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The use of modern polymer materials and wood in the construction of buildings in the form of geodesic domes

Olga Pastukh*[1][0000-0001-8946-8547], *Dmitrii* Zhivotov[1], *Andrey* Vaitens[1], and *Leonid* Yablonskii[1]

[1]Saint-Petersburg State University of Architecture and Civil Engineering, 190005 Saint-Petersburg, Russia

Abstract. Spherical structures have been used by mankind since time immemorial in religious and public buildings, as well as in engineering structures. With the development of lightweight design and construction, non-standard architectural and planning solutions are used. More and more frequently they are being successfully implemented in private home projects and becoming a fact of everyday life. This may be explained by certain advantages of the form, as well as by the opportunities offered to the construction industry by the age of new materials and technologies for the works performance. The functional and architectural-structural design of round-shaped buildings in the form of geodesic domes will allow creating comfortable, cost-effective, energy-efficient and environmentally expedient conditions for human habitation taking into account the shortage of land areas and increased demand for alternative housing options due to the environmental situation around the world. This article analyzes the experience of building spherical buildings of different types and scales. The authors present the results of research carried out in the field of the geodesic dome design improvement with the use of wood and polymer materials.
Keywords. Sustainable ecosystem, geodesic dome, composite materials.

1 Introduction

The article provides an overview of the existing architectural and structural solutions for the construction of spherical buildings for various purposes [1]. Examples of modern residential and public houses built for entertainment and religious purposes in European countries and Russia are given. Structural and engineering solutions and the use of various building materials, which are selected according to the climatic characteristics of the construction region and the current standards in the construction of spherical buildings, are substantiated. The article highlights the authors` elaboration on creating new technical solutions for geodesic domes of wood and high-strength polymers in laboratories and on unique equipment based on the Saint Petersburg State University of Architecture and Civil Engineering (SPbSUACE).

It is a matter of general experience that there exist two main structures of domed buildings – geodesic and stratodesic ones. The design of the geodesic dome has not significantly changed since its creation in the mid XX century, and the initial semantic message of this

*Corresponding author: past.ola.a@gmail.com

design has remained, namely, it is aimed at covering as much space as possible using the minimum amount of building materials, while maintaining lightness and reliable spatial rigidity [2]. It is the material used for construction of the dome structures that has changed. Instead of heavy reinforced concrete and metal which were initially used, it is proposed to build domes made of glued laminated wood and high-strength polymers. The covering material used in geodesic domes can be various, starting with windows with wooden frames and one-layer glass up to the application of insulated panels of various thicknesses, depending on the geographical location of such a structure. The only thing that unites all these technical solutions and products is the triangular shape which completely repeats the outline of the load-bearing elements of this building. The authors of this article propose to focus on several materials for the manufacture of these panels, depending on the region of construction, the temperature and humidity regime under the dome during the work process, and the need for insolation and artificial lighting. The use of modern materials and technologies for the construction of spherical structures will not only significantly reduce the overall weight of the structure, but also take care of the environment and energy efficiency, taking into account international standards for sustainable construction (GREEN, ZOOM) [3].

2 Methods

The relevance of the study of lattice shells serving as the supporting framework of the spherical structure (for example, a lightweight antenna structure) is multidimensional in nature, due to the automation of complex calculations and intelligent production systems. Geodesic dome is an architectural structure in the form of a sphere, formed by connecting rods in triangles on the honeycomb principle. The principle of building a dome-shaped frame was developed in the 1950s by the American architect R. Buckminster Fuller on the basis of the geometric shape of the Earth [4]. The surface of such domes consists of steel ribs of different lengths, which, when connected, form the shape of the dome. The practical application of the building contour geometry proposed by Fuller is based on the principle of vector space partitioning. Herewith, the basic unit is the tetrahedron. The mentioned partitioning principle allows achieving optimal space filling and the most complete use of the structural strength of the materials (Fig. 1).

Currently, work is underway aimed at developing a non-bolted connector with load-bearing rod elements of the structure frame. Since the connector is located inside suitable wooden elements, it is closed from all sides,which provides the nodes with a high standard-set long-term load-bearing capacity during fire exposure for the entire useful life of the building (structure), in contrast to the nodes made of metal and containing metal bolted connection (Fig. 2).

Technological order of buildings` construction on the example of dome shaped buildings is the following. Based on the selected architectural concept, a 3D model of the load-bearing structure is made. We apply preliminary data on the number of elements, nodes, and the load area, for example, by means of the program for calculating geodesic domes [5].

