DOI: 10.32347/2522-4182.17.2025.141-152
UDC 624.012

TECHNOLOGICAL ASPECTS OF FABRICATING A REINFORCED CONCRETE SHELL USING 3D CONCRETE PRINTING

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Annotation. The article focuses on the technological aspects of fabricating a reinforced concrete shell using concrete 3D printing combined with polystyrene formwork. A comprehensive literature review was conducted to analyze recent advancements in additive manufacturing methods for shell structures, with a particular emphasis on the development and application of flexible and stay-in-place formwork systems. A step-by-step manufacturing procedure for the test shell element was implemented, including the generation of a digital parametric model, followed by the fabrication of a custom polystyrene mold. The mold was assembled using layered foam sheets, which were cut according to pre-defined templates, bonded using adhesives, and manually refined to ensure geometric accuracy.
The digital model was processed in CAD software and converted into a format suitable for slicing. The slicing operation was performed to define the layer height, printing path, and tool trajectories. Based on the generated G-code, a robotic concrete printer (console-type, "UTU 3D") was employed to execute the additive layering process. The concrete was deposited layer-by-layer on the pre-installed polystyrene form, beginning from the bottom ring, which was reinforced with embedded steel bars to accommodate lifting hooks. Thixotropic concrete mix was used to maintain the stability of each deposited layer and to prevent slippage on the curved surface of the mold. Short pauses between layers were introduced to manage curing and maintain interlayer bonding.
The finished shell was allowed to cure under ambient conditions until the desired structural strength was achieved. The study confirmed the feasibility and efficiency of combining foam-based formwork and 3D printing for creating thin-walled curved concrete structures, offering significant potential for use in both experimental and industrial-scale applications in the construction industry.
Further research is aimed at conducting full-scale tests of the shell under the action of quasi-uniform static loading in order to determine the bearing capacity and deformability of the structure.

Keywords: concrete shell; 3D concrete printing; polysterene formwork; additive technology.

INTRODUCTION

Shell structures continue to represent one of the most expressive forms of architectural and structural solutions in contemporary construction.
Due to their curved geometry, they provide exceptional spatial rigidity while maintaining minimal thickness and low material consumption, making them highly efficient from an engineering perspective. At the same time, the complex shape of such elements poses a number of technological challenges for both designers and builders. The conventional construction of shells requires the use of custom-made formwork systems of

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complex configuration, high-precision layout, and strict geometric control at every stage.

The formation of double curvature is particularly difficult, often demanding expensive molds, flexible materials, numerous temporary supports, and specialized equipment. These processes are generally labor-intensive and resource-demanding, and their implementation is only feasible with the involvement of highly qualified specialists.

In modern construction, there is a growing demand for new approaches to shell fabrication that can preserve architectural freedom while optimizing manufacturing and assembly processes. One of the most promising directions is the use of digital form-generation technologies and three-dimensional concrete printing (3DCP) [1-3], which enables the elimination or significant simplification of complex formwork, transforming it into a flexible auxiliary element.

In this context, the present study investigates the production process of a test sample of a spherical concrete shell fabricated using 3D concrete printing. The experiment was carried out using the technology and industrial capacities of the Ukrainian company “UTU 3D“ [4].

ANALYSIS OF PREVIOUS RESEARCH

An analytical review of recent scientific achievements shows that interest in 3D concrete printing (3DCP) is steadily growing worldwide – including in Ukraine. In recent years, 3D concrete printing has been addressed by the scientific schools of Prof. V. Shmukler [5-6], Prof. M. Savitsky [7-8], and Prof. B. Demchyna [9-10], etc. Specifically, study [11] gives a structural solution for a building frame whose components – beams, columns, and slabs – are manufactured using 3D-printed concrete formwork. The design allows flexibility for use not only in new construction but also in renovation. Work [12] is devoted to a comparative analysis of bridge-type 3D-printer constructions used in construction; an improved model with two extruders was proposed. The results demonstrated a reduction in the cost of producing 1 m³ of products by 1.9–2.7 times and a decrease in metal consumption by 1.8–2.6 times compared to traditional printer designs. In article [13], a solution to the problem of transverse reinforcement in 3D-printed reinforced-concrete load-bearing beams was proposed. The developed technology enabled vertical reinforcement cages to be placed in their design position without interrupting the printing process, ensuring the ability of the structure to resist both bending moments and shear forces.

