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THE ROLE OF ROD STAYED-SHELL SYSTEMS IN STUDIES OF INNOVATIVE STRUCTURES IN CONSTRUCTION

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Annotation
The possibilities of using rod-stayed cable-shell systems to create innovative structures in construction are considered.
A method for numerically solving the problem of the stress-strain state of such structures with increased geometric non-linearity is developed. The effectiveness of the developed methodology is shown on a number of designs of large-sized space antenna reflectors.

Keywords: cable-stayed-shell system, tensogrity, construction, large-sized structure, domes.

Introduction

Currently, in the field of structural engineering, there are distinct trends in the creation of ultra-light large-sized transformable structures that can withstand heavy loads. Evidence of this is the popularization of rod-stayed-shell systems (RSShS), called tensogrity.

Tensorgrity - is a principle of constructing structures based on the use of elements that work only in compression or only in tension. Structures of this type have found wide application in architecture, art, urban planning, aerospace, fittings, and even biomechanics [1, 2]. In some cases, such structures have dimensions of hundreds of meters. Experimental testing of such large-sized structures requires large material and time costs. Therefore, computer modeling comes to the fore in the design and development of such structures. It allows you to track the entire process of creating a structure, its settings, etc., and predict its behavior in various conditions.

In order for each structural element to operate with maximum efficiency and economy, it is necessary to conduct a thorough analysis of the stress-strain state of the entire structure. Hence, there is a need to create a full-fledged model of the structure, and not be limited to the analysis of representative elements. On the other hand, the analysis of large-sized structures consisting of guy rods and thin-walled shells is hampered by the geometric nonlinearity of such systems, which creates a need to develop an approach that allows the numerical analysis of the above structures.[7][8][9][10]

Application of rod-stayed-shell systems in construction

Examples of strain gauge structures

On fig. Figure 1 shows the strain gauge structures used to create space antennas and civil engineering facilities [3][4][5][6]

The advantage of the shown structures is a small volume in the folded state, a relatively low cost in materials in the design, and environmental friendliness. When designing space antennas, their advantage is the ability to withstand heavy loads during the launch of spacecraft.

Fig. 1.

a) AstroMesh Deployable Space Antenna b) Millennium Dome in London v) The roof of La Plata Stadium in Argentina

Shell constructions

Shell structures are surfaces stretched with the help of elastic cords or special load-bearing frames made of rigid rods and beams (Fig. 1). The level of prestress in the shell surface must be sufficient throughout the entire service life to maintain the tension level and shape of the structure on the one hand, and to allow the shell material to remain in the zone of elastic deformation on the other. Under the influence of loads such as wind or snow, the stresses on the surface of the shell can increase by 10 times. For these reasons, the sheath material must have a prestress equal to 1/20 of the tensile strength. The strength of the material can change due to changes in temperature, humidity and creep. Therefore, the production requirements of the mechanical properties of materials are constantly checked with the help of special tests. In the general case, research is needed to find an inexpensive, fire-resistant, easy-to-use and transport material.[11][12][13][14][15]

When designing space antennas, in addition to the influence of prestress and temperature on the reflecting surface, it is important to monitor the standard deviation of the reflecting surface from the theoretical paraboloid. The standard deviation should be no more than 2-3% of the operating wavelength. Such restrictions impose more stringent requirements on antenna design and reflective surface material properties than on some civil engineering projects.

Today there is a wide choice of materials for the shells of the markets. The most commonly used are polyvinyl chloride (PVC), polytetrafluoroethylene (PTFE), glass selenium coatings. For example, the Millennium Dome, located on the Greenwich Peninsula in southeast London (Fig. 1. B), was originally planned to be made of PVC. However, to increase the service life, it was made of PTFE. For the manufacture of the reflective surface of the AstroMesh space antenna, a thin conductive mesh of molybdenum wire with a diameter of 0.03 mm, covered with gold, is used.[16][17][18][19]

Physico-mathematical model of rod cable-stayed-shell systems

There are foreign works on physical and mathematical models of RCSS. For example, the work is devoted to the formulation and solution of the problem of finding the equilibrium state of the tensogrity of structures subjected to external forces using the virial work method. The papers describe static and dynamic analyzes of such structures, as well as a quasi-static approach to their analysis. The authors are modeling the structures under consideration from the standpoint of the nonlinear theory of elasticity. Shell elements are modeled by a thin momentless membrane. Extended elements of the RCSS structure, such as cables, cables and other elements, were modeled by rod elements with effective characteristics that give the stiffness properties of these model elements the same as those of real structural elements. The stress-strain state of the RCSS is described by a stationary nonlinear system of equations of the theory of elasticity