According to the approved technical specification supplied by the customer, the calculation of the structure frame is made in the form of rod elements using the calculation program, applying the data regarding the snow (wind) loads combination [6].

For calculation, we use the loads coming onto the nodes from the shell surface, taking into account the own weight of all the load-bearing elements and the possible technological load, in order to assess the forces in the elements, under the most unfavorable combinations. Based on the data obtained and having determined the preliminary cross-sections of the bearing elements, we select the option of the node with a connector of a certain type. The resulting set of required connector types is marked according to their standard position. The complete set of nodes is made according to the technological maps (Fig. 3).

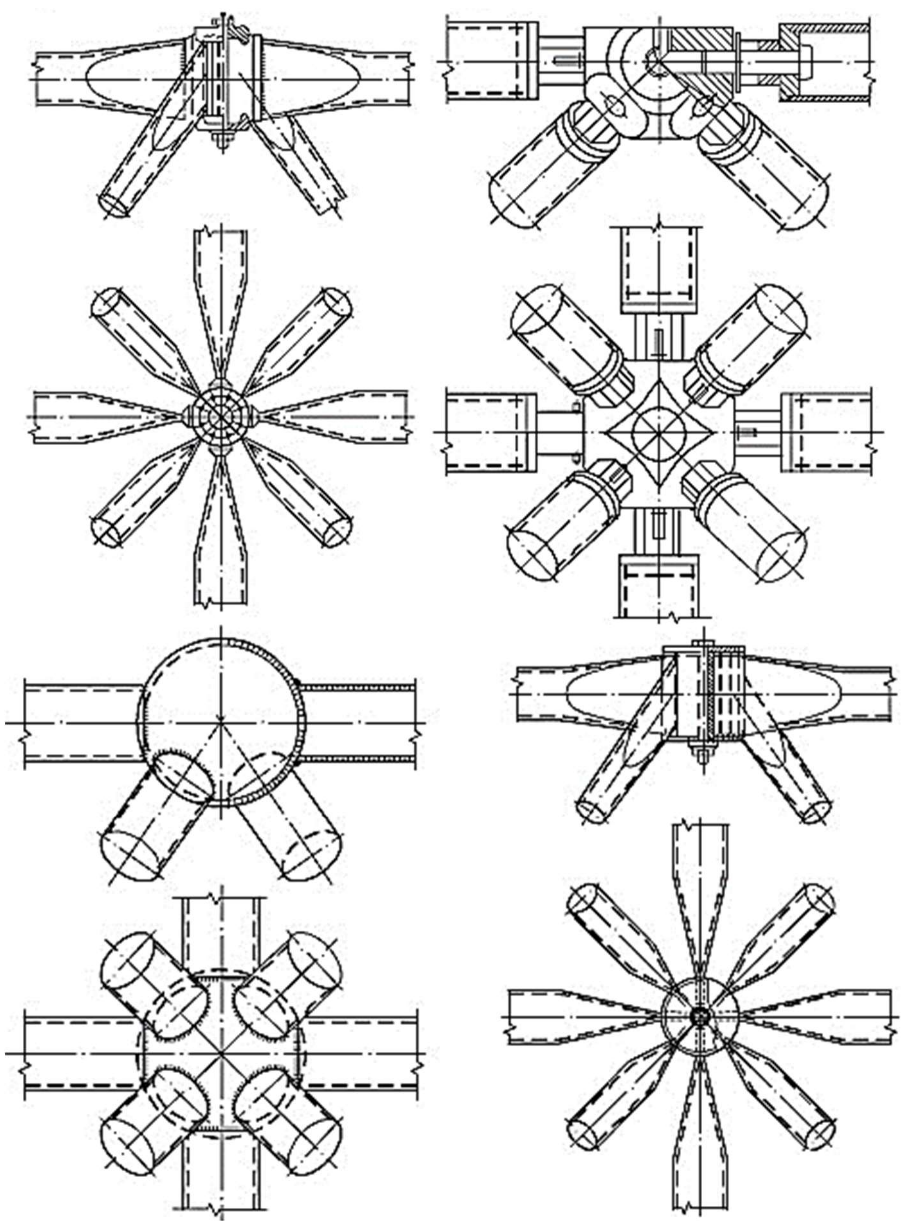


Fig. 1. The main nodal connections of the geodesic dome rods.

