Modeling of Seismic Resistance of Spatial Larg-span Unique Structures in the Operational Stage

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Abstract. The paper presents the results of the research of the stress-strain state of long-span unique spatial and shell constructions, subjected to long-term static and dynamic effects, and performed by using experimental methods of physical modeling obtained on experimental models and full-scale structures.

To ensure the operational safety of buildings and structures, the change in the structural properties of materials from unfavorable climatic conditions of long-term beyond design-basis static loadings and dynamic effects of high intensity compliance of bearing diagrams and the presence of local damage to structures was investigated. The evolution of the dynamic parameters of spatial and shell constructions during operation is investigated.

1. Introduction

At present, the theory and practice of the use of long-span spatial constructions of unique buildings and structures is receiving a high level of development [1-6].

In the regions of Central Asia, the beginning of the construction of shells for covering public buildings dates back to ancient times [3,4,7]. The preservation of these ensembles today testifies to the durability and reliability of their use for regions of high seismicity [3,4,7]. Meanwhile, intense seismic effects, unfavorable climatic and difficult ground conditions limit the introduction of long-span unique buildings. To solve this problem, a nonlinear theory of calculating spatial systems [4,7,9] has been developed, methods have been developed for calculating shells, plates and bar constructions, taking into account the duration of operation [2,7,10] seismic impacts, regional features of the construction areas.

Computer technology is widely introduced both in complex calculations and in computer-aided design [1,3,6].

The experience of introducing experimentally erected long-span unique structures showed, that ensuring their operational safety from progressive destruction resulting from all kinds of beyond design basis impacts, and preserving their structural ability over all its service life of hundreds of years can only be ensured by evaluating their work, by experimental modeling methods and implementation scientific and technical support in the design, manufacture and installation of load-bearing structures and during the period of its use [1,5,7,11,18].

Due to the development of the industrial base, with the expansion of housing and industrial construction in regions with unfavorable climatic conditions of increased seismic activity, the solution of the problem of overlapping buildings with long spans, the introduction of architecturally expressive
forms of spatial constructions, ensuring their efficiency and performance, the development of theory and methods of engineering calculation of spatial systems are becoming increasingly important. This present article is devoted to solving the problem.

Taking into account the complexity of modeling the seismic resistance of the operated unique long-span buildings and structures, the tasks of this problem were solved for spatial and shell systems in operation according to the following methodology:

- change in the structural properties of materials according to the criteria for ensuring operational safety under static and dynamic influences [4,10,12-17];
- ensuring operational safety under adverse climatic conditions [7,10,18];
- ensuring operational safety, taking into account the nature of the loading, the compliance of the contour diaphragms [2,7,10,18-20], changes in the dynamic parameters of structures over time [17-19];
- reducing the impact of emergency impacts from local damage and failure of individual most stressed zones of structural elements.

The complexity of creating the actual stress state of the systems under consideration, the reliability, assessment a calculation method, validity of the initial assumptions and taking into account the above-mentioned design features when solving the tasks of this problem, it was decided to synthesize theories with experiment, based on experimental methods of modeling and implementation of scientific and technical support in operated objects ... [1-3,8,11,18-20]

2. Experimental research technique
Experimental dynamic studies of long-span unique buildings and structures presented in this work are divided into two directions: [1,2,7-9]

1. Model dynamic research. 2. Field dynamic research.

In the first case, studies were carried out in laboratory conditions on models of spatial structures that are geometrically similar to nature. Dynamic loads on structures were created with the help of a special shaker and a vibration machine, the registration of dynamic phenomena in the models was carried out by a vibration measuring complex for a model studies. To recalculate the results of field studies formulas obtained on basis of dimensional analysis were used.

In the second case, the studies were carried out on real full-scale spatial structures. In this case, various sources of vibration excitation were used, including a special vibrating machine.

3. Model research technique
To carry out model dynamic studies in spatial structures, it is necessary to solve the following issues:

- to fulfill certain conditions of similarity allowing to unambiguously recalculate the obtained research; results for full-scale structures;
- to determine the scale of the model and the material for its manufacture, which is associated with the design and characteristics of the shaker, adapter devices for fixing the model, special vibrators for creating dynamic loads, etc. Special attention is required to the registration, processing and analysis of dynamic parameters taking into account qualitative changes that have occurred in recent years in measuring technology.

4. Similarity conditions for modeling, research
Physical modeling of spatial systems is based on the well-known concept of the similarity of phenomenon: two phenomena are called similar if, given the characteristics of one, one can obtain the characteristics of the other by multiplying constant coefficients.

