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CREATION OF REINFORCED CONCRETE STRUCTURES OF A COMPLEX GEOMETRIC SHAPE

S. Bugaevsky[1], N. Smirnova[2], A. Filatova[3], E. Sinkovskaya[1] and A. Ignatenko[1]
[1]Department of Bridges, Constructions and Building Mechanics, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine
[2]Road Building and Maintenance Department, Kharkiv National Automobile and Highway University,Kharkiv, Ukraine
[3]Department of Computer Engineering and Programming, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine
E-Mail: NataliaVS.0105@gmail.com

ABSTRACT

The analysis of modern technologies for the creation of buildings as a whole or of individual structural elements of a complex geometric shape is carried out. The aim of the study is to develop a new architectural and construction system "Monofant" using a self-supporting skeleton for the construction of monolithic reinforced concrete buildings and structures of a complex geometric shape. The subject of the research is the formation of a self-supporting skeleton consisting of a reinforcement cage and non-removable liners-void formers. On the basis of the shape of the main carrier element in the form of a Mobius loop, the layout of liners-void formers is made. The form of liners is adopted in the form of three-sided prisms of two sizes, based on the condition of minimizing the number of elements of the internal fixed formwork, as well as ensuring the rigidity of the structure. A comparison of three variants of the assembly technology of a self-supporting skeleton for the erection of a structure in the form of a Mobius loop is made. The task of creating a technology of manufacturing foam polystyrene liners for the construction of lightweight reinforced concrete structures of a complex geometric shape is solved. A "virtual" catalogue of fixed polystyrene liners for various curvilinear surfaces is obtained.

Keywords: self-supporting skeleton, reinforcement cage, non-removable liners-void formers, fixed formwork, polystyrene foam.

INTRODUCTION

Recently, there has been a tendency throughout the world to erect reinforced concrete buildings and structures of a complex geometric shape using the latest technologies, including 3D modeling and 3D printing in construction to create unique architectural objects. As know, one of the main disadvantages of reinforced concrete is its own heavyweight. As practice shows, the most effective method of reducing the own weight of reinforced concrete structures is the creation of internal voids. With monolithic construction, it becomes possible to bring voids of various configurations and sizes. However, in addition to reducing its own weight of elements, it is possible to achieve an additional effect due to giving the liners a deliberately reasonable (calculated) spatial configuration that it will lead to rational work of the structure. Internal voids can be created by placing in the self-supporting skeleton non-removable liners-void formers, made of light inexpensive materials that will play the role of permanent formwork.

In this case, before the designers and builders, there are various technical problems associated with the manufacture and reduction of the cost of fixed formwork, having a complex geometry, with the creation of reinforcement cages, including self-supporting, with the concreting process, etc.

LITERATURE REVIEW AND FORMULATION OF THE PROBLEM

A systematic analysis of the main modern technologies used for the construction of buildings or their elements with a complex geometric shape is discussed in this section.

The Dutch architectural bureau of Janjaap Ruijssenaars (Universe Architecture) used a 3D construction printer to print out large sections of a building specified by the program (the project called Landscape House), which ensured the production of blocks from a mixture of sand and binder material of 6x9 m^2 in almost any shape right on the construction site [1]. However, the project of a residential house in the form of an endless Mobius strip has the main disadvantage of reinforced concrete - great weight (Figure-1).

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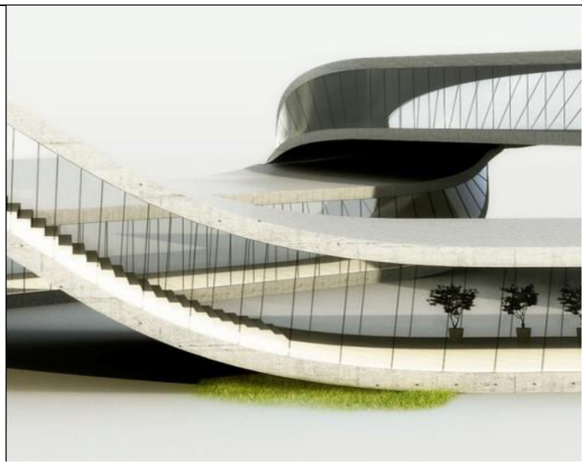
(a)

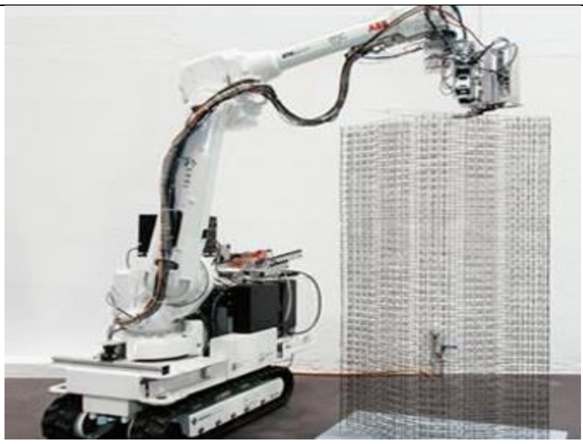


(b)

Figure-1. The project “Landscape House”: (a) building view; (b) floor construction.

Scientists from the Swiss Higher Technical School of Zurich, in the framework of the Mesh Mould project, developed a 3D printing method for continuous structures to create large geometrically complex structures [2]. The new technology is designed to make possible the production of more complex structures directly on the construction site (Figure-2).

However, the 3D printing system is able to efficiently produce a continuous metal construction from steel wire only 3 mm thick [3].



(a)

(b)

Figure-2. The project “Mesh Mould”: (a) creation of steel reinforcement cage; (b) the process of laying concrete mix.

Branch Technology Company from Chattanooga, Tennessee (USA) announced preparation for the start of construction of the first 3D print house in Chattanooga using the innovative 3D printing method: 3D printing Cellular Fabrication (C-Fab) [4]. The design of finished products resembles a honeycomb and is produced using an industrial robot Kuka KR 90, forming complex large-scale structures of up to 3 m^3 in size. These structures constitute, in fact, only the internal supports of the building, which can later be filled with traditional inexpensive building materials, for example, with assembly foam and concrete, to create the building elements (Figure-3).

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(a) (b)

Figure-3. Method of 3Dprinting C-Fab: (a) non-metallic reinforcement cage; (b) wall fragment.

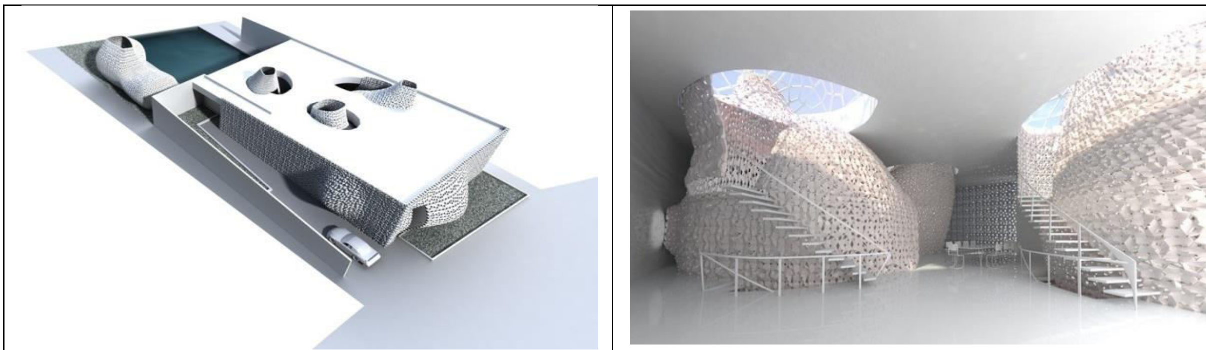
A completely different approach for the application of printing three-dimensional objects of industrial equipment is offered by Emerging Objects [5]. The project“ House of the Future”, which will take about a year to be implemented, has received the name “3D Printed House 1.0” (Figure-4).

At the same time, shotcrete technology is used for erecting buildings and structures of the curvilinear form [6, 7]. For the manufacture of a curved wall in the Warsaw Museum of the History of Polish Jews, a skeleton of metal pipes was used, to which curvilinear sheets of waterproof plywood, reinforced with special reinforcing meshes, are attached to a baffle (Figure-5(a)). The surface of the curvilinear walls after spraying a two-layer gunned concrete by the dry-mix method is shown in Figure-5(b).

