Transformable Steel Dome

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Abstract. The developed design of the lattice shell has the ability to fold by reducing its size in one direction and increasing it in another. The principal difference of this design lies in the feasibility of folding the dome as a wholly without the need for a complete disassembly of the shell into numerous elements. The positive side of this design is the possibility of factory production of elements, speeding up the installation process and increasing mobility – the dome can be easily folded and transported to a new place. The below step-by-step description of actions of the general method of constructing the surface of the shell allows you to simulate the frame of a folding reticulate dome. Recommendations for the construction calculation contain a description of the methods used for carrying out calculations manually, bringing the arguments in favor of a computer calculation, instructions on creating a model, setting rigidity and types of finite elements, as well as taking into account nonlinearity when designing the dome in the software package LIRA-CAD. The design of the calculation scheme and the calculation itself are carried out using the general theory of shells. The field of practical implementation of the folding net dome is quite wide – it is the construction industry, defense production, agricultural industry and industry as a whole.

1. Introduction

The desire of a person to facilitate his work, accelerate the implementation of work, as well as to reduce the cost of material resources led him along the path of inventions and discoveries. At present, a great experience has been gained in designing various types of building structures, both standard and unique ones [1]. The idea of folding designs is far from new, but over time this topic continues to be developed and supplemented. Proof of this is the existence of a large number of registered patents. Folding structures have wide potential for practical implementation in the construction, agricultural and military industries. Constructions, as a rule, are unique and require an individual approach to their calculation and design. At the moment, a large number of possible options of coatings for folding structures have been proposed (which is taken into account in the patent bases of both Russia and other countries). And this is not surprising, because the positive qualities make a significant contribution to the benefit of a folding alternative compared to a stationary one. First of all, folding structures stand out for their mobility. They can be brought to the construction site, laid out on the spot without significant costs of labor and material resources, and upon completion of the period of their use, they can also be folded and transported to a new place.
This article discusses the design of the reticulate surface with a fundamentally new idea, which consists in folding the whole shell. The lattice shells themselves have a large number of positive characteristics: light weight, high strength, durability, the ability to cover large spans, relatively low material costs for their production. The proposed design incorporates all the advantages of reticulate shells and folding structures. Among the limitations, it is possible to distinguish high demands on accuracy in the production of the finished casing, as well as complication of the design process.

2. The method of constructing the surface of the shell (dome)
The constructive scheme is shown in figure 1, where: 1 is a carrier element, 2 are flexible cables (single-rolled cables of type 1x19 (1 + 6 + 12) according to GOST 3063-80) are used in the initial approximation. Figure 2 shows the main types of construction. All intersections of the structure are hinges, which is necessary to ensure the possibility of folding. To ensure the rigidity and stability of the structure in the design position, it is necessary to introduce additional ties (light cables or ropes) that ensure the geometric immutability of the structure for any kind of loading.

![Figure 1. Structural scheme](image1)

![Figure 2. Views: a) frontal view, b) plan](image2)
From the point of view of architecture, the surface is a type of over-span roof – sailing dome. The surface is built on the basis of a segment of a sphere with the subsequent transformations described below.

In figure 3 it is shown the surface construction scheme, where: 1 is the main circle located in the Y0Z plane; 2 is the plane bounding the surface from below, 3,4,5 are the construction circles having the same radius, both between themselves and with the main circle.

![Figure 3. Scheme of construction](image)

When constructing the surface, it is necessary to specify a certain height along the Z axis, that is, camber of the dome, and also to know the dimensions of the object to be covered (span). Knowing these parameters, one can specify the main circle 1 in one of the directions (in this case, it is the Y axis). Next, select the length of one structural element (about 2-3 meters) and enter a polygon with a side of this length into the existing circle so that the angle of the n-gon lies on the Z axis in the lower part of the circle, and the Z axis and the side are in the upper orthogonal intersection n-gon. This is achieved by the odd number of sides of the n-gon. At this stage, it will be necessary to increase the radius of circle 1 so that the selected polygon fits correctly. Then it is necessary to “multiply” the existing circle with a polygon inscribed in it in the direction of the main circle 1 along the Y axis with a step equal to one element of the polygon, that is, the circles are transferred to the vertex points of the inscribed polygon. To do this, rotate a copy of the main circle with polygon 3 inscribed in it with respect to the Z axis by 90 ° and carry out the actions described above. "Multiplication" is carried out to the surface, which limits the required space, located in the positive direction of the Z axis in the selected coordinate system, by a circle (curve) 2. In this case, the last elements of multiplication are circles 5. Next, remove the construction lines, as well as the lines beyond the limits of circles 5, leaving only those parts of the polygons that are limited by circles 5. After that, rotate the copies of the remaining elements around the Z axis by 90 ° three times. As a result, we obtain the transfer surface shown in figure 4, where: 1 is the main circle located in the Y0Z plane, 2 is the plane bounding the bottom surface, 3 is the constructed surface.
All individual supporting steel structural members that make up quadrangular cells must be of the same length. This is the main condition of the property folding structure.