For conditions of dynamic similarity, inertial forces are essential

\[
P_H L_H / (m_H V_H^2) = P_M L_M / (m_M V_M^2) = \text{idem.}
\]

This expression represents the general law of dynamic similarity by Newton's similarity criterion.
From it can be obtained, for example, with the predominant influence of gravity forces - the Froude similarity criterion.

\[ \frac{V_H^2}{(g_H L_H)} = \frac{V_M^2}{(g_M L_M)} = F \]  \hspace{1cm} (2)

with the predominant influence of elastic and inertial forces - the Cauchy similarity criterion:

\[ \frac{V_{h \rho_M}}{E_{hi}} = \frac{V_{m \rho_m}}{E_m} = Ca. \]  \hspace{1cm} (3)

In this case, for the simultaneous satisfaction of the Cauchy and Froude similarity criteria, it is necessary to fulfill the condition

\[ \frac{E_{h \rho_M}}{E_{hi}} = \frac{L_{hi}}{L_m} = \lambda. \]  \hspace{1cm} (4)

For model studies of large structures, the linear dimensions of which reach 100 m and more, the fulfillment of the last condition at real geometric scales \( \lambda = 100 \times 500 \) is associated with very strict requirements for model materials. Therefore, in many cases, limited by the linear-elastic formulation of the problem, model studies are carried out on the basis of the Cauchy similarity criterion.

To obtain similarity criteria for \( \varepsilon_n \neq E_n \), the similarity theory can be applied using, for example, the concept of "the extended mechanical similarity," proposed by A.G. Nazarov, or dimension analysis can be applied, as it is shown in the work of Y.S. Vardanyan. [7,8]

The acceptance of the criteria lead to the following formulas for recalculating a number of parameters from model to field:

- time, periods of fluctuations \( T_H = T_M \sqrt{\frac{E_{h \rho_M} U_M L_H^3}{E_{hi} U_M L_H^3}} \)  \hspace{1cm} (5)
- acceleration \( W_H = W_M L_M E_{h \rho_M} / (L_{hi} E_{hi} \rho_{hi}) \)  \hspace{1cm} (6)
- stresses \( \sigma_H = \sigma_M E_{hi} U_M L_H^2 / E_M U_M L_H^2 \)  \hspace{1cm} (7)
- displacement \( U_H = U_M [E_{h \rho_M} L_M^2 / E_{hi} \rho_{hi} L_{hi}] \)  \hspace{1cm} (8)
- deformations \( \varepsilon_H = \varepsilon_M [P_{h \rho_M} L_M^2 / (P_{hi} \rho_{hi} L_{hi})] \)  \hspace{1cm} (9)

Let us express the loads \( P \) in terms of inertial forces

\[ \frac{P_H}{P_M} = \frac{W_{h \rho_M} L_H^3}{(W_{h \rho_M} L_M^3)} \]  \hspace{1cm} (10)

then the conversion formulas for displacements and deformations will be written in the following form:

\[ U_H = [W_{h \rho_M} E_{hi} L_H^2 / (W_{h \rho_M} E_{hi} L_M^2)] U_M \]  \hspace{1cm} (11)
\[ \varepsilon_H = [W_{h \rho_M} E_{hi} L_H / (W_{h \rho_M} E_{hi} L_M)] U_M \]  \hspace{1cm} (12)

The practical implementation of the above dependencies in preparation for conducting experiments on models allows us to accurately select materials for the manufacture of models, to develop the design of a special vibration stand for simulating dynamic loads, to select and debug a set of measuring equipment, to develop a methodology for preparing and conducting experiments.

When testing a model, dynamic effects are carried out by a vibrator. The parameters of spatial sys-
tems are recorded along the X, Y, Z axes. The loads on the investigated model and full-scale structure in accordance with the recommendations for modeling are determined taking into account the strength characteristics of the materials:

\[ q_m = q_h / \alpha_R; \quad F_m = F_h / (\alpha_R^2 \alpha_m); \quad q_{Ml} = q_{Hl} / (\alpha_m \alpha_R); \quad (13) \]

where \( q_m, q_h, F_m \) - respectively, evenly distributed over the area, distributed along the length (strip) and concentrated load on the model; \( q_{Ml}, q_{Hl} \) - respectively, on full-scale structures; \( \alpha_m = l_m / l_H \) - scale factor of geometric similarity; \( \alpha_R = R_h / R_M \) - is the material strength scale factor or force similarity scale; \( \alpha_E = E_h / E_M \) - scale factor of elastic module or deformation similarity; expression (13) the load on the full-scale structures of coatings is assumed to consist of the sum:

\[ q(x) = q = g + p + v + q_s; \quad (14) \]

where \( g \) is the constant load, \( p \) is the live load, \( v \) is the prestressing load at the design loading, equal to 10-15% of \( g + p \), \( g_x \) is the seismic component of the load. Wherein, the function \( g(x) \) can be either continuous or discontinuous:

According to the records of experimental studies, the maximum displacements were determined: w, u, v, \( \ddot{a} = \frac{d^2w}{dt^2}, \) frequency \( \omega \) and oscillation period \( T = 2\pi/\omega \). Inertial force and vertical static load were determined by the formulas:

\[ X = 12wEI/h^3, \quad Q = X/\eta\beta K_c, \quad (15) \]

where \( EI \) is rigidity, \( h \) – is the stand support height, \( K_c = A = a/g, \beta = 1/T \) - is a dynamic factor, \( \eta \) - mode factor, \( g \) - acceleration of free fall. Vertical and horizontal components of inertial forces were determined by the formulas:

\[ J_b = -ma_b = -QK_c^b, \quad J_r = -ma_r^2 = -QK_c^r, \quad (16) \]

Taking into account the noted features of the work of spatial systems, the expression for the seismic force corresponding to the \( i \)-th top of the natural vibrations of the structure can be represented as:

\[ S_i(x,y) = q(x,y)\mu\beta l(l,y,c)K_c\eta\beta(x,y) \quad (17) \]

where \( i, j \) number of half-waves corresponding to vibration modes; \( \mu(x,y) \) - distribution functions of portable movement; \( l \) - length of the building; \( \gamma \) - vibration damping coefficient, \( c \) - seismic wave velocity in the ground. The value of the full load is taken as the sum of the static and seismic components of the loads

\[ q = q_{sh} + q_s, \quad q_s = (q_{sh}/g)\beta d^2w/dt^2, \quad (18) \]

where \( d^2w/dt^2 \) – is vertical acceleration of a structure caused by an earthquake equal to 0,1; 0.2 and 0.4 for intensity 7, 8 and 9 magnitudes.

The above formulas are used to analyze the results of experimental studies of models of spatial and shell structures and to assess the nature of the operation of full-scale structures under various static and dynamic loads.
5. Dynamic parameters of the shell structure during operation, taking into account the compliance of the contour structures and local damage

Let us consider the determination of the dynamic characteristics of the shells of the coatings, taking into account the duration of the loadings and the compliance of the contour structure and local damage.

| Reinforcing steel class | Yield strength, N / mm² | Temporary resistance, Н/мм² | Relative extension δ₅ | δ₆ |
|-------------------------|-------------------------|-----------------------------|------------------------|----|
| A240 (A-I)              | 240                     | 380                         | 25                     | –  |
| A300 (A-II)             | 300                     | 500                         | 19                     | –  |
| A400 (A-III)            | 400                     | 600 (500)                   | 16                     | –  |
| A500 (Ar-IIIIC)         | 500                     | 600                         | 12                     | 4  |
| A 600 (A-IV, Ar-IV)     | 600                     | 740                         | 12                     | 4  |
| A 800 (A-V, Ar-V)       | 800                     | 1200                        | 12                     | 2  |
| A 1000 (A-VI, Ar-VI)    | 1200                    | 1400                        | 8                      | 2  |
| A 1200 (Ar-VIII)        | 1200                    | 1400                        | 6                      | 2  |

To calculate the natural vibrations of a coating with finite stiffness contours, we use the techniques developed [4,7,10,20]. The system of basic differential equations of the technical theory in relative coordinates α and β has the form:

\[ BR_2 V_k^2 \omega + V^4 \Phi = 0; \quad -D V^4 \omega + R_2 V_k^2 \Phi + R_2^4 Z = 0; \]  \hspace{1cm} (19)

where

\[ V^4 = \partial^4 / \partial \alpha^4 + 2 \partial^4 / \partial \alpha^2 \partial \beta^2 + \partial^4 / \partial \beta^4; \]

\[ V_k^2 = \partial^2 / \partial \alpha^2 + \kappa \partial^2 / \partial \beta^2 \]

To account for physical, geometric nonlinearity, we represent the resolving system of equations:

\[ (1 - EK) V^4 \Phi + BR_2 [0.5L (\omega, \omega) + V_k^2 \omega] - \psi_1 = 0; \]

\[ (1 - EK) [ L (\omega, \Phi) + R_2 V_k^2 \Phi + R_2^4 Z ] - D V^4 \omega - \psi_2 = 0, \] \hspace{1cm} (20)

Here \( \psi_1 = E \int_\tau^\tau L_1 (\Phi, M_\eta) K(t, \tau) d\tau, \quad \psi_2 = E \int_\tau^\tau L_2 (\Phi, M_\eta) K(t, \tau) d\tau, \) \hspace{0.5cm} (1 - EK) linear creep operator.

