Modeling of stage of construction and operation of unique large-span structures

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Abstract. The results of the study of long-span unique buildings and structures using spatial structures performed on full-scale models of structures subjected to prolonged static and dynamic effects are presented. According to the results of theoretical and experimental studies, the behavior of spatial systems of various geometric shapes under dynamic impacts of high intensity is revealed. The purpose of the maximum load level for seismic impacts of various intensities, the maintenance of spatial stiffeners, the inclusion of which contributes to the way out of the resonant state of the spatial system, is proposed.

1. Introduction

At present, the theory and practice of using large-span spatial structures in unique buildings and structures are receiving a high level of development [1-5]. In areas of Central Asia, the beginning of the construction of shells for coatings of public buildings dates back to deep antiquity [3,4]. Preservation of these ensembles today indicates the longevity and reliability of their use for the regions of high seismicity [3,4]. Meanwhile, intense seismic impacts limit the introduction of long-span unique buildings. To solve this problem, a nonlinear theory of the calculation of spatial systems was developed [3,6,7], methods for calculating shells, plates and bar structures taking into account the duration of operation [11,12], seismic effects [3,4,9,10] were developed, regional features of construction areas [9-10].

To increase the seismic resistance of structures, new effective structures have been developed - coating shells using spatial elements of stiffeners. Their use [4,9,10,16-20] favors the balancing of the reactive forces between the individual parts of the shell caused by resonant vibrations, and contributes to their exit from this state.

In connection with the development of the industrial base with the expansion of housing and industrial construction in regions with adverse climatic conditions and increased seismic activity, solving the problem of overlapping buildings and structures of large spans through the introduction of architecturally expressive forms of spatial structures ensure their efficiency and performance qualities at the same time, the development of the theory and methods of engineering calculation of spatial systems become extremely important. The present article is devoted to the solution of this problem. Taking into account the complexity of modeling the stages of construction and operation of unique large-span buildings and structures, the tasks of this problem were solved for long-term operated spatial systems according to the following methodology:
- changing of the structural properties of materials according to the criterion of ensuring operational safety under static and dynamic effects [3,9];
- the development of rational methods for the construction of structures creating favorable working conditions during the transition to an operational state [10,11];
- ensuring operational safety in adverse climatic conditions [11,12];
- ensuring operational safety, taking into account the type and level of loads, the flexibility of the contour diaphragms [13–15], changes in the dynamic parameters of structures over time [16–19];
- reducing the influence of accidental impacts from local damage and failure of some of the most stressed structural elements [3,16,20].

The complexity of creating the actual state of stress the systems under consideration, assessing the reliability of the calculation method, the validity of the accepted initial assumptions and taking into account the above-mentioned design features when solving the tasks of this problem, it was decided to synthesize a theory with an experiment based on experimental modeling methods [1-4,7-8], and the implementation of scientific and technical support in operating facilities.

2. Results and discussion

Assessment of the operation of long-running spatial structures under dynamic impacts

It is very difficult to model the true stress-strain state, which reflects the operational stage with the control of deflections and residual deformations [3,7,8]. In this regard, the models were subjected to long tests for 7 years, based on experimental methods.

It was established that the stress-strain state at the time of loading receives significantly developed as a result of the growth of long inelastic deformations, especially when temperature and humidity conditions are taken into account [9,12]. So, at the end of the observation, the limiting deflections of spatial structures of various geometric shapes from the moment of loading increased by 1.5 - 2 times, fiber deformations by 2.4 ... 2.75 times, the resulting cracks increased by 2 times. Residual deflections and fiber deformations were, respectively, 23-60% and 35-80%.

This led to a significant reduction in the rigidity of structures during long-term operation. To assess the state of structures taking into account the influence of climatic conditions, a resolving system of equations of shell deformation under nonlinear creep conditions was obtained, based on the theory of flexible shallow shells with large deflections:

\[ L_4(\dot{F}, D_i) + L_2(\dot{\omega}, D_i) + \dot{F}_{\beta\beta}(k_1 + \omega_{aa}) + \dot{F}_{aa}(k_2 + \omega_{\beta\beta}) + 2\dot{F}_{a\beta}^2 + \omega_{aa}\dot{\omega}_{a\beta} + F_{aa}\dot{\omega}_{\beta\beta} - 2F_{a\beta}\dot{\omega}_{a\beta} = L_4(\dot{F}, D_i(t)) - L_2(\omega^{A}, D_i(t)) \]

(1)

\[ = -L_3(\dot{F}, B_i(t)) - L_4(\omega^{A}, B_i(t)) \]

where \( L_4(\dot{F}, D_i(t)) - L_4(\omega^{A}, B_i(t)) \) – differential operators containing variable stiffness coefficients \( (D_i(t)), (B_i(t)) \), characterizing the properties of nonlinear creep of the reinforced body and derivatives with respect to the functions of forces \( \dot{F} \) and deflections \( \dot{\omega} \) along the; \( k_1, k_2 \) indice are the main curvatures of the shell. \( \beta \) and coordinates.

In the system (1), the dependences proposed by N.Kh. Arutuynyan are accepted as physical equations of the nonlinear creep of the material for spatial stress-strain state, multifactor parameters which are normalized in the designed recommendations developed by us. Their use allows us to evaluate and predict the stress-strain state of the shell in operational condition at any point in time. The functions of effort \( \dot{F}(\alpha, \beta, t) \) and deflection, \( \omega(\alpha, \beta, t) \) taken in combination (1), also make it possible to assess the influence of initial imperfections and deflections of spatial systems allowed in the stage of erection from the flexibility of contour diaphragms and the foundations of the structure [10,15,17].