At the installation site, the assembly of the unit is carried out. Individual fully prefabricated load-bearing elements arrive at the construction site marked and are connected in a certain sequence without any additional processing, creating a load-bearing frame of the designed building (structure). Since individual load-bearing elements have insignificant parameters in terms of weight and overall dimensions, it is possible to perform construction and installation work at the construction site without using heavy lifting machines and mechanisms, in fact, manually. The same applies to the disassembly of the supporting frame during disposal or transfer to another location. This technology of assembly/disassembly allows significantly speeding up the construction and installation work performance.

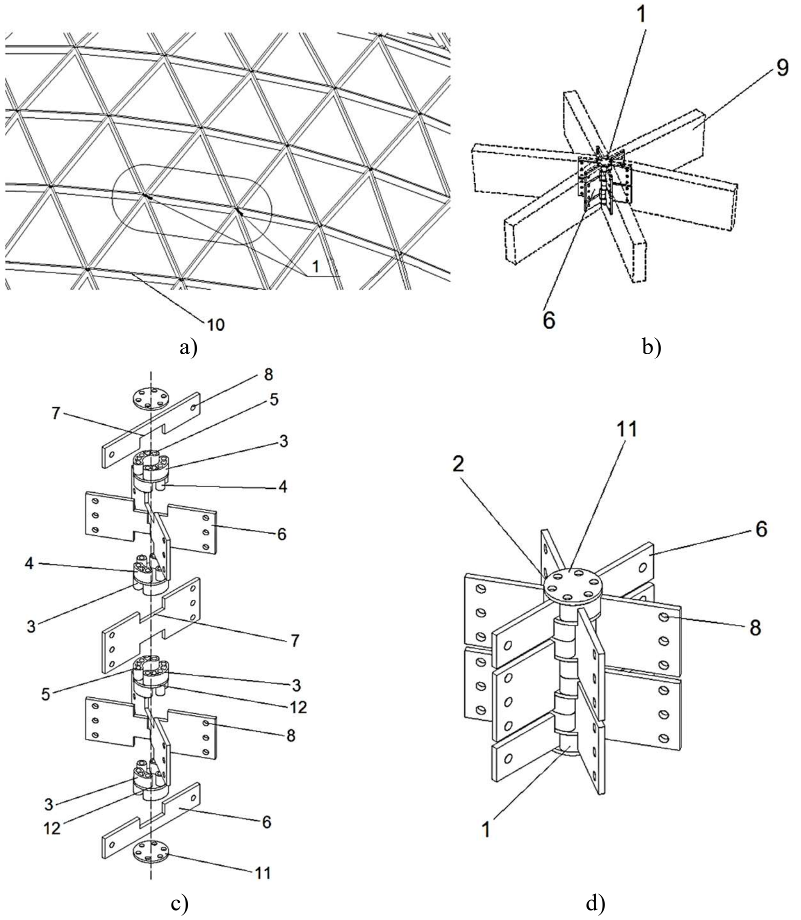


Fig. 2. The connection element of rod-shaped parts for geodesic domes and other spatial structures: a − the interface node of the rods by means of mortise steel plates; b – an enlarged view of the docking unit; c, d – metal fasteners; 1 − connection element of rod-shaped parts for geodesic domes and other spatial structures; 2 − non-metallic central rod; 3 − modular-block elements; 4 − projections; 5 − coaxial holes; 6 − flat elements; 7 –fascia; 8 − holes; 9 − bearing rod; 10 − spatial structure of the dome; 11 − end flange installed and fixed on top and bottom of the non-metallic central rod; 12 − base for the modular-block element.

Fig. 3. Installation of the geodesic dome structure.

3 Results

3.1 Spherical structures for public use

3.1.1 Wooden «Chapel of Silence», Finland

The Kamppi Chapel of Silence, a wooden chapel with a curving facade, located on Narinkkatori Square in the Kamppi district of Helsinki, was built in 2011-2012 by K2S Architectural Studio (Kimmo Lintula, Niko Sirola, Mikko Summanen) (Fig. 4). The height of the main hall is 11.5 m. The inner walls of the chapel are paneled with carefully fitted milled planks of black alder. The facades are made of horizontal spruce laths bent at different radii treated with wax glazing using nanotechnology. The frame of the building is made of massive milled glued wooden frames. Simplified furniture is made of solid ash [7].

a) b)

Fig. 4. a) Construction of the wooden Chapel of Silence in Kampi; b) «Kampinkappeli» Helsinki, Finland, photo by O.A. Pastukh, 2017.