In conjunction with shotcrete technology, a self-supporting metal skeletonis used that was created using a digital model and follows the shape of the future structure [7]. According to this technology, in the UK, designs of acoustic shells were created which are the stage and cover in scenic places (Figure-5(c)).

At the Danish Institute of Technology, using special software and robotic manipulators, there is cut out a voluminous external formwork from polystyrene foam blocks for traditional concreting of a curvilinear construction (Figure-5(d)). For better separation of the formwork from the concrete construction, a silicone membrane 0, 5 mm thick has been proposed [8].

All of these technologies solve only individual tasks in the design and construction of buildings and structures of a complex geometric shape from reinforced concrete and do not offer a holistic technology for creating reinforced concrete structures of a complex geometric shape from lightweight structures.



(a) (b)

Figure-4. The project “3D Printed House 1.0”: (a) building view; (b) internal volume (interior).

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Figure-5. Modern technologies for the construction of curved structures: (a) permanent formwork made of waterproof plywood**;** (b) curved walls of the museum; (c) reinforcement cage for acoustic shells; (d) production of foam polystyrene formwork.

AIM OF THE RESEARCH

The aim of the study is to create a self-supporting skeleton for the construction of monolithic reinforced concrete buildings and structures of a complex geometric shape of the new architectural and construction system "Monofant".

To achieve the stated objective this work addresses the following tasks:

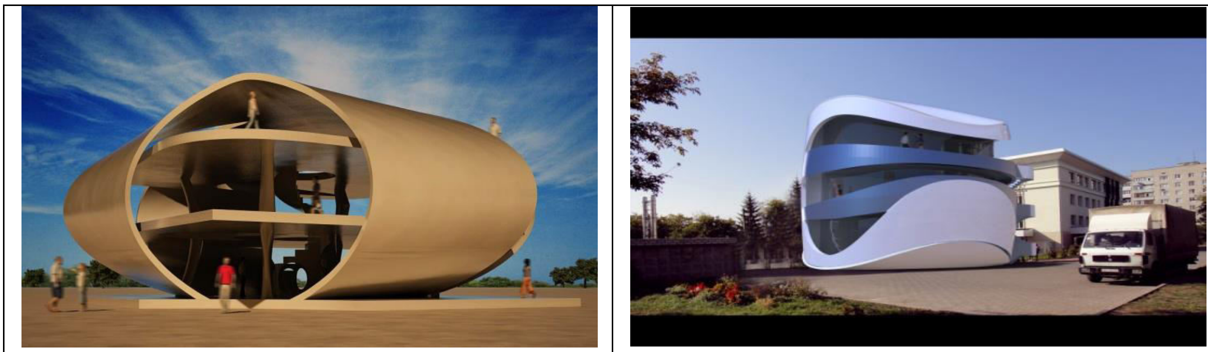
- minimization of standard sizes of non-removable foam polystyrene liners for creating permanent formwork, which is part of a self-supporting skeleton for the construction of monolithic reinforced concrete buildings and structures of a complex geometric shape;
- reduction of waste when cutting a flat rectangular sheet of polystyrene foam and the maximum reduction in the number of elements in the assortment for the manufacture of a triangular liner, which is an element of permanent formwork.

FEATURES OF THE ARCHITECTURAL AND CONSTRUCTION SYSTEM "MONOFANT"

For the construction of monolithic reinforced concrete buildings and structures of a complex geometric shape, there is developed the architectural and construction system "Monofant" (Figure-6) built on the following principles [9]:

- creating an arbitrary irregular grid of pillars;
- the use of various materials for non-removable liners-hollow cores in order to significantly reduce its own weight of the structure, as well as the cost is an order of magnitude lower than the cost of reinforced concrete;
- providing a complex configuration in plan and non-uniqueness of overlapping disks;
- providing (if necessary) the possibility of the location of the disc of overlap is not in the same plane;
- the organization of flat floors and ceilings;

- the choice of a rational topology of the ribs inside the overlap disk, which ensures the equalization of forces in the overlap slabs;
- creation of a complex configuration of hollow pillars;
- the device (if necessary, which is justified by calculation) of internal capitals.



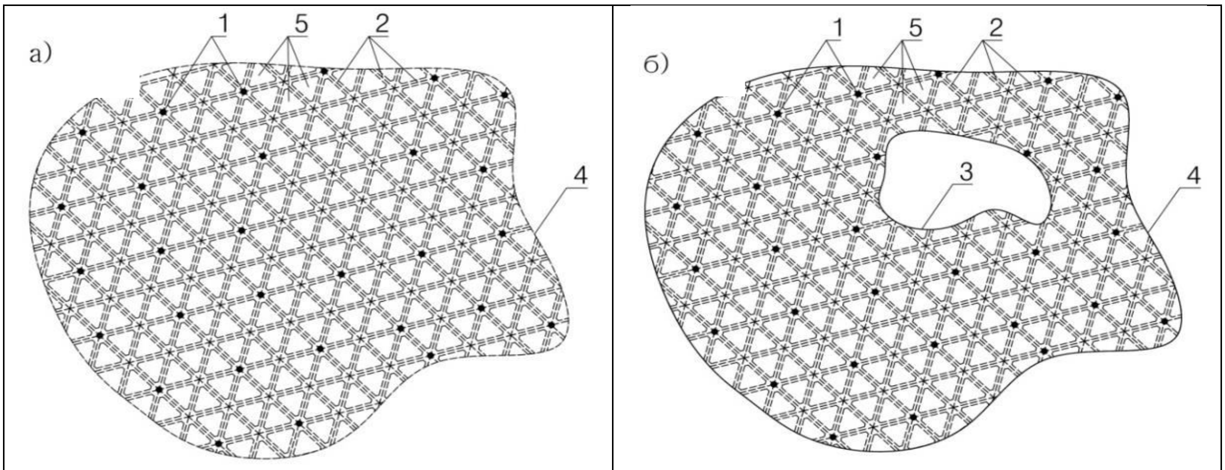
(a) (b)

Figure-6. Variants of the hotel project for pilots to rest at the airport Kharkiv (architectural and construction system “Monofant”).

Characteristic advantages of the proposed architectural and construction system are:

- constructions with arbitrary geometry;
- almost unlimited combinatory of volume-compositional solutions;
- free interior layout;
- the use of a given consumption of materials;
- high bearing capacity of elements;
- limited deformability;
- low weight;
- efficient erection technology and more.

The above features of the system are achieved due to the fact that in the proposed solution of the building, which contains the foundation, pillars, stiffness elements, floors, and coverings, all these elements are made of reinforced concrete with hollow sections through the installation of foam polystyrene or mineral wool inserts inside them, and all the junctions of the elements are made of monolithic reinforced concrete for a length not less than the larger side of the pillar (Figure-7 and Figure-8).



(a) (b)

Figure-7. The design of the base plate and floor slab: (a) base plate; (b) floor slab; 1 - pillar; 2 - internal stiffener; 3, 4 - internal and external edging by stiffener; 5 - liner.

The liners are made of polystyrene foam or mineral wool in the form of elements of solid or box section (Figure-9). The pillars are placed with an arbitrary pitch in the plan and are connected with stiffening ribs located inside the slabs or cover, forming a junction containing four to eight rods (Figure-8 (b)).

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When crossing nodes of “pillar-covering” and “pillar-overlapping” of more than four internal stiffeners, the capital of a polygonal or round shape is arranged (Figure-8 (b)).