$$\frac{\partial}{\partial x_k}\left(\sigma_{kj}\left(\delta_{ij}+\frac{\partial u_i}{\partial x_j}\right)\right)=0 \qquad (1)$$

$$\varepsilon_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_j}+\frac{\partial u_k}{\partial x_j}\frac{\partial u_k}{\partial x_i}\right); \qquad (2)$$

$$\sigma_{ij}=\frac{E_m}{2(1+v_m)}\left(\varepsilon_{ij}+\frac{v_m}{1-2v_m}\delta_{ij}\varepsilon_{kk}\right)+\sigma_{ij}^0; \qquad (3)$$

where δ_{ij} - Kronecker symbol; u_i, σ_{ij} $\sigma^0{}_{ij}$ ε_{ij} - components of the displacement vector, the second Piola-Kirchhoff stress tensor, the prestress tensor, the strain tensor; E_m, v_m - modulus of elasticity and Poisson's ratio of the m material.

The boundary conditions have the form;

$$u_i(\bar{x})=u_{i0}, \bar{x}\in S_1 \qquad (4)$$

$$n_k\sigma_{kj}\left(\delta_{ij}+\frac{\partial u_i}{\partial x_j}\right)=p_i^n, \bar{x}\in S_2 \qquad (5)$$

where $S = S_1 + S_2$ - area border Ω RCSS; p_i^n - tension at the border S_2, characterized by the normal vector $\bar{n}$; u_{i0} - movement at the border S_1.

Numerical solution of the problem of the stress-strain state of the RCSS

Problem (1) - (5) was solved using the finite element method using the ANSYS software package [4]. In the numerical solution of equations (1)-(5), the choice of the initial approximation plays a large role. Since the convergence region is small, it is difficult to determine a good initial approximation that allows one to obtain a solution to the stationary problem. Therefore, a sequence of solutions is built, in which each new solution uses the previous one as an initial approximation (Fig. 2).[20][21]

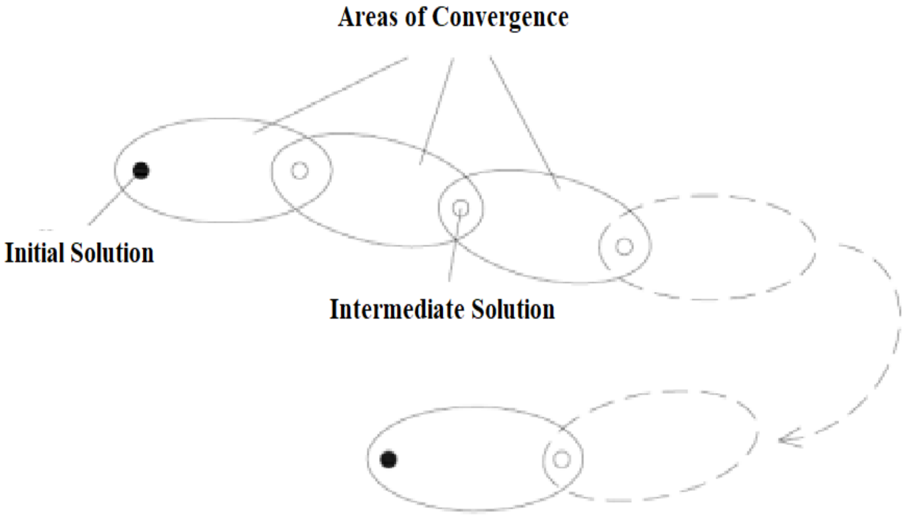

Fig. 2. The sequence of solutions used to find the sought solution.

Moreover, the desired solution will be the last in this sequence. The solutions correspond to various boundary conditions. To obtain the initial solution, an additional boundary condition is set.

$$u_i(x)=0, \bar{x}\in\Omega. \qquad (6)$$

Condition (b) corresponds to the complete fixing of the **RCSS**. The solution process will continue until a solution with boundary conditions (4), (5) is obtained. Such a procedure was developed and used in the numerical simulation of a separate large-sized umbrella reflector. The procedure for searching for the initial state does not yet have an unambiguous algorithm; therefore, a change in the design of the **RCSS** can lead to a significant change in the sequence of removing the fastenings.[22][23][24][25]

Numerical models of rod-stayed-shell systems on the example of large-sized space reflectors.