Contemporary international publications demonstrate a wide variety of research efforts aimed at automation, serial production, and reduction of the impact of labor-intensive factors in construction. In the field of shell-structure printing, a particularly relevant challenge remains the use of formwork – including stay-in-place formwork. In this regard, the work by A. Jipa and B. Dillenburger [14] should be mentioned, in which a comprehensive review of indirect methods for producing concrete components via 3D-printed formwork is conducted. In that article, five different technologies for 3D-printing concrete formwork (material extrusion, ink- or foam-jet printing, powder binding, etc.) are classified and approximately 30 implemented projects are analyzed. The authors discuss new geometrical possibilities, improvements in efficiency and sustainability in construction enabled by these technologies, and outline their advantages and challenges compared to traditional methods.

In the study by Ivaniuk et al. [15], the concept of assembling reinforced-concrete shell structures using robotic installation of modular falsework was examined. The authors describe the automated placement of rigid components that form the supporting geometry of a shell. The results confirmed the effectiveness of robotics in ensuring geometrical accuracy, reducing labor costs, and enabling the standardization of structural solutions. The method is suitable for serial production of curved shell buildings. Research [6] introduces a new technology called F3DP – robotic 3D printing of mineral foam to create stay-in-place formwork for lightweight, complex concrete elements. Two experimental demonstrations are provided: a perforated facade panel and an arched slab, where the foam inserts printed served as formwork for the concrete. The results showed up to 50 % savings in concrete volume and more than 60 % reduction in mass without loss of strength. The foam inserts remain within the elements, providing additional thermal and acoustic insulation.

In the article by Li et al. [16], a systematic review of modern formwork systems used in concrete construction is presented, with particular attention to their environmental friendliness, economic efficiency, and technological flexibility. The advantages and drawbacks of various types of formwork – timber, steel, modular, 3D-printed, and pneumatic – are summarized. The authors emphasize the relevance of developing reusable systems with reduced material consumption. A special section is devoted to formwork for geometrically complex shell structures, in which traditional solutions are often inefficient.

In work [17], a method is presented for printing concrete layers onto a temporary flexible formwork to create a thin shell. The researchers combined an adjustable flexible template (developed by TU Delft) with a gantry-type 3D printer, printing part of a shell onto a curved surface; the remaining sections were cast conventionally with concrete. As a result, a thin shell of ~5 m² was obtained: part was 3D-printed and part cast, using a CNC-milled polystyrene mold for support during printing. This work demonstrates the possibility to overcome the limitations of concrete's self-supportiveness during 3D-printing by employing temporary forms.

Article [18] describes the "Eggshell" technology, which consists of 3D-printing an ultra-thin (≈ 1–2 mm) plastic formwork and simultaneously filling it with concrete. This approach combines formwork fabrication and concreting in one process: a robotic system prints a hollow "eggshell"-shaped mold, and then a fast-hardening concrete mix is poured immediately inside. This enables efficient production of geometrically complex reinforced-concrete elements with minimal formwork waste. It was shown that reinforcement can be easily placed inside the thin printed shell; the resulting concrete elements (e.g., branching columns) have optimized geometry and strength unattainable by traditional methods.