It should be noted that these constructions were made without taking into account the optimization of the structure. Here a general method for modeling the idea of a folding reticulate surface is given.

3. Recommendations for the calculation of the shell

There are two approaches to the manual calculation of reticulate shells [2]:

1) Discrete approach (using classical methods of structural mechanics of beam systems);
2) Replacement of a discrete system with a continual model with equivalent rigidity properties (using the theory of plates and shells).

The discrete approach is difficult to implement due to the fact that the difficulty of obtaining numerical solutions to systems of equations increases with an increase in the number of joints and beams. On the basis of classical general theory of shells (Vlasov V.Z.) to simplify the calculation a theory of thin elastic reticulate shells was created by Pshenichnov G.I. [3], which made it possible to calculate reticulate shells as continual structures with the possibility of a reverse transition from the efforts of an equivalent continuous shell to forces in individual rods.

The approaches described above require a high concentration of attention and a large amount of time in the calculation. However, at present, the level of development of computer technology makes it possible to carry out a fairly fast calculation of complex spatial systems using computational software systems. As an example, the calculation of the reticulate-like folding surface was made in the LIRA-CAD software package.

The calculation scheme was created in the AutoCAD program and imported into the LIRA-CAD software package. Before starting the scheme is packaged; for proper packing, it is necessary to exclude the conditional joints in the crosshairs of the cables from the “stitching”. The supports set the limitation of movements in all directions, for the cables of the carrier contour the movement along the Z axis is prohibited, in the movable joints ensuring the folding of the structure, the hinges at the ends of the steel elements are set to allow rotation relative to the local Z axis. Next, the construction is divided into blocks with the subsequent assignment of their rigidity (as a first approximation) (Figure 5).
Figure 5. The calculation scheme with the indication of rigidity, where: 1 - steel carrier elements, 2 - cables of the carrier contour, 3 - main cables

1 – steel carrier elements ("molodechno” curved welded rectangular profile, steel C345, type of element – column);
2 – cables of the carrier contour (finite element FE 310, single lay rope of type TK construction 1x19 (1 + 6 + 12) Ø16 mm in accordance with GOST 3063-80);
3 – main cables (FE 310 finite element, single lay rope of type TK of construction 1x19 (1 + 6 + 12) Ø12 mm according to GOST 3063-80).

Due to inserting of hinges, the system becomes geometrically variable; therefore, to ensure rigidity and stability, ropes are added that pass along the carrier contour and separately through each cell of the shell, which are then tightened on one of the four structural supports (look at figure 5 number 2 and 3).

The design is calculated on the load from its own weight, snow and wind loads. To simplify the snow and wind loads, a tent cover over a dome of technical fabric with a designated FE 342 type (geometrically non-linear universal triangular shell FE) is designed in general. Modeling of nonlinear loadings of a structure is carried out using the step method, provided that the automatic step selection for geometrically and physically nonlinear problems is used. The calculated combinations of forces and the calculated combinations of loads (CCL) in LIRA-CAD are applicable only to linear calculations using the superposition principle. When calculating with regard to nonlinearity, it is necessary to find out how the loads are interrelated in time. Thus, it is required to select the least advantageous combination of loads manually. LIRA-CAD software makes it possible to speed up this process, allowing you to manually set the required load combinations (similar to the CCL table), which makes it possible to simulate the operation of this shell with sufficient certainty in LIRA-CAD, to obtain the calculation of loadings of various kinds and as a result, select the required section of the elements.

4. Results and discussions
The authors have developed in detail the nodes and working drawings. A decision was received on issuing a patent for a utility model on application No. 2017121515/03 (037267) of 06/19/2017.

5. Conclusions
Construction - folding reticulate dome can be applied in various areas of industry. For example: in agriculture - as a temporary grain store; as exhibition pavilions and entertainment buildings (mobile circus), in the defense industry as temporary hangars for helicopters, in the space industry as sliding mirrors of telescopes, and the like.
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