3.1.2 Wooden sphere «In Motion Park Seenland», Germany

The wooden sphere «In Motion Park Seenland» is a recreation center that includes viewing platforms, walking paths, a number of attractions for active recreation and cafes. The structure was built in 2019 according to the project of the company «Hess Timber» (which is also a manufacturer of wooden structures). The sphere is located in the municipality of Steinberg Am See (Germany). The height of the sphere is 40 m, the diameter in the horizontal direction is 50 m. The total weight of wooden structures exceeds 500 tons of laminated veneer beams, and the weight of steel structures is 190 tons. The sphere is designed for a simultaneous stay of 950 people inside. The structure is assembled from twenty vertically arranged arches, each of them has a length of about 50 m, and lifting height of the curved part is 15 m. Each of the arches consists of two starting marks weighing 17 tons, manufactured at the Kleinheubach factory. At present, «In Motion Park Seenland» is the largest wooden «recreation sphere» in the world [8].

3.1.3 Sphere as an exhibition pavilion, Ruskeala, Karelia, Russia

This example is a clear illustration of experiments with mobile lightweight dome structures, which are a collapsible structure made of an aluminum frame and a tent shell (Fig. 5). Such geodesic domes are used as pavilions for temporary exhibitions, fairs of achievements of the national economy, etc. [9].

a) b)

Fig. 5. The exhibition pavilion in the form of geodesic dome in the Ruskeala National Park: a) general view of the pavilion; b) a fragment of the structure, Karelia, Russia, photo by O.A. Pastukh, 2020

3.2 Greenhouse homes in the European Union and Russia

3.2.1 Sweden. The Bengt Warne concept, 1970-s

In the 1970^{s}, Swedish architect Bengt Warne proposed and tested the idea of building economical wooden buildings inside a glass greenhouse. The first such house was built in 1974-1976 in the suburbs of Stockholm. Already in those days, the building used quite modern «green» technologies, such as the collection and use of rainwater, composting of kitchen and garden waste, and enriching the air with oxygen using plants.

The building required only minimal heating during the colder periods of the year, and a high-efficiency stove was used for this purpose. Under the glass dome, even in winter, vegetables could be grown, and in the warmer months, a whole range of Mediterranean fruits could be harvested. Until 1981, this house, called Nature House, served as the architect's research center, but then it was sold and continues to be operated up to this day. After the death of Bengt Warne, the topic of greenhouse buildings remained in oblivion for some time, but then the Göteborg architecture firm Tailor Made Arkitekter continued his research, having established the Greenhouse Living advisory group and developing concepts for sustainable buildings using more modern engineering systems.

One of this studio’s projects, Uppgrenna, which includes a hotel and spa, is located on the shore of Lake Vättern in Southern Sweden. The dining rooms and meeting rooms are located on a mezzanine floor under a pitched glass roof surrounded by a garden, while the spa treatment rooms and guest bedrooms are located in a wooden section that partially extends into the grassy slope.

Another project under the name of «Nature House» was built in the suburbs of Stockholm in 2015. A wood-burning stove is also used to heat the building, but the heating period itself lasts six months instead of the usual nine months in Sweden, and the energy consumption is significantly lower than that in ordinary home. In this case, a ready-made house was purchased first, and then a greenhouse with 4 mm glazing was built around it. In the warm season, the greenhouse windows are opened and the building is operated as usual.

3.2.2 Norway

In 2011-2013, the domed greenhouse home Naturhuset was built on the Sandornoya Island in the northern part of Norway. The place has a harsh climate conditions, heavy wind and cold are common phenomena for the Norwegian Arctic. Naturhuset greenhouse home is an energy-efficient solution for the Norwegian Arctic. The design of the house is as follows: at the base there is a basement made of cellular concrete with a monolithic reinforced concrete floor. Above it, a geodesic dome is erected – an aluminum frame with glass panels (360 pieces) that covers an area of about 180 m^2. The diameter of the dome is 15 m, the height is 7.5 m. The glass is single, 6 mm thick. The geodesic dome was built by a specialized Norwegian company and is made of an aluminum frame with glass panels. The building is featured with its protective shell, namely, a glass geodesic dome, under which not only the house, but also a small plot of land with plants is located. Outside the house there is a garden and a vegetable garden. Under the dome, the farming season lasts five months longer than outside. The construction of the house shell was carried out already inside the dome, in «greenhouse» conditions. The house was built from straw and clay by a married couple and their friends. The house is a two-story building with a flat roof. It has five bedrooms, a spacious living-dining room, two bathrooms, as well as utility rooms [10].