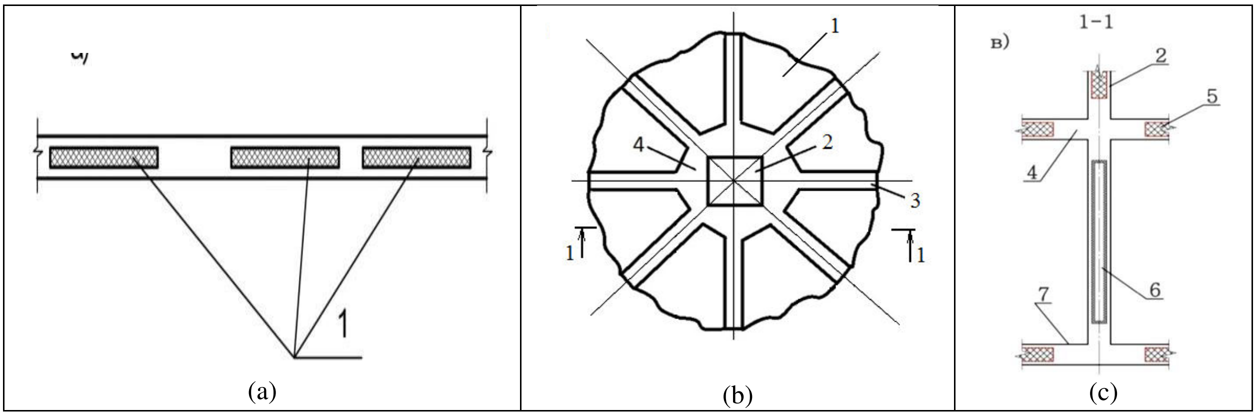

Figure-8. Constructions with liners: (a) floor slab; (b) capital (top shelf not shown); (c) liners in the building elements; 1 - liner; 2 - pillar; 3 - internal stiffeners of the slab; 4 - capital; 5, 6 - the liner with solid and box section; 7 - foundation.

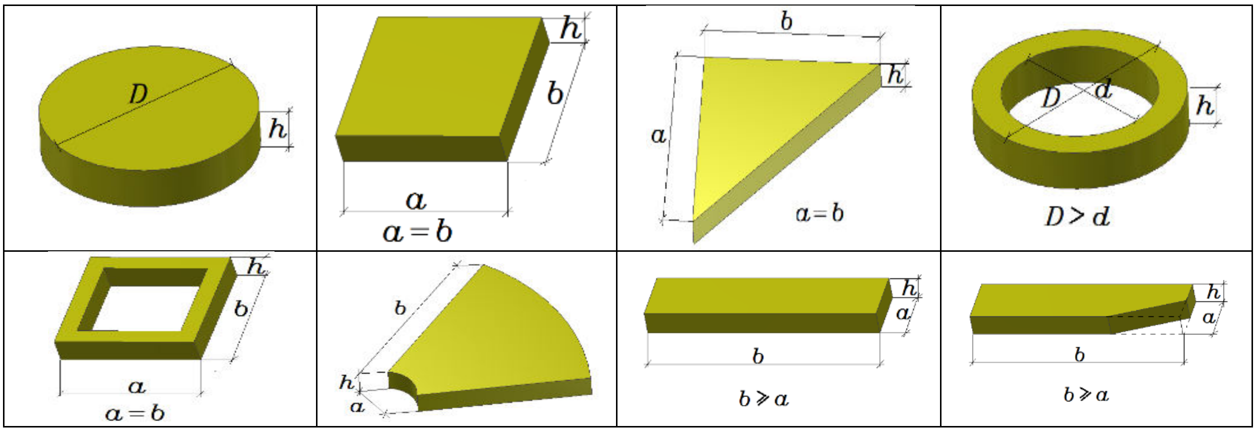

Figure-9. Liners for hollow formers.

For the effective erection of buildings and structures of the curvilinear form of the system “Monofant”, a wet shotcrete technology of a concrete mix onto a self-supporting skeleton is proposed. Skeleton structure, in this case, consists of a spatial curved reinforcing cage and liners (internal fixed formwork), which form a given geometry of the structure and are a baffle on which the concrete mix is wet sprayed from both sides. The gaps between the liners to create a solid baffle are closed with chain-link mesh or a perforated metal sheet (Figure-10).


(a) (b)

Figure-10. Concreting structures of complex geometric shape: (a) self-supporting skeleton with foam polystyrene liners; (b) concrete shotcrete.

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Laying the concrete mix with non-metallic fiber by wet shotcrete method allows significantly speeding up the process of erecting a monolithic reinforced concrete building, reducing the rebound and getting fiber reinforced concrete with high tensile strength, which prevents the formation of cracks in the stretched zones. The proposed technology allows compressing the concrete mix without vibration. The rationality of this technology is confirmed by a patent for an invention [10].

Due to the use of the spatial structure of the reinforcement cage, which is the outer shells and the system of flat ribs connecting them, the necessary rigidity and bearing capacity of the skeleton for shotcrete concrete are provided.

CREATING A NON-REMOVABLE FORMWORK FOR SELF-SUPPORTING SKELETON

One of the important tasks that need to be solved for the manufacture of the self-supporting skeleton is the creation of internal non-removable formwork, subject to the minimization of liner sizes and their rational layout.The use of CAD tools is appropriate here. In particular, two approaches are possible when constructing complex curvilinear models:

a) use of standard three-dimensional objects (sphere, cone, cylinder, etc.) which combine in various ways (addition, union, subtraction, etc.);

b) use of a family of curvilinear and/or rectilinear segments R^2, which are transformed into a network or surface, followed by the production of solid-state objects R^3.

Building a model of the structure presented in Figure-11, 12 is performed by converting curved and straight guides into a solid object. Previously, the entire surface of the model is divided into separate elements representing segments of characteristic geometric surfaces: FBandCG - cylindrical, BC - cyclic, FA and GE-cylindrical andAE - helical with turning on 90º.

Figure-11. Project visualization.

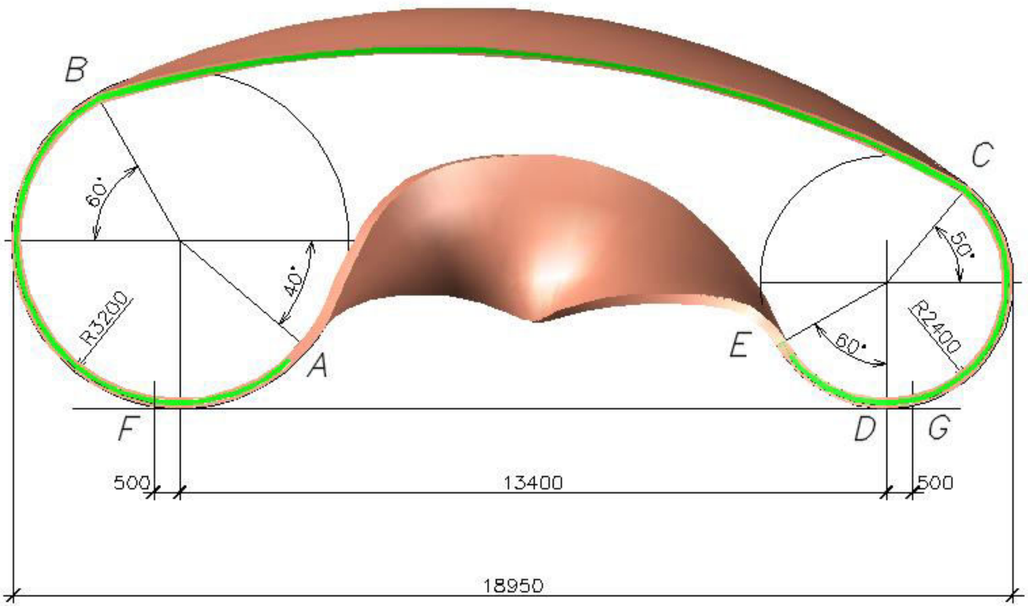

Figure-12. The shape of the main structural element of the Mobius loop.

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The fragments of the model are designed taking into account the arrangement of the forming and guiding cylindrical, cyclic and helicoid surfaces, after which they are all combined into one model. The design of the simulated surface consists of three layers (Figure-13): the upper and lower shelves 50 mm thick (reinforced concrete) and a layer of liners 100 mm thick (polystyrene foam). The form of inserts is adopted in the form of three-sided prisms of two standard sizes, based on the condition of minimizing the number of elements of the internal fixed formwork, as well as ensuring the rigidity of the structure (Figure-13).