The equations (20) after some transformations takes the form

\[ \frac{1}{Eh} V^4 \Phi + BR_2 [ L (\omega, \omega) + V_k^2 \omega ] = 0; \quad -D V^4 \omega + L (\omega, \Phi) + R_2 V_k^2 \Phi + R_2^4 Z = 0; \] \hspace{1cm} (21)

where \( E = E(1 - R^*); \quad D = D(1 - R^*); \)

\( Z = -\gamma \hbar / g (\partial^2 \omega / \partial t^2), \) - characterize inertial loads

Yet us consider vibrations of a bend-type shell. For free oscillations, the system of differential equations (19) taking into account (20) becomes.
\[(1 - EK)\nabla^4 \Phi + BR_2[0, 5L(\omega, \omega) + \nabla_k^2(\omega)] - \psi_1 = 0;\]
\[(1 - EK) \left[ L(\omega, \Phi) + R_2\nabla_k^2\Phi + \frac{\gamma h_3}{g} \frac{\delta^2 \omega}{\partial t^2} R_2^4 \right] - D \nabla^4 \omega - \psi_2 = 0\]  
we represent the system of equations relatively to \(\omega\) as:

\[\nabla^4 \nabla^4 D \omega (1 - EK) + C^2 B R_2^2 2 \nabla_k^2 \nabla_k^2 D \omega + C^2 R_2^2 \nabla_k^2 D \frac{1}{2} L(\omega, \omega) - (1 - EK) \nabla^4 R_2^4 \frac{\gamma h_2}{g} \frac{\partial \omega}{\partial t^2} = 0,\]  
where \(C = 12h_1 / h_2^3\).

As the results of experiments have shown, free vibrations of shell constructions occur according to a harmonic law with an angular frequency \(\omega\). Then the accepted boundary conditions will be satisfied by the solutions \(\omega\) and the inertial load, represented in the form of trigonometric functions:

\[D \omega(\alpha, \beta, t) = D \omega(\beta) \sin \lambda \alpha \sin \omega t; \quad Z(\alpha, \beta, t) = \frac{\gamma h_2}{g} \frac{\delta^2 \omega}{\partial t^2} \alpha(\beta) \sin \lambda \alpha \sin \omega t;\]  
where \(\lambda = \pi R_2 / a, \ a - \text{shell size}\)

Substituting (24) into (25), we obtain:

\[
\left(\delta^2 / \delta \beta^2 - \lambda^2\right) D \omega(\beta) (1 - EK) + C^2 R_2^4 \left(K \delta^2 / \delta \beta^2 - \lambda^2\right)^2 D \omega(\beta) +
+C^2 R_2^4 \left(K \delta^2 / \delta \beta^2 - \lambda^2\right)^2 D \cdot 0,5L(\omega, \omega) = (1 - EK) R_2^4 \left(\delta^2 / \delta \beta^2 - \lambda^2\right)^2 \omega(\beta) \omega^2 \gamma h_2 / g.
\]  
The solution to this inhomogeneous equation can be represented for the shell [7] in the form

\[D \omega = R_2^2 (C_1 \Phi_1 + C_2 \Phi_2 + C_3 \Phi_3 + C_4 \Phi_4),\]  
where \(C_1 - C_4\) arbitrary constants depending on the conditions of support of the shell along the longitudinal edges \(\Phi_1 - \Phi_4\) linearly independent particular solutions.

Taking into account in that the presence of the edge effect in the shell, we take arbitrary constant \(C_4 = \ldots = C_8\)

Substituting (27) into (26), we obtain the values of the circular frequency of natural vibrations of shells with arbitrary boundary conditions at the edges, which are absolutely rigid in their plane.

The frequency of natural vibrations, taking into account the vertical compliance of the contour design and the presence of initial non-beliefs, deflections and damage to the shell, is determined by disclosure of external static uncertainty and the solution of a system of equations expressing the conditions for compatibility of deformations.

To illustrate the stated method for calculating the frequency of natural vibrations, numerical experiments were performed by comparing the experimental data of the investigated long-term loaded shells of various geometric shapes (Table 1).