In study [19], an innovative technology for creating curved shells using 3D-printed flexible formwork is described. Initially, a flat mesh formwork made of a special polymer is robotically printed; then this mesh is elastically bent into the shell shape and used as a base for applying concrete (e.g., via shotcrete) or laying fibre-reinforced concrete. It was experimentally confirmed that approximately 80 kg of the printed mesh formwork successfully supported about 400 kg of fresh concrete. This method enables the construction of thin, doubly-curved reinforced-concrete shells with complex geometry without traditional rigid formwork; the printed formwork may remain as part of the structure or be reused.

The analytical review leads to the conclusion that current research in 3D-concrete printing, especially for shell structures, is aimed at overcoming the technological limitations of traditional monolithic construction, reducing material consumption, and introducing automated systems. The main trends include the development of stay-in-place and flexible formwork systems, integration of reinforcement during printing, and the use of lightweight forming materials (foam, plastic, polymer meshes), allowing the realization of complex-geometry shells. The most economically efficient technologies proved to be those in which 3D printing is applied not only to concrete itself but also to the production of the formwork.

PURPOSE AND METHODS

The aim of the study was to test a method for constructing a concrete shell with a diameter of 2200 mm, a thickness of 40 mm, and a rise of 300 mm using 3D concrete printing technology. In this study, the implementation of a rationalized [20] concrete shell formed using expanded polystyrene formwork is presented.

The objectives of the research included:

- the preparation of a digital model of the shell based on preliminary calculations using the finite element method (FEM);
- the cutting and fabrication of the expanded polystyrene mold, which served as a supporting surface for the application of concrete extrusion;
- the printing of the concrete shell using a cantilever-type 3D printer manufactured by UTU 3D.

MAIN PART OF RESEARCH

To generate the shell geometry and define the contours of the formwork layers, the Autodesk Fusion 360 software package was used in combination with a parametric modeling module. The shell geometry was created as a solid body with adjustable parameters for diameter, height, and thickness. Subsequently, the digital model was stratified into layers according to the thicknesses of the polystyrene foam sheets (50 mm and 20 mm).

The design dimensions of the shell were obtained as a result of FEM analys according the energy rationalization approach [21-22] and defined as follows: a diameter of 2200 mm, a rise of 300 mm, and an average thickness of 40 mm. A general view of the shell with the integrated polystyrene formwork insert is presented in Fig. 1.

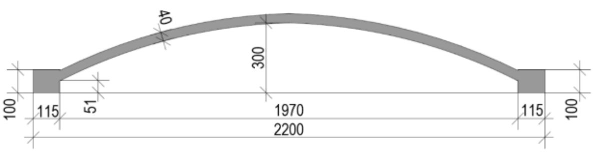

Fig. 1 General view of the concrete shell
Рис. 1 Загальний вигляд бетонної оболонки

Given the relatively small dimensions of the test shell, the use of a polystyrene foam screen was considered the most rational solution, as it is capable of withstanding the weight of freshly placed concrete without deformation [23].

Standard expanded polystyrene (EPS) sheets of type PS-30 with dimensions of 1×1 m and thicknesses of 50 mm and 20 mm were used to shape the precise geometry of the shell. This thickness gradation was chosen to increase the accuracy of the form, based on the calculated shell geometry.

A total of four 50 mm layers and five 20 mm layers were cut. Since the overall size of the shell exceeded the width of a standard sheet, most layers had to be assembled by bonding multiple sheets together.

Silicone adhesive and a hot glue gun were used for this purpose. Each prepared layer was marked with the outer and inner contours, after which cutting was performed along the outer line.

The geometry of the shell and the cutting strategy of the EPS screen are shown in Figure 2. Figure 3 presents the cutting layouts for each formwork layer, using EPS blocks measuring 2×2 m and individual sheets of 1×1 m.