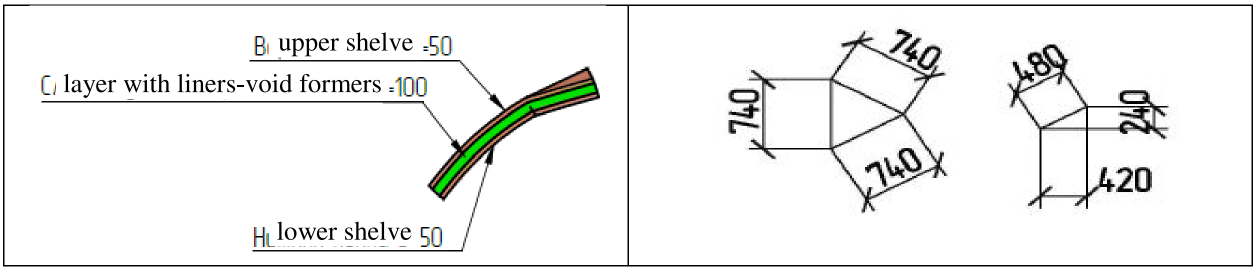

Figure-13. Fragment of the construction and dimensions of liners.

The inserts were laid out from point F through points B and C to point G (Figure-12) along accepted guides of these surfaces by rolling. The distance between the liners is taken 150 mm to ensure the placement of flat reinforcement cages in the internal edges of the structure (Figure-14).

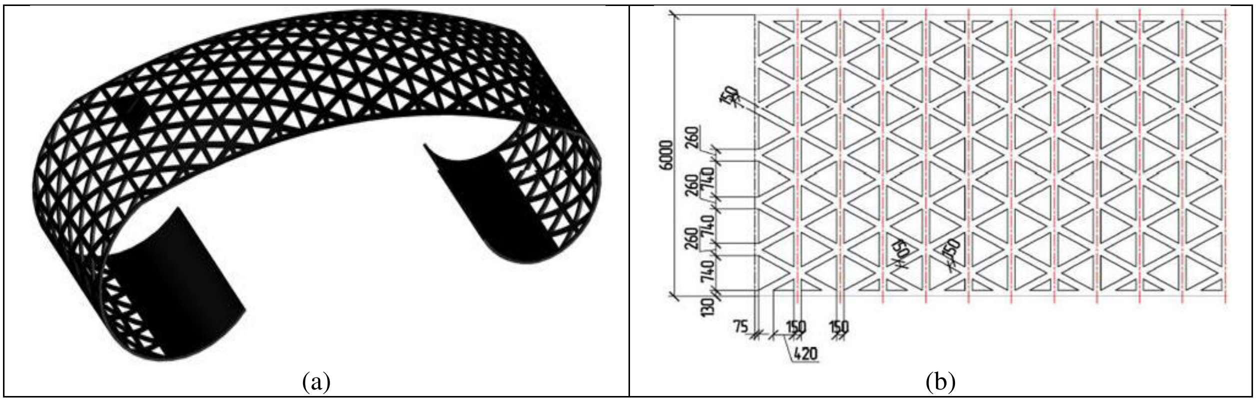

Figure-14. Layout liners and the shape of the internal edges of the structure: (a) lightweight part of the structure; (b) liner layout fragment.

Reinforcement of flat frames with transverse reinforcement is taken in the form of a “zigzag” grid, similar to the patents of the Russian Federation [11, 12], having the shape of a grid of chain-link mesh (Figure-15).

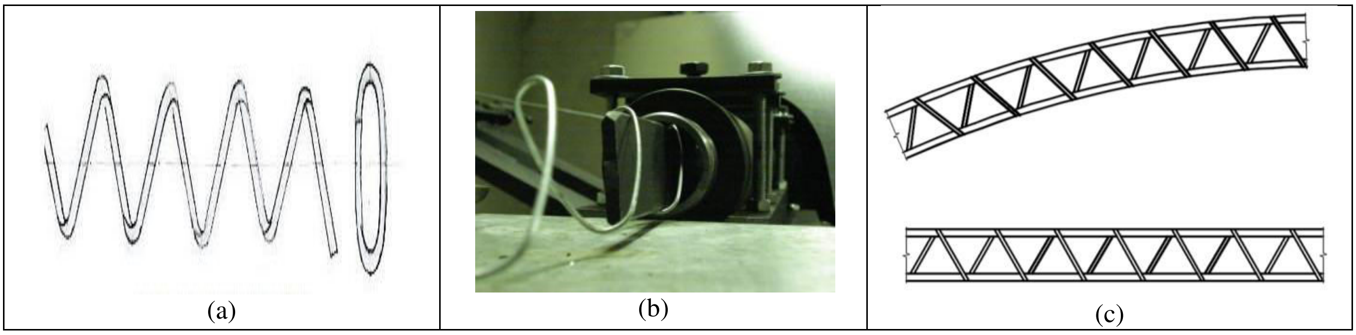

Figure-15. The design of flat skeletons: (a) transverse reinforcement for flat skeletons; (b) manufacturing technology of transverse reinforcement; (c) construction of flat skeletons:

The longitudinal rods of the flat cages of the internal ribs together with the continuous transverse rods in the form of a zigzag mesh simplify the manufacture of the framework for the reinforced concrete structure, increase the rigidity and immutability of the shape of the framework, the reliability of anchoring the longitudinal and transverse reinforcement of the framework, due to the continuity and smoothness of its ends, and strength coupling of curved rod reinforcement with concrete. The use of continuous reinforcement for transverse rods

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reduces the volume of its cutting, reduces by 5-8 times the number of simultaneously welded transverse rods, allows mechanizing the production of reinforcement works and makes it possible to wind on the stand of continuous reinforcement for the manufacture of flat skeletons. The absence of sharp ends of reinforcing bars reduces the injury of people working in the manufacture of flat skeletons. The use of rounding at the ends of the transverse bars of the reinforcement cage reduces the shrinkage stresses in the concrete and increases the strength of the inclined sections of reinforced concrete elements in bending moments and lateral force [12].

The construction of a Mobius loop consists of two elements: the upper one in the form of a lightweight construction (F-B-C-G) and the lower one in the form of a solid construction without liners (F-A-E-D).

The technology of erecting a lightweight construction of a structure involves three variants for assembling a self-supporting skeleton. In the first variant, three hexagonal spatial structures 1 (Figure-16 (a)) are pre-assembled, which are a three-dimensional element consisting of flat reinforcement cages of the ribs and reinforcing meshes of the upper and lower shelves together with six liners. The blocks are fastened to each other along one of the faces, and a rhombus 2 is formed between the hexagons, which require placing one flat skeleton and two liners during assembly. At the corners of the hexagons, six longitudinal rods are joined by three flat reinforcement cages of the internal ribs. The main disadvantage of this version of the assembly is the double overspending of the reinforcement of flat frames at the junctions of the blocks. According to the second variant, two and three hexagons are pre-assembled in block 1 (Figure-16 (b)) and alternate by joining in staggered order, joining only in the nodes, avoiding overspending of the reinforcement on the assembly and installing additional liners only in triangles 2 formed between in blocks. The main disadvantage of the second method is the need for additional assembly of edge plots at the installation sites of blocks consisting of only two hexagons.

Both options have a significant drawback associated with the need to constantly check the geometric parameters of the entire form of lightweight construction. The third variant is adopted as the final version of the lightweight construction, which is an assembly of two guides in the form of curvilinear beams 4 (Figure-16, (c)) of rectangular section 300x200 mm^2 reinforced with spatial reinforcement cage 2 at the ends of the Mobius loop in the F-B-C-G direction.Then diagonal frames 3 are installed.