3.2.3 The United Kingdom

The building, erected in Suffolk (the UK) by the architectural studio dRMM, is an example of energy-efficient kinetic architecture. Sliding House consists of three separate modules: a residential part, an extension and a garage between them.

A special feature of the house is the sliding structure of the walls and the roof, which covers the glass house, the courtyard and the extension like a case. The 20-ton roof stands on railway track on a special platform. Thanks to this, the living space of the house can show or hide its glazed part, and the space between residential and non-residential buildings can become an open or closed courtyard.

3.2.4 Russia

Experiments with domed greenhouse homes are also carried out in Russia. In November 2019, an experimental dome was installed over a residential building in the city of Yakutsk (Tomsk 2019). It has various sensors for measuring humidity, temperature, and the permafrost house base (the first experimental dome structure in Yakutsk). The project of the greenhouse building was developed by the North-Eastern Federal University together with the Sinet Group company and it involves a number of modern energy-saving technologies. The main feature of the project is a geodesic dome with an energy-saving transparent film that completely covers the building. The diameter of the dome is 20 m, the height is 10 m. Based on the results of the experiment, a comprehensive conclusion will be drawn up on the influence of the dome on the climatic and geological conditions of permafrost, the behavior of building structures, the characteristics of energy efficiency and energy conservation, as well as a conclusion on the medical and psychological features of living in such conditions. If the results of the experiment are considered positive, the project of buildings under the dome (including industrial ones) will be further developed in the zone of the cryolithic zone propagation [11].

4 Discussion

In Russian practice, spatial wooden structures are not so widely used, which is mainly due to not always successful experience in the construction of buildings, insufficient reasonableness of design solutions and the regulatory framework.

The intrinsic geometry of the geodesic dome is based on using a network of triangles mounted from rods. The rods are located on geodesic lines (the shortest lines connecting two points on a curved-based surface). Such arrangement allows achieving the optimal space filling and the most complete use of the structural strength of the materials [12]. The construction technology consists in the tiered-like erection of rod triangular cells of various types and sizes from bottom to top [13]. The triangular elements converge from the base to the top of the dome, which entails in each tier a change of the rods size, their inclination angles in relation to the nodal connections, and a different amount of fasteners [14].

It should be pointed out that in recent decades the environmental situation in the world has not significantly changed for the better. The ongoing natural disasters force humanity to think about the need to reduce CO_2 emissions, to create technical solutions aimed at using natural materials with a minimum amount of waste in the production process. Such building materials are considered to be wood and wood-based materials. Wood is a constantly renewable resource, easy to process and does not leave any inorganic substances after application [15].

Polymer materials are of interest both due to their technical and physic-mechanical properties. The wide range of properties of these materials, changing through using various manufacturing methods, yields a lot of opportunities for scientific and scientific-technical solutions in the future [16].

At present, solutions for the production of geodesic domes from metal and reinforced concrete structures are widely used. However, the authors are of the opinion that it is the combination of wood and polymer materials in the construction of geodesic domes that is the most advantageous combination in all the fields, namely, in engineering, financial and economic, energy and even environmental ones.

The main advantages of geodesic domes are:

- large load-bearing capacity;
- any spans from 24 m to 150 m;
- fast installation speed compared to traditional frame and frameless building construction methods;
- the weight of the dome elements reduces the cost of materials and preparatory work;
- the structural and technological features of spatial dome structures are the installation of frame elements made of marked rods and nodes, which reduces the construction time. The cellular structure will allow for the assembly of block-cells, which will significantly reduce the construction time of the building;
- spatial dome structures have an ideal aerodynamic shape with high resistance to seismic, wind and hurricane impacts. Scientists continue to study the possibility of using the geodesic dome by changing its shape, configuration, material of manufacture and many other parameters [17].