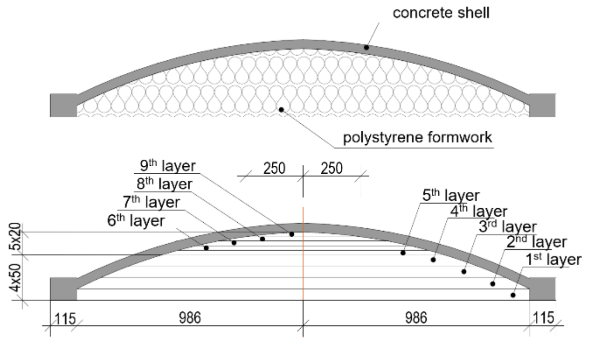

Fig. 2 Shell with a polystyrene screen (top) and vertical layer-wise cutting of the polystyrene screen (bottom)
Рис. 2 Оболонка з пінопластовим екраном (вгорі) та розрізання екрану з пінопласту на шари по висоті (внизу)

The cutting of polystyrene sheets was carried out in accordance with layouts prepared in the design software environment. The entire process was performed in several stages:

1. Marking of layer contours was carried out manually.
2. Initial cutting of sheets to the required dimensions and their assembly into blocks of the desired thickness was performed, with staggered joints to enhance structural integrity.
3. Mechanical shaping was conducted using: a construction knife (for rough cutting), a hot knife (for curves and radii), and a wire-type thermal cutter (for precise shaping of curved areas).

The blocks were assembled into the final form sequentially, with visual control of dimensional and geometric accuracy. The layers were glued together, and surface irregularities at transitions were sanded. A tensioned string and manual visual inspection were used to verify compliance with the design profile.

After cutting the formwork layers, each segment was trimmed along its edge to match the geometric profile of the shell. During the fabrication process, it became evident that small and thin segments were difficult to process using thermal cutting tools due to a sharp drop in accuracy. The high temperature of the equipment caused local melting of the polystyrene, and due to the slow processing speed, the risk of damaging the workpiece beyond correction increased significantly.

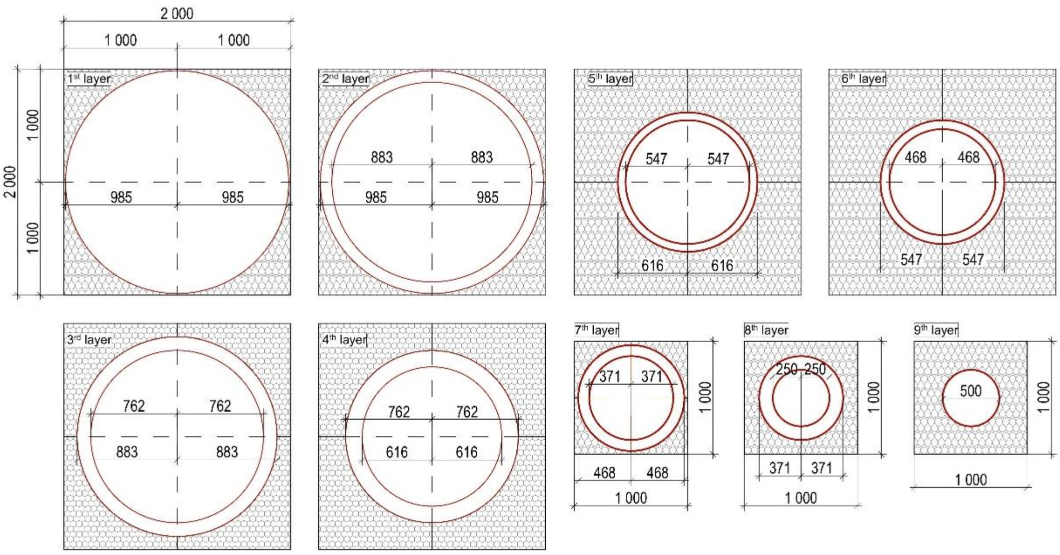

Fig. 3 Cutting layouts of polystyrene sheets
Рис. 3 Схеми розкрою листів пінопласту