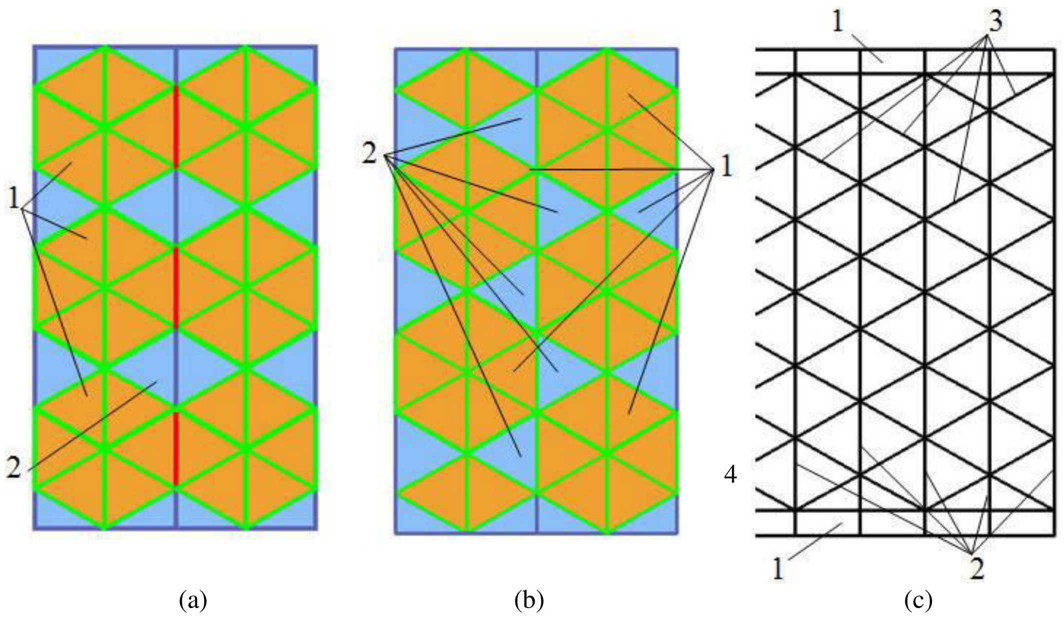

Figure-16. Assembly options self-supporting skeleton: 1 - hexagonal block; 2 – spatial reinforcement cage; 3 - diagonal frames; 4 - curvilinear beams.

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In Figure-17 shows the spatial structure of the reinforcement with rectilinear and curvilinear flat skeletons (Figure-15 (c)), the voids between which are filled with liners (Figure-13, Figure-14).

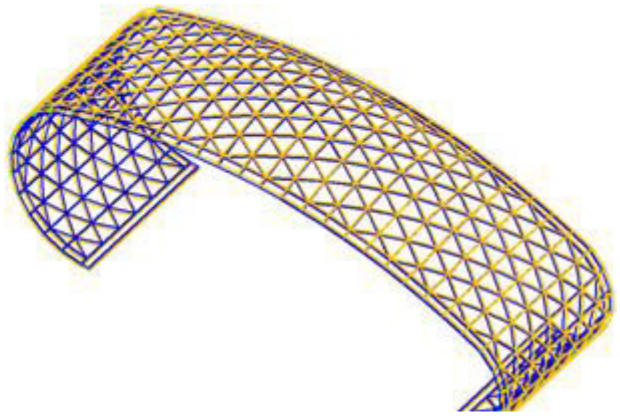

Figure-17. Spatial-rod structure of reinforcement.

When choosing the sizes of the ribs of spatial reinforcing elements to provide the necessary boom h between the bend radius of the surface R and the length of the reinforcement rib l, the thickness of the concrete protective layer is taken into account:

$$R = \frac{1}{2h}\left(l^2 + h^2\right).$$

The coagulation of spatial structures is performed using the rules of spherical trigonometry (Figure-17). The rest of the structure is assembled in the form of rectangular spatial elements of 1, 12 m by 6, 0 m in size and fixed at the ends to the guides.

Consider the problem of reducing waste when cutting a flat rectangular sheet of polystyrene foam and maximally reduce the number of elements in the range for the manufacture of a triangular liner for fixed formwork of the nodoidal shell (Figure-18). To optimize the cutting of liners, eight liners are made at once as a single whole liner, followed by cutting it into pieces (Figure-18 (c)). The resulting elements for the manufacture of fixed formwork (Figure-18) can be divided into two, three and four parts to increase their packing density on a rectangular sheet of expanded polystyrene foam (Figure-19). The maximum length of the elements of the fixed formwork of the nodoid is from 1493 mm to 804 mm (Figure-20). Variants of the layout of the fixed formwork of the nodoid on a rectangular sheet of polystyrene foam are presented in Figure-21.

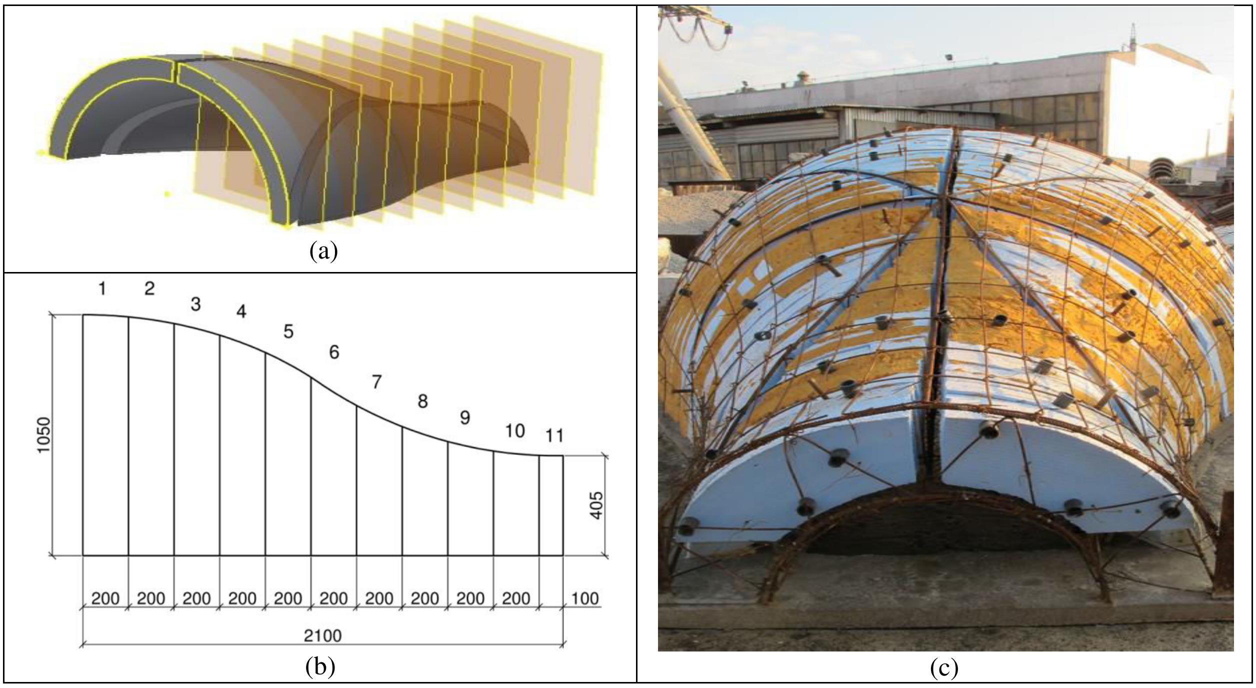

Figure-18. Fixed formwork for the manufacture of the design of the nodoidal shell: (a) cutting planes across the nodoid; (b) quantification of elements; (c) liner form; 1-11 - element numbers.

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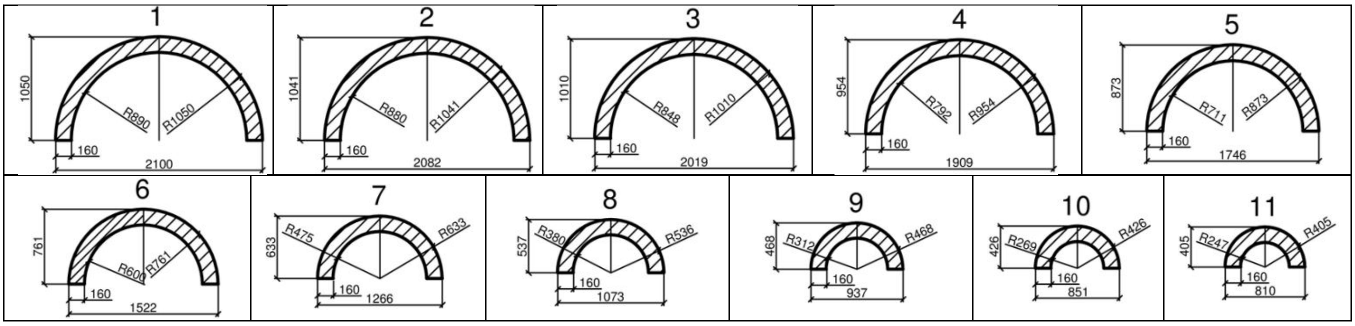

Figure-19. Form of elements for the manufacture of formwork of the nodoidal shell.