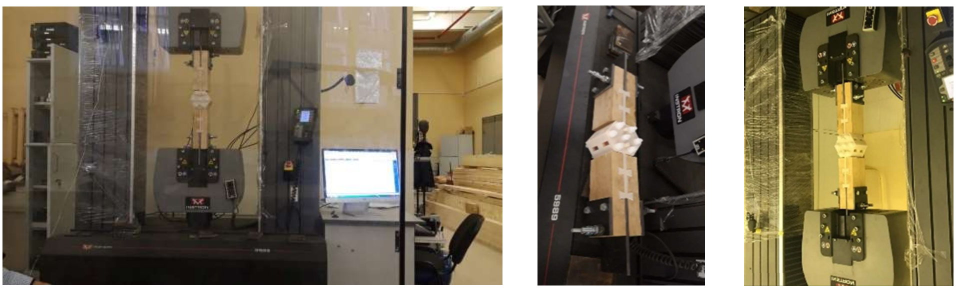
The honeycomb configuration of the many available Diamatic dome templates is particularly convenient for converting with mutual element support. This is due to the fact that only three elements of the lattice rods intersect at any vertex, regardless of the number of rod elements used to form the node polygon [18].

The disadvantages of geodesic domes include the fact that the production of modern building materials is aimed primarily at the construction of buildings made of rectangular materials (plywood, glass, rigid insulation mats) [19]. Thus, the triangular cells of geodesic domes will require additional labor cost for cutting and fitting the material to create external enclosing structures with a large overrun, increasing the cost and complexity of manufacturing the building as a whole.

The known schemes confirm the statement about the complexity of the nodal connectors, their low adaptability of installation, high labor intensity and material consumption of products. Nodal connectors, regardless of the material of the rods, are made of steel. Theoretical scientists and professional experts around the world continue their research in the field of obtaining renewable energy from natural sources. The use of the geodesic dome surface is an excellent solution to this issue [20].

The authors make their opinion not only on the base of the existing experience research in the construction and application of geodesic domes in various areas of construction, but also from their own experimental studies of the nodal dome connection with the application of various loads, in order, to simulate real processes in the operation of the structure and determine the actual load-bearing capacity of nodes and elements.

These tests were carried out on specialized equipment in the mechanical laboratory of SPbSUACE at a normal temperature of 22^0C (Fig. 6 a-c).



a) b) c)

Fig. 6. a) experimental study of the geodesic dome block; b) assembly; c) joint testing by the Instron 5998 machine. Photos by D.A. Zhivotov, 2018-2020.

The authors of the article study the structural and technological features of a new nodal connection with the use of wood in the form of rods and high-strength polymers in nodal joints in specialized laboratories of SPbSUACE. In 2017, RU No. 170483 patent was obtained for a utility node model for geodesic domes and other structures.

5 Conclusions

1. According to the authors of the article, the construction of buildings for various purposes of spherical shape made of wood and polymer materials will allow to implement creative architectural and constructive ideas of architects, providing comfortable, cost-effective and energy-efficient conditions for human habitation in conditions of shortage of land plots and increased demand for alternative housing options.

2. The technological sequence of assembly specified in the article allows you to significantly reduce the labor and material consumption of the construction of such buildings in comparison with metal up to 25-30%. However, the authors continue their research in this sphere.

3. The conducted experimental studies of the nodal connection showed the viability of the proposed design and technological scheme. During the experiment, the behavior of individual elements and the design of the node as a whole was studied. The load-bearing capacity of the nodes in the experimental studies corresponded to the calculated values. Design and technological solutions for the construction of geodesic domes of various sizes and purposes (residential, public) made of wood and polymer materials, according to the authors of the article, are viable for all climatic zones of construction.

References

1. D.A. Zhivotov, O.A. Pastukh. *Construction of geodesic domes made of wood and composite materials during restoration and conservation of cultural heritage objects*, E3S Web Conf. **164**, 9 (2019). DOI: 10.1051/e3sconf/202016402020.