When modeling a large-sized space reflector, assumptions are introduced for the application of the finite element method:

- the dimension of the problem is reduced, for example, for a reflecting surface with its thickness of the order of fractions of a millimeter, we can assume that the variables of the problem do not change in thickness and, thus, solve a two-dimensional problem;
- it is assumed that the cable-stayed elements of the antenna structure do not resist compressive forces, which introduces a significant non-linearity into the behavior of the structure.[26]

On fig. 3-4 shows the finite element models of large space reflectors and their corresponding numerical models implemented in the ANSYS software package..

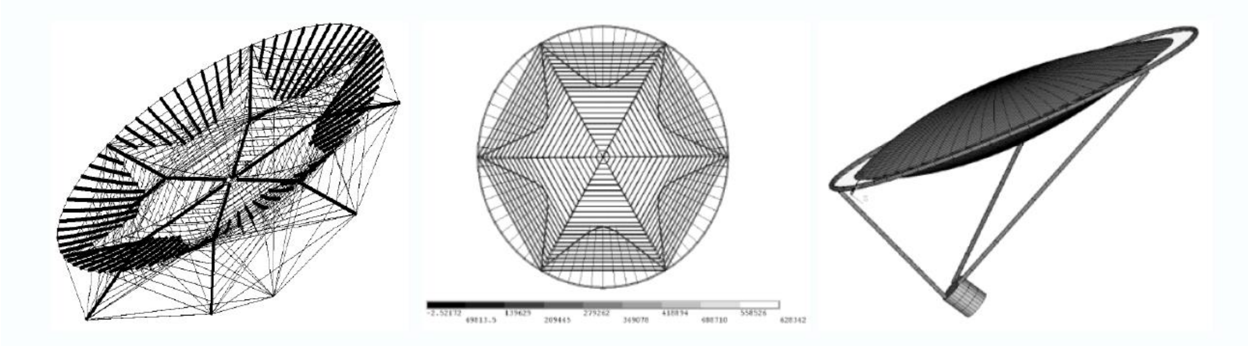

Fig. 3.

a) Umbrella type reflector with 50 m aperture **b) Reflector frontal network voltage, Pa** **v) Inflatable reflector with 50 m aperture**

On fig. 4.a shows the voltages of the frontal network of the reflector as a result of the tension of its cords. On fig. 4.b shows the displacement of the reflector nodes when the reflecting surface is stretched.[27]

For the reflector in Fig. 4.c the calculation of the deviations of the reflecting surface from the paraboloid given by the equation $z=\left(x^2+y^2\right)/4F$, where F - focal length, in order to estimate the RMS of the reflecting surface. More detailed information about the presented models can be found in the works.[28]

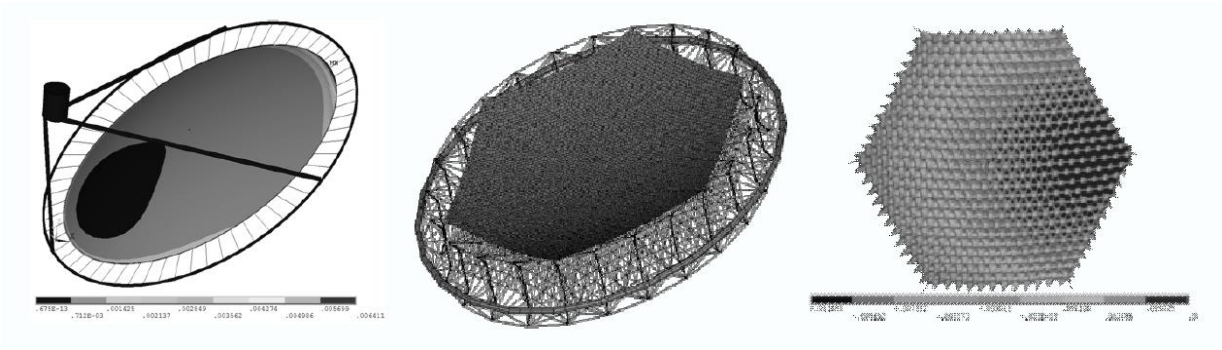

Fig. 4.

a) Reflector deformation **b) Reflector with tensor - chest rim aperture 48** **v) Distribution of deviations in a reflective surface**

For all structures, to obtain the initial solution, zero boundary conditions were set for the displacements of the nodes. Further, to obtain intermediate solutions, these boundary conditions were not set for some of the nodes, and the process continued until the desired solution was found.

The main reason for using the proposed technique is the large geometric nonlinearities that occur in cable-stayed shell structures.

Conclusions

The possibilities of using rod-stayed-shell systems for creating innovative structures in construction are considered.[29]

A technique has been developed for numerically solving the problem of the stress-strain state of such structures with increased geometric nonlinearity.

The effectiveness of the developed technique is shown on a number of designs of large space antenna reflectors.

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