Development of Large Span Curving System of Sailing Dome Structure

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Abstract. The article is devoted to the space-planning and structural solution of dome structures for the regions of the Far North. The article analyzes the predecessors of these design solutions, emphasizes important aspects of bioarchitecture, the possibility of widespread use of this style; disclosed existing problems. A solution for the construction of quick-assembly structures is proposed, which allows widespread use of the developed solutions for the active development of the Far North regions. The possibility of manufacturing planning and structural elements is proposed. However, in life, most of the settlements in the northern part of Russia are built up with wooden barrack-type houses, or typical dull five-story panel houses, clearly not meeting climatic conditions, which are quickly destroyed under the influence of climatic conditions. The task of our work was to develop a large-span design solution with a high bearing capacity, reducing wind and snow loads, having collapsible properties, allowing, if necessary, moving the structure, which is important for the regions of the Far North. The optimal solution for Northern construction is a dome, one of the oldest structures formed by a spherical surface of revolution.

1. Introduction
The development of the Northern territories with harsh climatic conditions has been and will be one of the priority tasks of Russia. The northern territories are rich in deposits of natural resources, more than 30% of the world's undeveloped reserves of hydrocarbons and ore resources are concentrated in the Arctic shelf zones, and more than 20 countries of the world are ready to fight for them.

The task of our work was to develop a large-span design solution with a high bearing capacity, reducing wind and snow loads, having collapsible properties, allowing, if necessary, moving the structure, which is important for the regions of the Far North [1-2].

There is a fairly large number of developments in the field of Northern construction in Sweden, Finland, Norway, aiming at adapting architecture to harsh climatic conditions. The optimal solution for Northern construction is a dome, one of the oldest structures formed by a spherical surface of revolution.

The most unusual, alas, not embodied, solutions were proposed in the 1950-60s by young Leningrad architects of the USSR Academy of Civil Engineering and Architecture. Developed in 1961, the project of the polar city of S.P. Odnovalov and M.V. Tsimbala, the first project with an artificial climate, which had to be located in the direction of the wind to minimize snow drifts and a domed and cylindrical shape, and for freedom of movement between houses, transitions were planned above the level of the first floor [3-4].
Figure 1. The project for the development of the Arctic zone by Stanislav Odnovalov and Maya Tsimbal.

2. Statement of research objectives

The most ambitious development of recent times was the Arctic Trefoil military complex. The project of a polar city with an artificial climate "UMKA", presented in 2011 at the Second International Arctic Forum, with a possible place of implementation is Kotelny Island, deserves interest.

Figure 2. Project V. Rzhevsky "UMKA".

However, in life, most of the settlements in the northern part of Russia are built up with wooden barrack-type houses, or typical dull five-story panel houses, clearly not meeting climatic conditions, which are quickly destroyed under the influence of climatic conditions.

The development of LVL timber has contributed to the widespread use of timber in construction, limiting the possibilities of application to almost only the decisions of architects. The main advantages of structural casings are the minimum consumption of wood and metal, good thermal insulation...
properties. In terms of shape, spatial wooden structures are divided into thin-walled, solid, ribbed and mesh domes and cylindrical vaults, divisible by the shape of the figures that make up the grid, for example, circular mesh systems connecting at the nodes, in a strict geometric order [5-6].

![Fig. 3. Types of wooden dome structures: a- ribbed-circular, b- circular-domed, c- ribbed-circular domes.](image)

A non-ordinary solution in the form of a thin-walled solid dome structure made of solid timber was proposed by the Bioarchitecture company. This development has a significant drawback, the maximum material consumption.

![Fig. 4. Dome structure made of solid timber from the company "Bioarchitecture".](image)

3. Research methods
Rotating surfaces made of arched and mesh structures developed from LVL-beams are stadiums in Tacoma (USA), with a diameter of 256 m, an ice rink in Grenoble (France) - 327.9 m in length, 90.6 m in width and 52, 2 m in height, as well as the shopping and entertainment complex (SEC) "Piterland" in St. Petersburg with a diameter of 92 m. The main elements of the mesh domes are wooden rods resting on a support ring, connected by means of knots and couplings that provide ease of connection and perceive the forces of compression and tension arising from external loads. Welded joints have increased rigidity, low deformability, but requires high qualifications of workers, and large labor costs for installation and does not allow the possibility of subsequent disassembly, without destruction [7-8].

A connection was developed for a glue-wood structure with glued metal rods of periodic section, presented below.
Figure 5. General view of the node of the wooden mesh dome:
1 - elements made of glued wood, inside which are placed metal rods 2; 3 - metal plates on the ends of the rod elements; 4 - metal cores to which the elements are attached, 5 - coaxial holes along the perimeter, through which the connection is fastened with nuts - 6. Section 2-2 shows a section of the assembled assembly, consisting of an element 1 made of glued wood, metal rods 2 with threads 7, metal plates 3, metal cores 4 with holes 5, bolts 8.