2. V. Zemlyansky, I. Kurta. Procedia Eng. **165**, 1542-1546 (2016). DOI: 10.1016/j.proeng.2016.11.891.
3. M.A. Porta-Gándara, V. Gómez-Muñoz. *Solar performance of an electrochromic geodesic dome roof*, Energy **30**, 2474-2486, (2005). DOI: 10.1016/j.energy.2004.12.001.
4. R. Fuller. Geodesic domes. Available at: https://ongreenway.org/2014/12/geosfera-fullerageodezicheskij-kupo/ (accessed: 02.09.2020).
5. Y. Ibrahim, R. Kempers, A. Amirfazli. *3D printed electro-thermal anti- or de-icing system for composite panels*, Cold Reg. Sci. Technol. **166**, (2019). DOI: 10.1016/j.coldregions.2019.102844.
6. D. Zhivotov, Y. Tilinin. *Experimental studies of the strength of nodal joints of geodesic domes made of wood and fiberglass made on a 3D printer for the Arctic and Northern territories*, Publication Series of LAB University of Applied Sciences, part 2, Lappeenranta, 57−65 (2020). Available at: https://www.theseus.fi/bitstream/handle/10024/335985/LAB_2020_02.pdf?sequence=5.
7. D.A. Zhivotov, O.A. Pastukh, Yu.I. Tilinin. *Architectural and spatial planning solutions of spherical shape buildings*, Contemporary Problems of Architecture and Construction, Proceedings of the 12th International Conference on Contemporary Problems of Architecture and Construction, 6 (2021). DOI: 10.1201/9781003176428.
8. Pastukh O.A. *Transformation and development of coastal industrial zones with using large-span construction structures. European experience of 1990-2000s*, Contemporary Problems of Architecture and Construction, Proceedings of the 12th International Conference on Contemporary Problems of Architecture and Construction, 4 (2021). DOI: 10.1201/9781003176428.
9. J. Chilton. *Tensile structures – textiles for architecture and design*, Textiles, Polymers and Composites for Buildings, 229-257 (2010). DOI: 10.1533/9780845699994.2.229.
10. D.A. Zhivotov, O.A. Pastukh, A. Panin, L. Yablonskii. *Application of engineering composites for elements of architectural and construction structures operated in Arctic zone*, Contemporary Problems of Architecture and Construction, Proceedings of the 12th International Conference on Contemporary Problems of Architecture and Construction, 5 (2021). DOI: 10.1201/9781003176428.
11. Gusev E.L., Ivanova M.A., Chernykh V.D. *The development and application of generalized models long-term forecasting of the residual resource composite materials and structures at the impact of extreme climate factors of the Arctic zone*, Procedia Structural Integrity **20**, 294-299 (2019). DOI: 10.1016/j.prostr.2019.12.154.
12. Jian-peng Wei, Li-minTian, Ji-pingHao. *Improving the progressive collapse resistance of long-span single-layer spatial grid structures*, Construction and Building Materials **171**, 96-108 (2018). DOI: 10.1016/j.conbuildmat.2018.03.126.
13. F. Asdrubali, B. Ferracuti, L. Lombardi. *A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications*, Building and Environment **114**, 307-332 (2017). DOI: 10.1016/j.buildenv.2016.12.033.
14. Y. Guan, L.N. Virgin, D. Helm. Structural behavior of shallow geodesic lattice domes, International Journal of Solids and Structures 155, 225-239 (2018). DOI: 10.1016/j.ijsolstr.2018.07.022.
15. Z.Y. Shen, Y.Q. Li, Y.F. Luo. Instability research of single layer reticulated shells at Tongji University, Fourth International Conference on Advances in Steel Structures **I**, 83-92 (2005). DOI: 10.1016/B978-008044637-0/50012-3.
16. Nickolay Kasyanov. *The Evolution of Architectural Morphogenesis at the Beginning of XXI Century in the Context of Scientific Advances*, Procedia Engineering **153**, 266-270 (2016). DOI: 10.1016/j.proeng.2016.08.113.

17. M.P. Lebedev, O.V. Startsev, A.K. Kychkin. *Development of climatic tests of polymer materials for extreme operating conditions*, Procedia Struct. Integrity **20**, 81-86 (2019). DOI: 10.1016/j.prostr.2019.12.119.
18. S.A. Kuzmin, A.D. Egorova, D.A. Krasilnikov, Z.V. Emelianova. *Durability of construction materials modified by polymeric additives*, Procedia Struct. Integrity **20**, 278-283 (2019). DOI: 10.1016/j.prostr.2019.12.152.
19. S. Halliwell. *Ageing of composites in the construction industry*, Ageing of Composites Woodhead Publishing Series in Composites Science and Engineering, 401-420 (2008). DOI: 10.1533/9781845694937.3.401.
20. Y. Wu, M. Takatsuka. *Spherical self-organizing map using efficient indexed geodesic data structure*, Neural Networks, IEEE Trans. Neural Networks **19**, 900-910 (2006). DOI: 10.1016/j.neunet.2006.05.021.