in the total building height without a corresponding increase in usable space. However, the greater structural depth also provides an opportunity for accommodating engineering services within the structure, which can be considered an additional advantage.

Taking into account technological and design requirements, the following geometric dimensions of the specimens were adopted: 1190 (l) × 320 (h) × 180 (b) mm. The thickness of the planar truss elements was set to 50 mm, which is determined by the geometric parameters of the printing nozzle, in particular its diameter of 25 mm. The selected parameters ensure the stability of the extrusion process and the formation of layers with the specified thickness.

Before the start of fabrication, the three-dimensional model of the structure underwent preliminary processing in specialized software

- a slicer. The main functions of this software include generating the toolpath for the print head, setting its movement speed, regulating the parameters of material deposition, as well as configuring extrusion parameters and the geometry of the layer-by-layer construction process.

As a result of this processing, the software generates control code (G-code), which represents a digital sequence of commands for the equipment and ensures the reproduction of the model by transforming geometric data into a controlled manufacturing process.

The specimens were printed using a gantry-type construction 3D printer equipped with a screw-based material feeding system from a container mounted on a moving frame. A ready-made dry construction mixture was used as the printing material, which was mixed with water prior to application. The composition of the mixture included Portland cement, mineral aggregates, modifying additives, and fiber reinforcement.

The main printing parameters were as follows: print head travel speed - 60 mm/s, layer height - 25 mm, and nozzle height above the working surface - 40 mm. The quantitative water content in the prepared mixture, its mechanical properties, and the values of the printing parameters were determined experimentally during the preparation stage prior to the fabrication of beam specimens.

The beam specimens were printed in a horizontal orientation. Therefore, when installed in their design position, the applied load acts perpendicular to the direction of layer deposition (printing filaments). As noted earlier, concrete exhibits low tensile strength, which necessitates the use of reinforcement to resist tensile forces. For this reason, reinforcing bars were incorporated during the fabrication of the beam specimens. A conventional reinforcement method was adopted, in which bars of the required dimensions were manually placed between the layers of the concrete mix during the printing process.



Fig. 1 View of the beam structure: *a* - during the printing process; *b* - after completion of the printing process. Photo by K. Sirenok

Рис.1 Вигляд балкової конструкції: *a* - в процесі друку; *б* - після завершення процесу друку. Автор фото К. Сіренко

Steel reinforcing bars of class Vr-1 with a diameter of 4 mm were used. They were positioned in the top and bottom chords, as well as in the outer vertical members of the truss. In total, two layers of reinforcement were provided, located between the 2nd and 3rd layers and between the 5th and 6th printed layers.

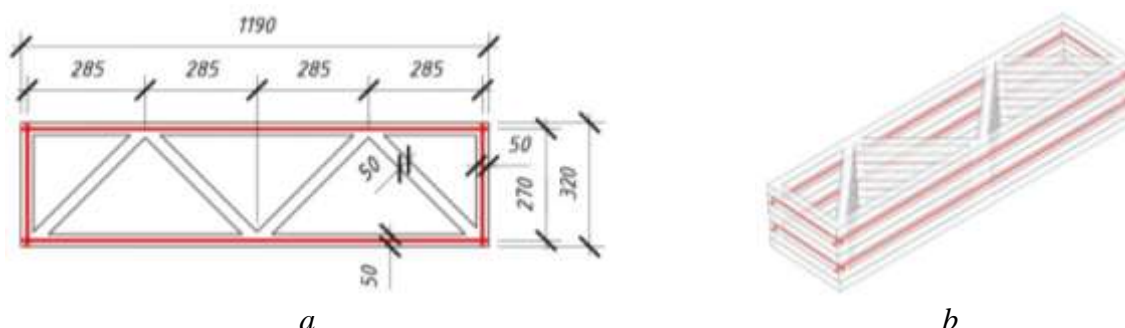


Fig. 2 Structural model of the element: *a* - geometric scheme of the beam specimen; *b* - three-dimensional model.

Note: the red line indicates the location of the reinforcing bars.

Рис.2 Модель конструкції: *a* - геометрична схема балкового зразка; *b* - об'ємна модель.

Примітка: червоною лінією позначено місцезнаходження стержнів арматури

Thus, three experimental specimens were fabricated. After reaching the age of 28 days and attaining the design strength of the concrete mixture, they were subjected to testing in order to determine their load-bearing capacity.