The comparison of experimental and theoretical data provides a fairly good match, taking into account the peculiarities of the shell behavior of various geometric shapes under long-term static and short-term dynamic impacts. To prevent brittle destruction of shells located in an operational state from progressive destruction subjected to seismic and other beyond design basis effects of various in-
tensities, in order to control the destruction mechanism, criteria have been developed that limit the values of the limiting static and seismic load.

\[ q = q_l + q_s \leq k q_u \]  

(28)

where \( q \) long-term operating load; \( q_s \) is the seismic component of the load, determined from expressions (17); \( q_u \) static breaking load, taking into account the operational state of the structure, determined by the solution of the system (21) or (1) [4,7].

The research results showed that for earthquakes with an intensity 7,8 and 9 magnitudes, the value of the limiting long-term static and seismic load, in accordance with expressions (28), can be taken respectively: \( q = 0.7 q_u \); \( q = 0.65 q_u \); \( q = 0.6 q_u \)

### Table 2. Frequencies of natural vertical vibrations of the investigated shells.

| №  | Construction                              | Span, m | Load kN / m² | Oscillation frequency, Hz |
|----|------------------------------------------|---------|--------------|----------------------------|
| 1  | Composite shells with side elements of positive curvature loaded for a long time from the level of breaking loads of 0.42 / 0.72 in the denominator | 1.8х1.8 | 1.7 | 18.3/13.4 | 20.5/15.1 |
|    |                                          |         | 5.0 | 14.6/9.2 | 15.7/10.2 |
|    |                                          |         | 8.2 | 12.2/7.0 | 12.9/7.5 |
|    |                                          |         | 12.0 | 10.3/5.9 | 10.4/6.3 |
|    |                                          |         | 15.0 | 8.5/5.5 | 8.8/5.7 |
| 2  | Composite shells with side elements of negative pressure with a loaded short-term continuous load | 4.8х4.8 | 1.7 | 12.3/13.8 | 13.5/10.4 |
|    |                                          |         | 3.2 | 9.8/8.2 | 11.1/8.9 |
|    |                                          |         | 6.5 | 7.2/6.6 | 7.7/5.8 |
|    |                                          |         | 8.2 | 6.3/- | 6.1/4.9 |
|    |                                          | 12х12 | 2.9 | -/8.55 | 12/9.7 |
| 3  | Conical multi-free canopy loaded with short-term / long-term load. | Ø3.6 | 2.0 | 6.5/5.7 | 7.4/6.2 |
|    |                                          |         | 4.0 | 5.0/4.6 | 6.1/4.3 |
|    |                                          |         | 6.0 | 4.3/3.5 | 4.7/3.8 |
|    |                                          |         | 8.0 | 3.7/2.9 | 4.1/3.3 |
| 4  | Spherical meridio-non annular ribbed dome with / without regard to contour compliance | Ø30 | 2.0 | 28.6/31.8 | 34.3/40.1 |
|    |                                          |         | 2.4 | 2/2.5 | 2.3/3.1 |
| 5  | Spherical medially annular ribbed dome with / without regard to contour compliance | Ø44 | 2.0 | 26/31 | 30.6/60.2 |
|    |                                          |         | 25.2 | 3.5/3.9 | 4.0/5.8 |
| 6  | Shallow shells of positive curvature with / without consideration of the compliance of contour diaphragms | 6х6 | 3.6 | 5.7/6.3 | 6.4/10.4 |

The results of studies carried out on long-term loaded shell models by creating dynamic loads of
high intensity showed that the seismic resistance of the shell to vertical impacts can be ensured by using discretely located ribs (grids) necessary to enhance the shell field, as well as by limiting the size of one of the spans of the components elements. The perception of horizontal seismic loads requires to use specially developed design solutions given in [3,4].

Based on the results of the conducted studies of modeling the seismic resistance of spatial long-span unique structures in the operational stage, the following conclusions can be drawn:

6. Conclusions
- at the present stage of development of the construction of unique long-span structures with the use of spatial shell structures, taking into account regional peculiarities, the use of experimental methods of modeling followed by scientific technical support of the operated structures is actual one;
- to ensure the operational safety of buildings and structures of spatial systems, it is obligatory proposed to take into account the changes in the structural properties of materials and dynamic parameters over time;
- in long-loaded models and full-scale spatial structures of buildings and structures, according to the test results, the influence of climatic conditions, compliance of contour structures, the presence of initial imperfections, local damage and failure of the most stressed elements, on the operation of the structure, ensuring the further operational safety;
- the assignment of the maximum levels of external and beyond design loads, seismic effects of various intensities is proposed, ensuring the operational safety of spatial systems of buildings and structures during high-intensity earthquakes.

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