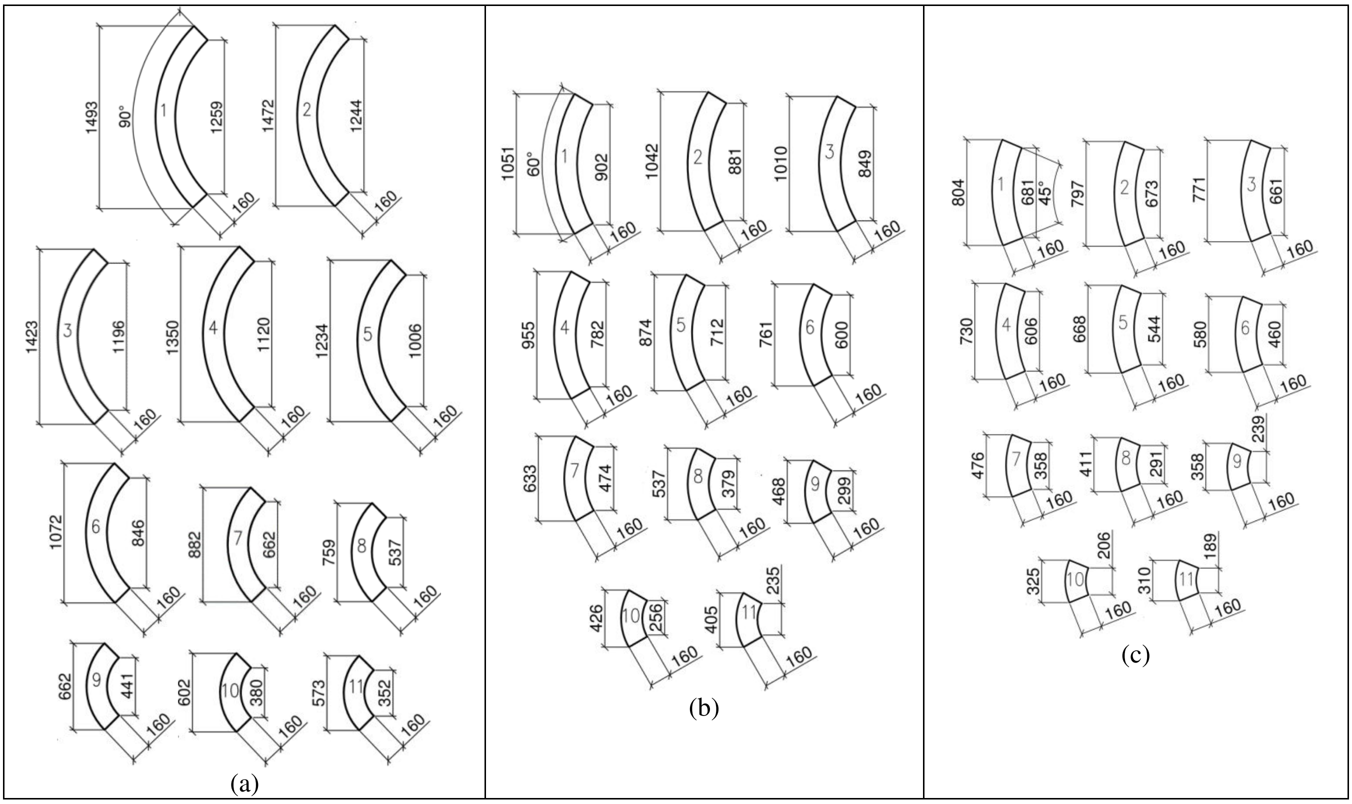

Figure-20. The range of elements for the manufacture of fixed formwork of the nodoidal shell when breaking the element: (a) into two parts; (b) into three parts; (c) into four parts; 1-11 - element numbers.

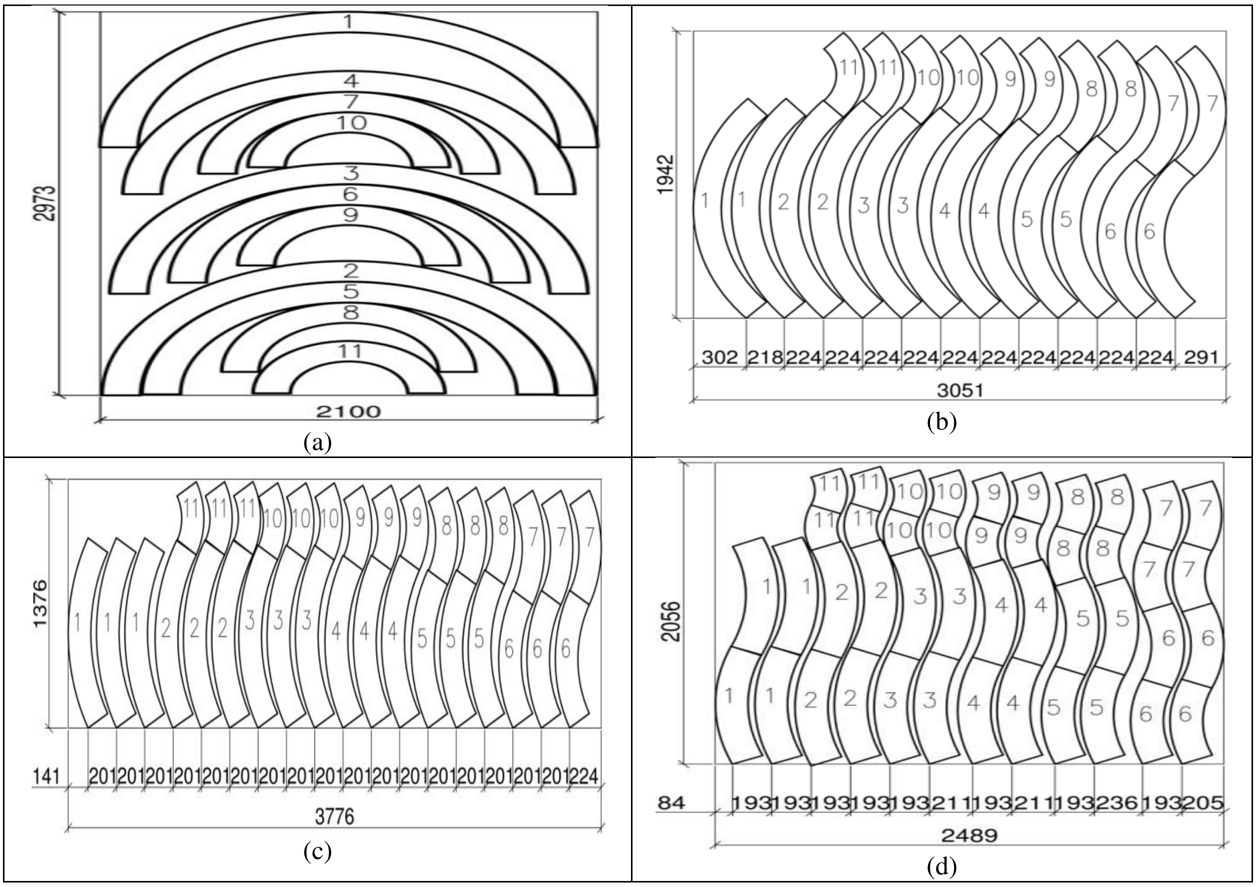

Figure-21. The layout of the elements: (a)-(d) layout options; 1-11 - element numbers.

The difference in packing density between the third and fourth options for dividing into elements is insignificant, but the third option has a significant advantage due to the smaller total number of elements, which simplifies the process of cutting and assembling fixed formwork (Table-1).

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Table-1. Table of the assortment of elements for the manufacture of fixed formwork of the nodoidal shell.