Fig. 4 shows the results of cutting using a hot knife (Fig. 4a), a heated nichrome wire (Fig. 4b), and a standard utility knife (Fig. 4c). The labor intensity and time required for manual shaping led to a significant increase in production time. For future industrial-scale applications, the use of CNC-controlled equipment is recommended to ensure precision and efficiency.

a *b* *c*

Fig. 4 Polystyrene processing: a) with a hot knife, b) with a heated wire, c) with a utility knife. Photo by V. Tenensku
Рис. 4 Обробка пінопласту: а) термоножем, б) гарячою струною, в) будівельним ножем. Автор фото В. Тенесеску

After all layers had been cut according to the prepared design drawings, the assembly of the polystyrene formwork into a single three-dimensional structure was initiated. The primary objective at this stage was to ensure geometric compliance with the design shape, provide secure bonding between individual components, and create a smooth, monolithic surface capable of withstanding the load from the concrete mixture.

Before assembly, each layer was carefully cleaned of dust, debris, and glue residue from the previous cutting operations. Any rounding or surface irregularities that could result in deviations from the desired form were manually corrected using sanding mesh or abrasive paper. To bond the polystyrene components, two types of adhesive were employed: a silicone-based construction adhesiv**e** was used for bonding large surface areas, providing sufficient working time; and hot melt glue (applied with a glue gun) was used for quick point-fixation at joints and curved sections.

The layers were stacked sequentially, starting from the bottom, with strict adherence to orientation markings. The adhesive was applied in narrow strips, after which the next layer was firmly pressed into position and held under slight pressure for 10–15 minutes to achieve initial bonding.

Upon completion of the assembly, surface alignment and sealing were performed. Some layers were additionally trimmed with a utility knife; joints, gaps, and irregularities were filled using an acrylic-based putty. After drying, the filled areas were sanded using abrasive tools to ensure a smooth transition between layers and an even surface finish.

The step-by-step formwork making is presented in Fig. 5.


a


b


c


d


e


f

Fig. 5. Procedure for creating polystyrene formwork: a) manual marking of individual polystyrene sheets; b) basic cutting of fragments with a utility knife; c) general view of blanks before edge trimming; d) blanks after edge trimming; e) shape adjustment after assembling the formwork; f) puttying of seams and joints. Photo by V. Tenensku

Рис. 5. Процедура створення опалубки з пінопласту: а) розмітка окремих листів пінопласту вручну; б) базове нарізання окремих фрагментів будівельним ножем; в) загальний вигляд заготовок до зрізання країв; в) заготовки після підрізки країв; г) підрізка форми після формування опалубки; г) шпатлювання швів і стиків. Автор фото В. Тенесеску

Subsequent operations involved the transportation of the assembled formwork to the printing site and the concrete 3D printing process itself using a console-type 3D printer. Before initiating the printing, it was essential to properly prepare the digital model. A CAD program was used to model the volume of the shell structure, taking into account thickness, curvature, and reinforcement layout. The model underwent mesh and geometry validation and was then exported in STL format.

Next, a specialized slicing software was used to divide the model into thin horizontal layers [24]. Parameters such as layer thickness, extruder path, reinforcement insertion levels, and other print settings were defined. Based on this data, the slicing software generated G-code for the 3D printer. When needed, a print simulation was conducted to check for collisions, sagging, or printing errors. Only after this verification process was the print job initiated. This approach allowed for the transformation of complex 3D geometry into an executable construction sequence, while accounting for technological constraints

At the construction site, the polystyrene formwork was installed in its project position, and the printing of the outer concrete ring began (Fig. 6a).