In the nodal connection, the following elements are included in the work:
- ends of ribs 1 (work for crushing);
- the protruding ends of the reinforcement of 2 ribs of 1 of the dome (they work for shear and tension);
- steel core 4 (works in compression);
- steel plate 3 (thickness is taken constructively).

The support ring works mainly in tension and bending (transverse and torsion).

Reinforcing bars are usually glued into grooves located in one row across the section width and milled along the length of the plates. The shape and dimensions of the groove are selected based on the conditions for ensuring reliable adhesion of the reinforcement to the wood and the minimum consumption of the adhesive composition.

Bolted connections are versatile and quick to assemble, and work on axial forces. Reinforcing bars are usually glued into the grooves. The shape and dimensions of the groove should ensure the reliability of gluing the reinforcement to the wood. The distance between the axes of the rods must be at least two diameters [9-10].

The dimensions of the cross-section of the beam are selected based on the conditions for ensuring the bearing capacity and the rigidity of the structure, the calculated ratio of width to height is at least 1/6. (Fig. 6)
Figure 6. Variants of manufacturing glued reinforced beams: a - with seam cutting on the finished product; b - with cutting a seam on pre-fabricated beam elements, the latter are much easier to manufacture, and allow the replacement of metal rods with carbon reinforcement.

Thin-walled glue-wood structures generally have a lancet or domed outline, with various types of ties that reduce the spacer loads and transfer them to the supports. The closer the surface of revolution is to the drop shape, the more stable the structure is. (Fig. 7)

Figure 7. Design scheme of the equilibrium drop shape.

However, tall domes are difficult to adapt to the needs of the industrial sector. Industrial depots and train stations will have to be covered with enormous domes.

The subject of this study was the loaded state of a wooden mesh structure in order to identify the factors that affect its operation and select the optimal solution.

A study was carried out of several options for structural structural solutions of wooden mesh shells made of LVL-bar of standard sizes 10 * 20cm, using the finite element method in the Lira-CAD program, for the action of constant, temporary (snow and wind) and short-term dynamic loads, the choice was made on curved structure, a kind of a kind of large-span vault - a sail dome that allows you to overlap maximum spaces. To assess the strength and deformation parameters, a model of the transfer surface has been developed, with a given dome rise of 20°. (Fig. 8)

Figure 8. The final surface: 1 - the main circle in the Y0Z plane, 2 - the plane limiting the surface from below, 3 - the constructed surface.
4. Practical application and results
Taking into account the needs of the Far North regions for insolation, the following roof design was adopted, with a given slope of 20°: the element of the load-bearing roof is the girders on which the segments with enclosed two-chamber double-glazed windows 30 cm thick with an outer layer of transparent solar panels based on titanium dioxide and nickel oxide, which have the same radius of curvature as the basic shape, and the segments of the structure are inserted during the manufacturing period, then they do not require any rework on the construction site. Fastening of the cover is made in contour nodes. All structural units are hinged, which is necessary to ensure the possibility of collapsibility [11-12].

All structural elements made of reinforced wood for the purpose of unification and the possibility of subsequent industrial production, and collapsible structures are set to the same length, with a rigid and elastic connection of the elements to each other.

In the final model, you defined the elements of the metal parts of the mesh, including the sloped weldments. For the initial approximation in the calculation, single lay steel ropes of the TK type of construction 1x19 (1+6+12) are used in accordance with GOST 3063 (hereinafter - cables), and it is also possible to replace metal parts with carbon fiber that does not corrode, and is much lighter in weight, good adhesion, with the help of a special glue, with wood, thus increasing the strength of the elements in the stretched zones, and in the zone of action of transverse forces. For the perception of the spacer stresses in this case, a support "ring" is designed. To maintain equilibrium forces, the mesh segments must be aligned with the principal lines of curvature in the sense of "relative" differential geometry, with the Airy potential as the unit sphere.

The flooring undoubtedly perceives some of the efforts; in this work, a method for determining the stiffness of the dome system is used, which makes it possible to determine the proportion of the flooring included in the operation of the core frame, obtained in the course of a numerical and full-scale experiment.

The calculation of the dome includes several parameters - the rigidity of the support ring, ribs, purlins and decking, as well as the discreteness of the dome structure. The deployed dome allows the support ring to be as close as possible to the shape of a rectangle, to accept the minimum slope angle, which will reduce the load load on the underlying structures and reduce material consumption. (A spherical dome is conventionally considered to be shallow when the ratio of the rise to the length inscribed in the diameter is \( f/d \approx 1/5 \).) To increase the construction volume of an industrial building, the construction of a dome structure with a "skirt" is planned. The joints of the ribs of the dome and the support ring are rigid. (Fig. 9)

![Figure 9](image_url)

**Figure 9.** Structural diagram (a), frontal view (b) and plan (c): 1 - load-bearing element, 2 - flexible cables adopted for the structure according to the first option. In the case of using carbon fiber, these connections are stored only in the places of tightening, the support ring.
Climatic loads are determined by calculation method.