Cutting option	Size of polystyrene foam sheet, m^2	Liner element / Quantity	The area of one liner / area of liners of this position, m^2/m^2	Waste area, m^2	Packing density, %	Cutting option	Size of polystyrene foam sheet, m^2	Liner element / Quantity	The area of one liner / area of liners of this position, m^2/m^2	Waste area, m^2	Packing density, %
1	2,973x2,1 =6,24	1/1	0,49/0,49	2,59	58,49	3	1,376x3,776 =5,20	1/3	0,16/0,49	1,55	70,19
		2/1	0,49/0,49					2/3	0,16/0,49		
		3/1	0,47/0,47					3/3	0,16/0,47		
		4/1	0,44/0,44					4/3	0,15/0,44		
		5/1	0,40/0,40					5/3	0,13/0,40		
		6/1	0,34/0,34					6/3	0,11/0,34		
		7/1	0,27/0,27					7/3	0,09/0,27		
		8/1	0,23/0,23					8/3	0,08/0,23		
		9/1	0,19/0,19					9/3	0,06/0,19		
		10/1	0,17/0,17					10/3	0,06/0,17		
		11/1	0,16/0,16					11/3	0,05/0,16		
2	1,942x3,051 =5,93	1/2	0,24/0,49	2,28	61,55	4	2,056x2,489 =5,12	1/4	0,12/0,49	1,47	71,29
		2/2	0,24/0,49					2/4	0,12/0,49		
		3/2	0,23/0,47					3/4	0,12/0,47		
		4/2	0,22/0,44					4/4	0,12/0,44		
		5/2	0,20/0,40					5/4	0,10/0,40		
		6/2	0,17/0,34					6/4	0,09/0,34		
		7/2	0,13/0,27					7/4	0,07/0,27		
		8/2	0,11/0,23					8/4	0,06/0,23		
		9/2	0,09/0,19					9/4	0,05/0,19		
		10/2	0,08/0,17					10/4	0,04/0,17		
		11/2	0,08/0,16					11/4	0,04/0,16		

Let us apply the principle of manufacturing one whole liner with its subsequent cutting into parts and for the fixed formwork of the reinforced concrete structure of the hyparidal shell (Figure-22, Figure-23).

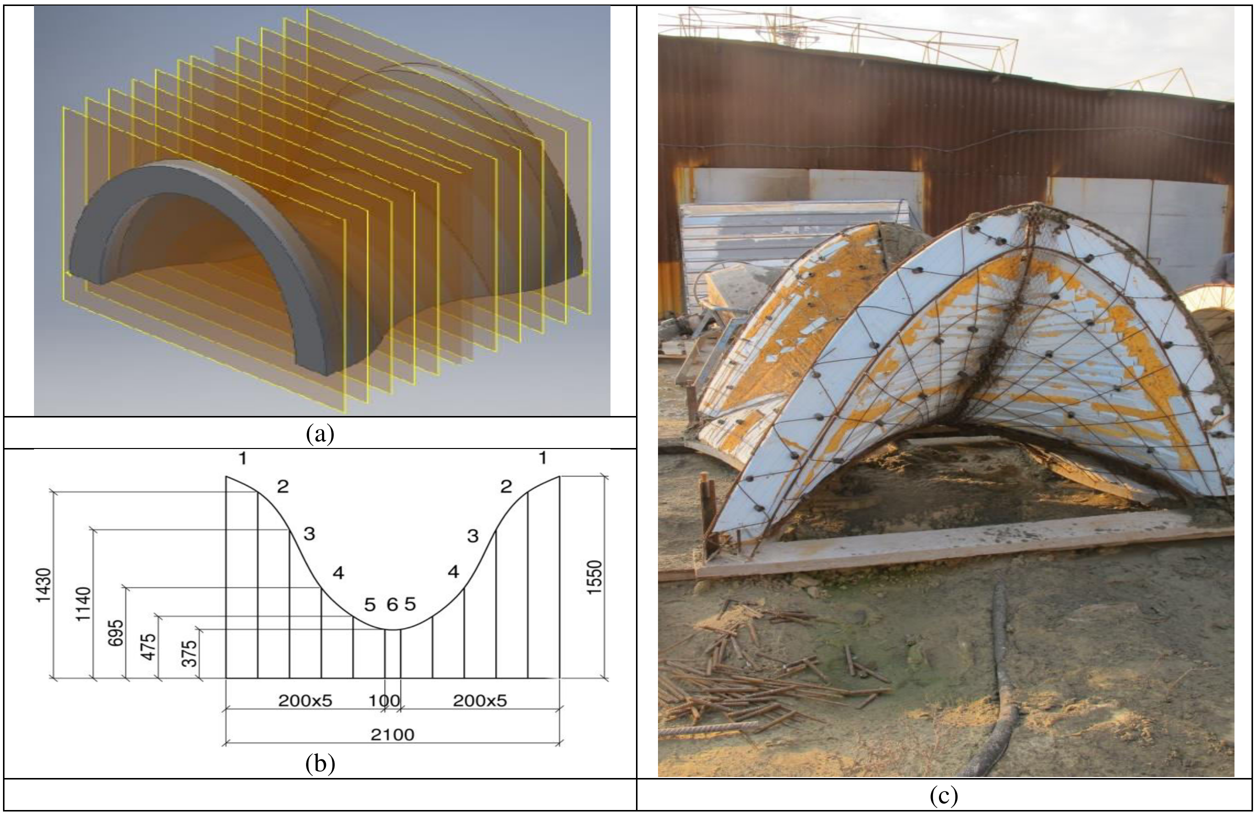

Figure-22. Fixed formwork for the manufacture of the construction of the hyparidal shell: (a) cutting planes across the hypara; (b) determining the number of elements; (c) the form of liners; 1-6 - element numbers.

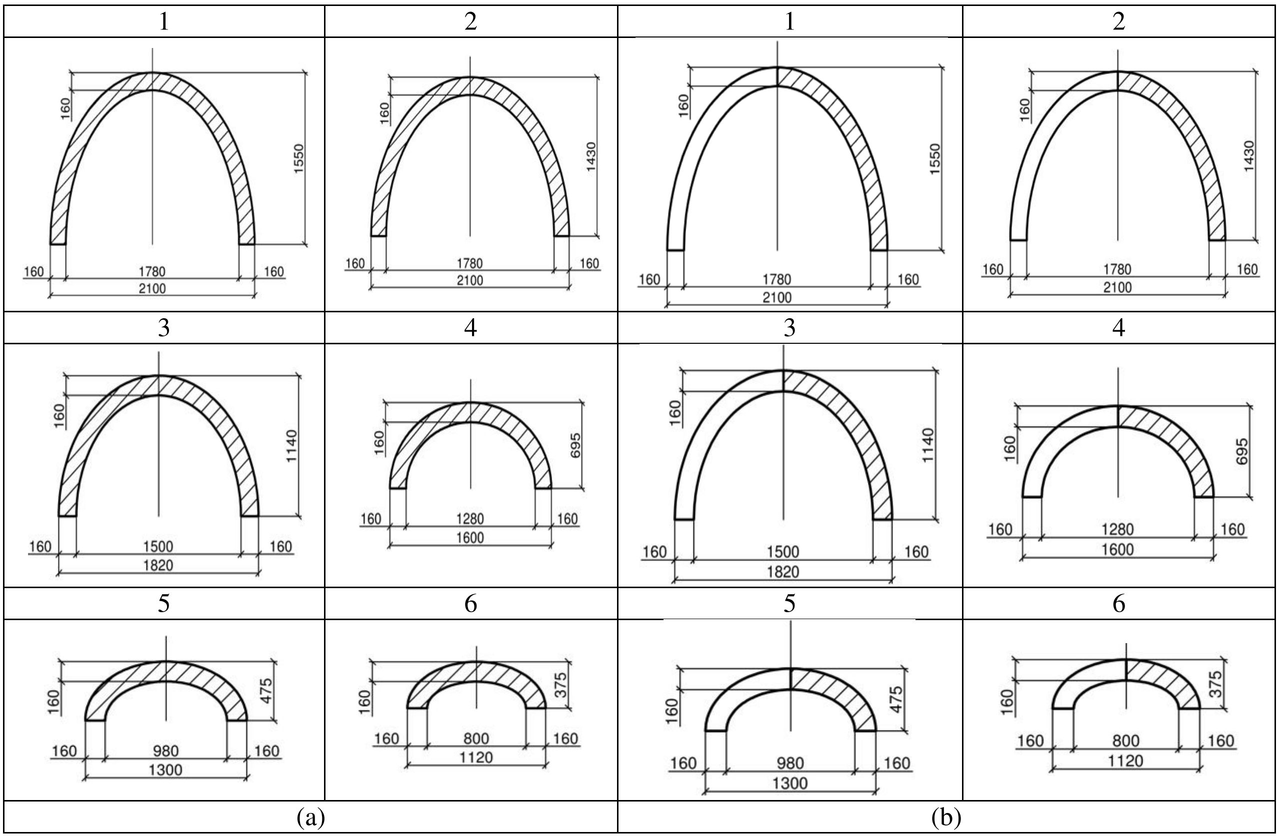

Figure-23. The breakdown of elements for the manufacture of formwork: (a) into solid parts; (b) into two parts.