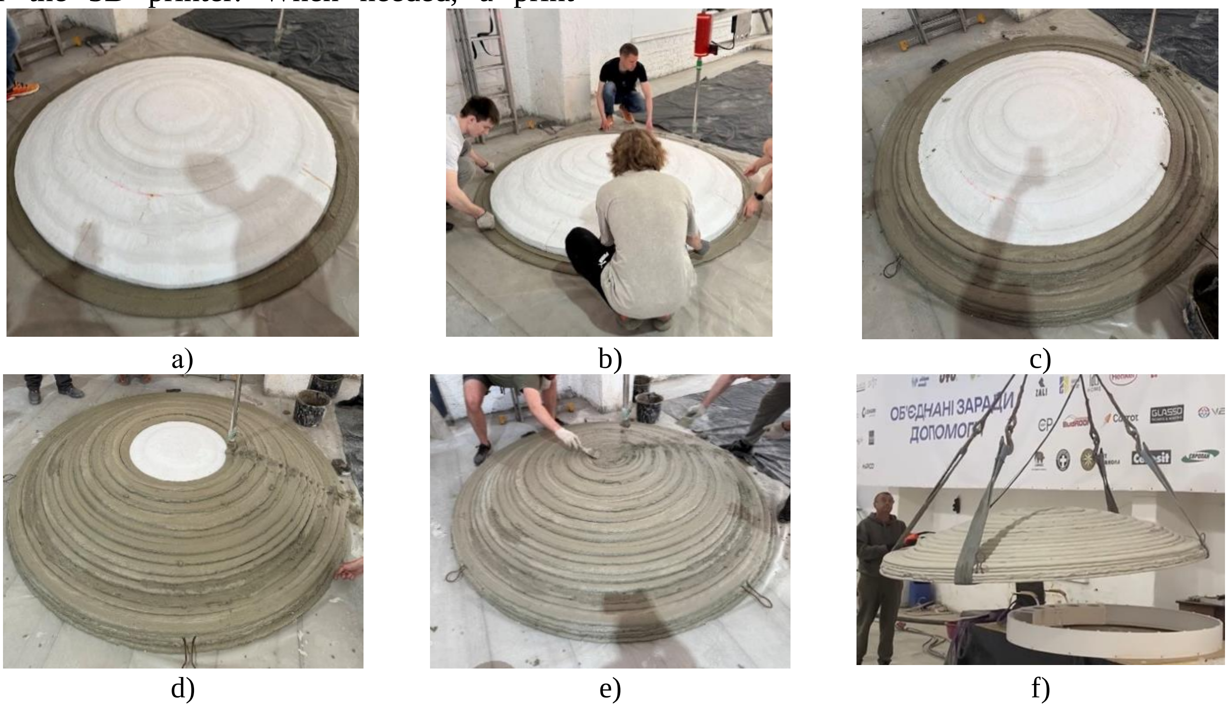

Fig. 6. Stages of shell printing: a) installation of the formwork and printing of the support ring; b) placement of reinforcement and mounting loops; c–e) layer-by-layer extrusion of concrete along the height of the formwork; f) transportation of the shell after it has gained sufficient strength. Photo by V. Tenensku

Рис. 6. Етапи друку оболонки: а) встановлення опалубки і друк опорного кільця; б) укладання арматури та монтажних петель; в-д) пошарова екструзія бетону по висоті опалубки; ж) транспортування оболонки після набрання нею міцності. Автор фото В. Тенесеску

The printing proceeded vertically from the base of the form upward. The structure was designed without area-wide reinforcement, except for the lower support ring. In this region, 10 mm diameter steel bars were placed to secure four 6 mm mounting loops (Fig. 6b), fastened using steel binding wire. These reinforcement elements were embedded within the initial extrusion layer and subsequently enclosed by additional printed layers (Fig. 6c–d). Technological pauses between layers were allowed, though their duration was minimized to prevent cold joints and ensure interlayer bonding. At the same time, considering the curved geometry of the formwork, short breaks helped prevent sliding of fresh concrete layers due to the weight of upper layers.

The concrete mix used for printing exhibited thixotropic properties, essential for layer-by-layer extrusion. Upon completion of printing, the concrete shell was left to cure under ambient conditions until it reached the required strength (Fig. 6e). After hardening, the structure became suitable for further transportation (Fig. 6f) and integration into larger construction processes.