For testing the beam specimens, a test rig of the following configuration was assembled. Supports were mounted on a fixed trolley, arranged symmetrically with respect to its center so that the distance between them was 1140 mm. The test specimen (beam) was placed on these supports via steel plates with a bedding layer of cement-sand mortar.

Along the upper chord, at the joints of the truss diagonals, support elements were installed

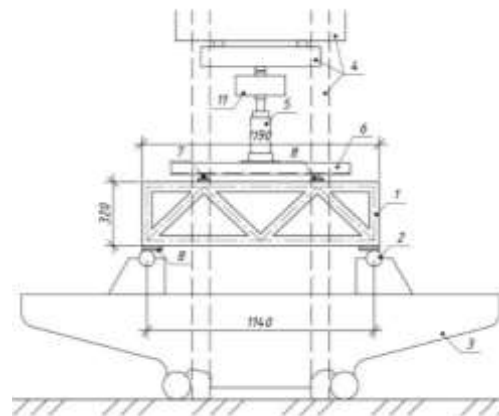
at two cross-sections, through which the load was transmitted to the beam. The loading was applied using a hydraulic jack through a distribution beam (traverse) mounted on these support elements. The upper reaction for the jack was provided by a movable plate of the press frame. To measure the applied load, a dynamometer was installed between the jack and the press plate. Prior to testing, preliminary strength calculations of the truss structure were performed in order to determine the design ultimate load. The physical and mechanical properties of the concrete used in the calculations were obtained through laboratory testing [25], while the reinforcement

characteristics were adopted in accordance with relevant standards.

As a result of the preliminary calculations, the ultimate load that the given floor structure can withstand was determined to be 16 kN.



a



b

Fig. 3 Test stand for beam specimens: *a* - general view of the stand; *b* - schematic diagram of the stand:

1 - beam specimen; 2 - support; 3 - fixed carriage; 4 - press frame; 5 - jack; 6 - crossbeam; 7 - support elements; 8 - support plates; 9 - dynamometer. Photo by K. Sirenok

Рис.3 Стенд для випробування балкових зразків: *a* - загальний вигляд стенду; *b* - схема стенду:

1 - балковий зразок; 2 - опора; 3 - нерухомий візок; 4 - силова рама пресу; 5 - домкрат; 6 - траверса; 7 - опорні елементи; 8 - опорні пластини; 9 - динамометр. Автор фото К. Сіренко

The loading of the beam specimens was carried out incrementally, with a step of 160 kg, which corresponded to 1/10 of the estimated ultimate load. At each stage, a holding period of 10–15 minutes was maintained to ensure more accurate identification of the moment of specimen failure.

During the testing, the moments of crack initiation and their subsequent development were recorded as the load increased incrementally.

The crack development exhibited a clearly defined staged behavior. The first cracks were observed at a load range of 1120–1440 kg. Cracks appeared in similar zones for all specimens, namely in the support regions, in the lower chord between the nodes, and in the

central node of the lower chord. This pattern of cracking indicates the occurrence of tensile stresses in these areas.

At the second stage, under a load of 2080–2560 kg, an intensive opening of previously formed cracks was observed, along with the formation of new ones. The primary localization of cracks remained in the support zones and additionally appeared at the load application nodes, indicating stress concentration in these sections.

Failure of the specimens occurred at loads in the range of 2400–2880 kg and was accompanied by further crack propagation and a loss of the load-bearing capacity of the structure..

Table 1. Results of load-bearing capacity tests of beam specimens

Табл.1. Результати випробувань з визначення несучої здатності балкових зразків

Specimen No.	First Cracking Load, kg	Failure Load, kg
1	1440	2880
2	1120	2560
3	1280	2400



Fig.4. Overall view of cracks: *a* – first stage; *b* – second stage. Photo by K. Sirenok
Рис.4. Загальний вигляд тріщин: *a* – перший етап; *b* – другий етап. Автор фото К. Сіренко

The analysis of the test results showed that all experimental specimens exhibited a similar load-bearing behavior. Crack development occurred in zones corresponding to areas of maximum stress. The close values of the loads at different stages of specimen performance indicate the stability of the obtained results and the uniformity of the fabricated structures. It is important to note that a significant load interval was observed between the appearance of the first cracks and the attainment of the ultimate load, indicating the presence of a reserve load-bearing capacity even after the onset of cracking.