**Table 1.** Characteristic of loads per 1 m² of coating, kN/m².

| Load                        | Regulatory | γf | Estimated |
|-----------------------------|------------|----|-----------|
| 1. Constant                 |            |    |           |
| 1) double-glazed window unit 30 mm thick | 0.4        | 1.1| 0.44      |
| 2) From suspended equipment |            |    |           |
| Всего Постоянная:           | 0.5        |    | 0.57      |
| 2. Temporary                | 1.55       |    | 1.55      |
| Snowy                       |            |    |           |
| Total:                      | 1,571      |    | 2.1       |

The development of a mathematical model was carried out on the basis of the method of displacement of nodal points, and the principle of minimum potential energy of the system, the momentless stress state is the most advantageous for the operation of the shell [13-14].

The concentrated forces are determined taking into account the cargo areas on which the loads act:Or constant: \( F_n = G \cdot A \)

- Snow view: \( F_n = \gamma_{fm} S_0 \cdot \mu C_e C_{alt} \cdot A \), where \( A \) - load area.

The modeled mesh shell of the coating is shown in (Fig. 10).

The test of the structure of the mesh shell with the selection of values for critical parameters, as well as taking into account the actions of various factors on the dome itself, showed that for the given parameters, the parameters at the maximum angles \( \alpha \), angle \( \beta = 90^\circ \), highlighted in the table in red, and when the angle \( \beta = 45^\circ \), \( \alpha = 0 \), \( \mu 3 = 0 \).

![Figure 10. Calculated coverage scheme.](image)

According to the experimental calculation in the LIRA program, the critical values of the parameters of the section of the mesh shell of the wooden frame, and the permissible snow loads on the dome with different parameters of the forces on the mesh frame, were also found; it was also possible to derive the regularity of the redistribution of stresses in the ribs of the dome and deck [15].

The results obtained were verified on a mock-up using field tests in a wind tunnel.
It was also revealed that the combination of the self-weight of the structure and the acting loads applied at different angles, tensile forces arise in the lower chord, and the maximum compression of the rods, of the second tier, the combination of loads can cause shear forces.

The sail canopy can be mounted without the use of tower cranes, but only with the condition of using hydraulic self-lifting devices mounted on the wall of the “skirt” of the dome, and elements of the winch mechanism, which is important for the conditions of the Far North. The assembly diagram of the assembled coating is shown in Figure 11.

**Figure 11.** Installation diagram of the assembled sail canopy cover with dimensions 48 × 48 m using self-lifting mechanisms and a system of straps: 1 - belts; 2 - racks; 3-braces; 4 - successive positions of the structure during lifting; 5 - hydraulic self-lifting supports; 6 - temporary reinforcing structures; 7 - an element of the winch mechanism.

5. Conclusion

The developed constructive solution will make it possible to use it not only for the development of structures of rotation, but also for more complex forms of dome coverings of second-order surfaces, for example, a one-sheet hyperboloid of revolution, an elliptical cylinder, an elliptical paraboloid, as it were, formed by the movement of one parabola along another, a paraboloid of circular cylinders.

All of the above emphasizes that the proposed constructive solution is technologically and economically justified, which will allow much in a shorter time to develop construction objects and locate infrastructure in covered spaces, which is very important in the Far North.

6. References

[1] Abu-Khasan M, Egorov V, Rozantseva N, Kuprava L 2018 Load carrying wood and metal structures of trusses of covering of long spanned rail depot IOP Conference Series: Materials Science and Engineering 463(4) 042075 DOI: 10.1088/1757-899X/463/4/042075

[2] Veselov V, Abu-Khasan M, Egorov V 2020 Innovative design of wooden beams in the far North IOP conference series: materials science and engineering DOI: 10.1088/1757-899X/753/2/022024

[3] Abu-Khasan M, Rozantseva N, Egorov V, Kuprava L 2020 Prefabricated Dome Structures with Walls Made of Soil Composites and Urea-Formaldehyde Foam Insulation (UFFI) as a Way to Solve Transport Infrastructure Problems in Permafrost Regions IOP conference series: materials science and engineering 022022 DOI: 10.1088/1757-899X/753/2/022022

[4] Temnev V, Abu-Khasan M, Charnik D, Kuprava L, Egorov V 2020 The mesh of shells of a bionic type to be operated in extreme habitats IOP conference series: materials science and engineering 022023 DOI: 10.1088/1757-899X/753/2/022023

[5] Egorov V, Kravchenko A, Abu-Khasan M 2020 The Application of Evolutional Algorithm Optimization of Sprengel Systems of Transport Buildings and Structures for Northern Districts
[20] Shershnev M, Puzanova Y, Sakharova A Geocoprotective technologies from heavy metal ions pollution for transport construction in permafrost regions *Lecture Notes in Civil Engineering* **50** pp 329-338 DOI: 10.1007/978-981-15-0454-9_34