CONCLUSIONS AND RECOMMENDATIONS

The article presents the technological sequence of producing a reinforced concrete shell of complex geometry using polystyrene foam formwork and concrete 3D printing. An efficient approach is proposed for shaping the curved surface by means of layer-by-layer assembly of foam formwork, which ensured high geometric accuracy while minimizing material consumption and labor resources. The process of digital model preparation, fabrication and assembly of the polystyrene base, as well as subsequent concrete printing using a 3D printer, confirmed the viability of the proposed technology under real-life experimental conditions.

The proposed method significantly simplifies the fabrication of complex-shaped elements by avoiding the use of traditional rigid formwork and can be adapted for different construction scales. The feasibility of using foam-based formwork as a foundation for printing was confirmed, with subsequent application of concrete mixture without compromising geometric precision or structural integrity.

Further research is aimed at conducting experimental investigations of the concrete shell to determine its deformability and load-bearing capacity.

AKNOWLEDGMENT

The author sincerely acknowledges the invaluable support provided by "UTU 3D" in the development and realization of the printed concrete shell structure. Special thanks are extended for their expert consultation and technical assistance throughout all phases of preparation, calibration, and execution of the 3D printing process.

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ТЕХНОЛОГІЧНІ АСПЕКТИ ЗВЕДЕННЯ БЕТОННОЇ ОБОЛОНКИ ЗА ДОПОМОГОЮ 3D-ДРУКУ БЕТОНОМ

Владислав ТЕНЕСЕСКУ

Анотація. У статті основна увага приділена технологічним аспектам виготовлення залізобетонної оболонки за допомогою 3D-друку бетону в поєднанні з полістирольною опалубкою. Було проведено комплексний огляд літератури для аналізу останніх досягнень у методах адитивного виробництва оболонкових конструкцій, з особливим акцентом на розробці та застосуванні гнучких та незнімних опалубочних систем. Було реалізовано покрокову процедуру виготовлення тестового елемента оболонки, включаючи створення цифрової параметричної моделі, а потім виготовлення спеціальної полістирольної форми. Форму було зібрано з використанням шаруватих пінопластових листів, які були вирізані за заздалегідь визначеними шаблонами, склеєні за допомогою клеїв та вручну вдосконалені для забезпечення геометричної точності.

Цифрову модель було оброблено в програмному забезпеченні CAD та перетворено у формат, придатний для слайсування. Операція слайсування була виконана для визначення висоти шару, напрямку друку та траєкторій руху сопла. На основі згенерованого G-коду для виконання процесу адитивного нашарування було використано роботизований бетонний принтер (консольного типу, «UTU 3D»). Бетон укладався шар за шаром на попередньо встановлену пінополістирольну форму, починаючи з нижнього кільця, яке було армовано вбудованими сталевими стрижнями для розміщення вантажопідйомних гаків. Тиксотропна бетонна суміш використовувалася для підтримки стабільності кожного нанесеного шару та запобігання сповзання по криволінійній поверхні форми. Були введені короткі паузи між шарами для керування твердінням та підтримки міжшарового зчеплення.

Готовій оболонці дали затвердіти в нормальних умовах до досягнення бажаної структурної міцності. Дослідження підтвердило доцільність та ефективність поєднання опалубки на основі полістиролу та 3D-друку для створення тонкостінних криволінійних бетонних конструкцій, що пропонує значний потенціал для використання як в експериментальних, так і в промислових цілях у будівельній галузі.

Подальші дослідження спрямовані на проведення повномасштабних випробувань оболонки під дією кваз-рівномірного статичного навантаження з метою визначення несучої здатності та деформативності конструкції.

Ключові слова: бетонна оболонка; 3D-друк бетоном; опалубка з пінопасту; адитивні технології.

Received: *October 22, 2025.*
Accepted: *November 30, 2025.*