The discrepancy between the results of the preliminary calculations and the experimentally determined load-bearing capacity ranged from 33% to 50%. This may be attributed to several factors, including simplifications made during the calculations, as well as potential inaccuracies in determining the actual concrete strength. In particular, concrete strength was assessed by testing concrete cubes cast in standard molds, which may not fully reflect the material properties within the assembled structure.

CONCLUSIONS

The technology of construction 3D printing opens new opportunities for the fabrication of structural elements in buildings and structures; however, it requires addressing a number of issues related to ensuring their reliable performance, particularly for elements subjected to bending. One of the key aspects is

the effective integration of reinforcement within the layer-by-layer construction process.

To address this issue, experimental studies were conducted to fabricate floor structures and determine their load-bearing capacity. Beam specimens in the form of a truss structure were produced using a gantry-type 3D printer and reinforced with steel bars using a conventional method - by manual placement between layers of the concrete mixture.

The load-bearing capacity of the specimens was determined using a stepwise loading method with a hydraulic jack. The test results revealed characteristic load values for different stages of structural performance: the first cracks appeared at 1120–1490 kg, intensive crack propagation and formation of new cracks occurred in the range of 2080–2600 kg, and specimen failure was observed at 2480–3000 kg. Cracks were primarily localized in the support zones, the lower chord, and at the load application points, corresponding to areas of maximum tensile stress.

The results indicate a significant interval between the onset of the first cracks and structural failure, confirming the presence of reserve load-bearing capacity after crack initiation. The close values of loads corresponding to different stages for all specimens suggest relative stability of the experimental results and uniformity of the fabricated structures.

At the same time, a substantial discrepancy of 33–50% was observed between the calculated and experimentally determined load-bearing capacities. This difference may be attributed to several factors, including

simplifications made during the calculations and potential inaccuracies in determining the actual concrete strength.

Overall, the results confirm the functionality of the proposed floor structure and its effectiveness when using conventional reinforcement. They also highlight the potential for optimizing structural designs in terms of material efficiency and enhancing the effectiveness of 3D printing in construction.

Promising directions for further research include investigating alternative reinforcement methods (including automated integration of reinforcing elements), studying the influence of printing parameters on mechanical properties, and scaling the results for larger structural elements.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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ДОСЛІДЖЕННЯ НАПРУЖЕНО- ДЕФОРМОВАНОГО СТАНУ ПЕРЕКРИТТІВ ВИГОТОВЛЕНИХ МЕТОДОМ БУДІВЕЛЬНОГО 3D-ДРУКУ

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Анотація. У даній роботі наведено результати експериментальних досліджень конструкцій перекриття, виготовлених із застосуванням технології будівельного 3D-друку, з акцентом на особливостях їх створення та армування. Узагальнено сучасний стан розвитку технології будівельного 3D-друку, зокрема в частині матеріалів і напрямів

наукових досліджень. Висвітлено основні наукові підходи у даній сфері, проаналізовано застосовувані матеріали та розглянуто існуючі концепції армування, що можуть бути використані при виготовленні конструкцій методом 3D-друку. Запропоновано конструкцію балкового елемента у вигляді плоскої ферми, що дозволяє підвищити ефективність використання матеріалу та зменшити його власну вагу.

Наведено опис технології виготовлення зразків за допомогою 3D-принтера порталного типу з використанням бетонної суміші та традиційного армування сталевими стержнями, яке інтегрувалося в процес друку шляхом ручного укладання між шарами. Представлено методичку та результати експериментальних випробувань із визначення несучої здатності зразків. Встановлено характерні стадії роботи конструкції, зокрема появу перших тріщин, їх розвиток та руйнування, а також зони їх локалізації.

Виявлено наявність резерву несучої здатності після початку тріщиноутворення і до повного руйнування конструкції та загальну стабільність експериментальних результатів.

Отримані результати підтверджують працездатність запропонованого конструктивного рішення та можливість застосування традиційних методів армування у конструкціях виконаних за допомогою адитивних технологій. Крім того, отримані дані можуть бути використані для подальших розрахунків конструкцій та прогнозування їх роботи при зміні вихідних параметрів. Робота має практичне значення для розвитку технологій будівельного 3D-друку та їх застосування у відновленні пошкоджених об'єктів внаслідок повномасштабної агресії російської федерації.

Ключові слова: будівельний 3D-друк; адитивні технології; конструкції перекриття; армування.

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