Variants of the layout of the fixed formwork of the hypara on the rectangular sheet of polystyrene foam are shown in Figure-24.

The second version of the breakdown into elements has a significantly better packing density (Table-2).

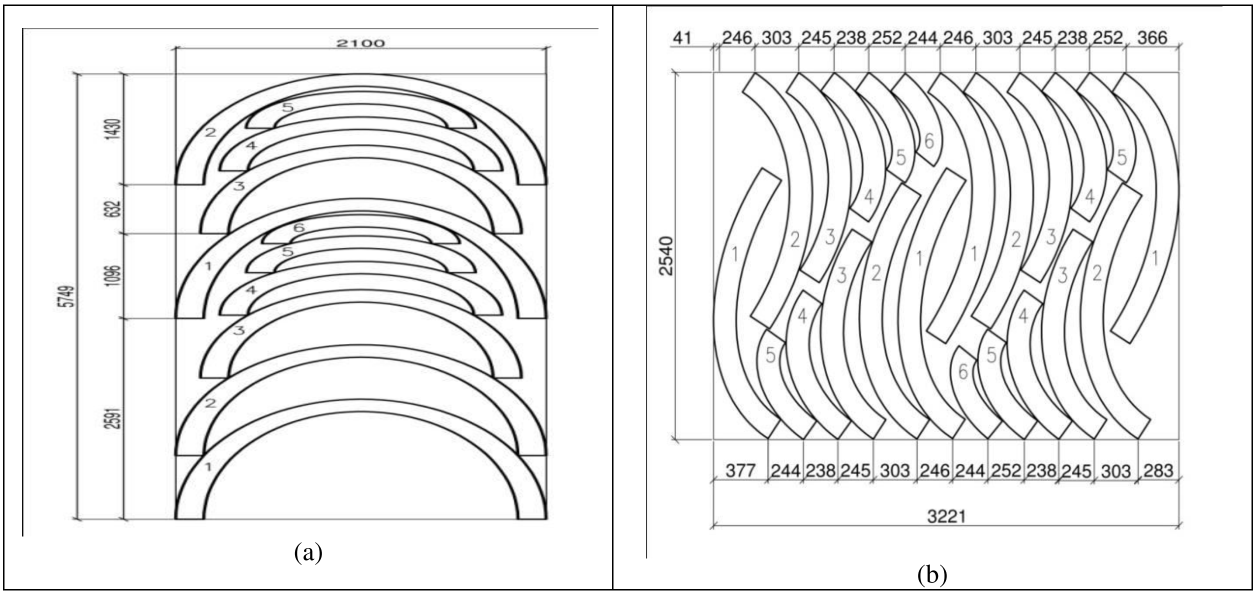

Figure-24. Layout of elements: (a), (b) layout options; 1-6 –elementnumbers

Table-2. Assortment table of elements for the manufacture of fixed formwork of hyparidal shell.

Cutting option	Size of polystyrene foam sheet, m^2	Liner element / Quantity	The area of one liner / area of liners of this position, m^2/m^2	Waste area, m^2	Packing density, %
1	2,1x5,749=12,07	1/2	0,65/1,30	7,17	40,60
		2/2	0,62/1,24		
		3/2	0,50/1,00		
		4/2	0,34/0,68		
		5/2	0,24/0,48		
		6/1	0,20/0,20		
2	2,54x3,221=8,18	1/4	0,33/1,30	3,28	59,90
		2/4	0,31/1,24		
		3/4	0,25/1,00		
		4/4	0,17/0,68		
		5/4	0,12/0,48		
		6/2	0,10/0,20		

CONCLUSIONS

Thus, the task of creating the technology of manufacturing foam polystyrene liners for the construction of lightweight reinforced concrete structures of complex geometric shape is solved, while reducing waste when cutting a flat rectangular sheet of polystyrene foam and minimizing the number of elements in a range for manufacturing triangular liners that are used to create fixed formwork providing concreting of curvilinear reinforced concrete structures of the system “Monofant” with concreting of shotcrete method without formwork. The results confirm the effectiveness of the use of lightweight structures of the system “Monofant” which are up to 40% thinner than structures that have a solid thickness and allow creating a “virtual” catalog of liners for fixed polystyrene foam formwork to produce various curved surfaces.

These technologies expand the possibilities of building construction and structures using the system Monofant which provides a significant reduction in the own weight of structures (foundations, pillars, stiffeners of overlapping discs and floors), a rational topology of the ribs inside the overlap disc to equalize the forces in the floor slab and creating complex internal configuration of pillars and stiffeners.

REFERENCES

[1] http://www.universearchitecture.com/landscapehouse/xoskt5thlwpeykzn3f9f1v3ufew1il.

[2] Norman Hack. 2017. Timothy Wangler, Jaime Mata-Falcón, Kathrin Dörfler, Nitish Kumar, Alexander Nikolas Walzer, Konrad Graser, Lex Reiter, Heinz Richner, Jonas Buchli, Walter Kaufmann, Robert J. Flatt, Fabio Gramazio and Matthias Kohlera. Mesh mould: an on site, robotically fabricated, functional formwork.http://www.researchgate.net/publication/314952069_MESH_MOULD_AN_ON_SITE_ROBOTICALLY_FABRICATED_FUNCTIONAL_FORMWORK.

[3] Norman Hackand Willi Viktor Lauer. 2014. Mesh-Mould: Robotically Fabricated Spatial Meshes as Reinforced Concrete Formwork. Architectural Design, Special Issue: Made by Robots: Challenging Architecture at a Larger Scale. 84(3): 44-53. https://doi.org/10.1002/ad.1753.

[4] Branch Technology.http://www.3dprintetbyggeri.dk/pdf/profilbeskrivelser/Branch%20Technology.pdf.

[5] Ronald Rael, Virginia San Fratello. 2018. Printing Architecture Innovative Recipes for 3D Printing. Princeton Architectural Press, ISBN-10: 1616896965

[6] Jasiczak J., Majchrzak W. and Czajka W. 2015. Construction of undulating walls using dry-mix shotcrete. Concrete international. 37(6): 31-35.

[7] Jason Flanagan. 2015. Acoustic Shells. Shotcrete, winter. 17(1): 16-19.

[8] Thomas Juul Andersen, Wilson Ricardo Leal da Silva, Lars Nyholm Thrane. 2016. Lessons from the Tailor Crete Project. Innovative industrial methods for future digital concrete architecture. Concrete international. 38(3): 54-61.

[9] Babaev V., Shmukler V., Bugayevskiy S., Nikulin V. 2016. Cast Reinforced Concrete Frame of Buildings and Methods of Its Erection. Journal of Civil Engineering and Construction. 5(2): 143-156.

[10] Shmukler V.S., Babayev V.M., Buhaevskyy S.A., Hrubyh A.N. The method of construction of elements of the building of curved shape. Patent of Ukraine №113669. Published: 10.12.2015.

[11] Il'in N.A., Slavkin P.N., Shepelev A.P. Reinforcement cage for reinforced-concrete members. Patent RF № 2388877.Published:10.05.2010.

[12] Il'in N.A., Slavkin P.N., Shepelev A.P. Manufacturing method of reinforcement cage for reinforced-concrete members Patent RF № 2392396.Published:20.06.2010.