The long stress-strain state of the shells during dynamic (seismic) tests was created by overload with control of the deflection at the loading stages using the previously established non-linear laws of load-
deflection deformation (Figure 1). The studies were carried out with strain measurements and recording dynamic parameters under free and forced vibrations with various combinations of high-intensity static and dynamic loads. Fluctuations of the structure were fixed in the direction of the three axes expected during earthquakes.

Forced vibrations in the vertical and horizontal directions were created by a vibrating machine with accelerations corresponding to 7.8 and 9 points of the calculated seismicity, with the construction brought to a resonant state [3,4,7,8]. The tests were carried out on models and full-scale spatial structures with spans of 4.8, 12, 18, 24, 30 and 36 m of freestanding and conjugated multi-wave conical domes with spans of 18, 30 and 42 m. The scale of the models is 1: 4-1: 10.

The results of the studies show that under strong seismic influences, with increasing the magnitude of external loads and the duration of the loads, the dynamic stiffness of the structure significantly decreases, which is expressed in experimental conditions by an increase in the period of the fundamental vibration tone.

According to studies, it is shown that although the deformations of spatial constructions from seismic effects are two-digit, they accumulate in one law in the same direction as deformations from static loading.

This eliminates the formation of double-digit plastic joints and damage of individual zones. Seismic effects, causing inertial loads, only accelerate the occurrence of a zone of damage and local damage, which lead to a coincidence of the forms of damage. To assess the state of the composite shell in the resonance zones, the forced vibrations of the shells were studied with a change in the frequency of the disturbing force from 3 to 40 Hz. In this interval of frequency changes at all stages of loading, two resonant states of the structure were observed.

**Figure 1.** Graphs of deflections changes the frequency of vertical vibrations of the shells depending on the level and duration of the load and the boundary conditions of restraint; 1, 3 - at short and long loading; 2, 4 - the same, recovery of deflections after unloading; d, e - for a restrained and free supported shell.
An analysis of the resonance curve slabs for composite shells and conical domes with vertical and horizontal forced vibrations showed a smooth decrease in the oscillation frequency with an increase in the value of static loads.

For composite shells, a characteristic feature is that after turning off the energy of the vibrator, the resonant vibrations of the shells quickly damped due to the overlap (resistance) of the vibrations of the side shells. This led to an increase in the dynamic stiffness of the structure, contributing to a way out from the resonance state of the entire spatial system.

At horizontal forced vibrations, one resonant state of the structure was revealed, corresponding to the frequencies of free vibrations. Moreover, the shell fluctuated as a hard single spatial disk. It also revealed two resonances of the structure in the vertical direction, similar to those previously obtained at vertical forced vibrations, but shifted relatively to the latter about a quarter of the period and slightly less than the amplitude of the vibrations.

As for the evaluation of the work of the shell in resonant states in the horizontal direction, special attention must be paid to it. Constructive measures should be taken to ensure rational inclusion of shell constituent elements in the operation of the entire system for the perception of horizontal seismic effects and the transfer of their reactions to the foundations of structures.

3. Evaluation of seismic resistance of spatial structures of various design solutions

Evaluation of the seismic resistance of the studied models and full-scale structures was carried out by creating a dynamic load of high intensity with bringing the construction to a resonant state. For models of composite shells with a 4.8 m span, loaded with a distributed load of $1.7 \ldots 6.5 \text{kN/m}^2$, identified in the first and second resonance, the acceleration from forced vibrations was $(0.373-0.09) \text{g}$ and $(1.04-0.447) \text{g}$. In the horizontal forced oscillations at a load of $6.5 \text{kN/m}^2$, only one resonance state was revealed, for which the acceleration was $0.351 \text{g}$.

A composite shell with a span of 12 m was tested in the operational stage at a load of $2.8 \text{kN/m}^2$. In the first and second resonances, the acceleration from the vertical forced oscillations was $0.08 \text{g}$ and $0.258 \text{g}$. From the horizontal forced oscillations, the acceleration in the resonant state was $0.03 \text{g}$.

In the tested models of the conical dome, two vertical resonance states were revealed. At a load of $2 \ldots 8 \text{kN/m}^2$, the acceleration in the first and second resonances was, respectively, $(0.054-0.012) \text{g}$ and $(1.03-0.349) \text{g}$. At forced horizontal oscillations from the load of $8 \text{kN/m}^2$, the acceleration in the resonant state was $0.349 \text{g}$.

An analysis of the results of experimental studies of composite shell models at high levels of seismic effects showed that taking into account the duration of operation, the development of cracks and the increase of deformations of contour structures over time (ductility) led to a decrease in the initial dynamic stiffness. The possibility of destruction of separate of the most stressed zones and connections from unprofitable combinations of operational and seismic loads was also observed.

Spatial structures in design standards are usually considered rigid and it is assumed that during earthquakes the entire building oscillates in one phase, i.e. is accepted

$$\lambda = CT_0 >> L$$

where $\lambda$ is the seismic wavelength; $C$ is the velocity of its propagation, $T_0$ is the period of ground vibration corresponding to the period of the fundamental tone of the building’s vibrations; $L$ - is the length of the building.

However, the results of studies [1, 2, 3] of models and full-scale spatial structures have shown that with an increase of the span (length) of spatial structures, especially erected on non-dense soils, for which the wave propagation velocity is low, it may turn out to be that $L = 2\lambda$, or $L = \lambda$.

In this case, the traveling wave effect leads to the movement of the base in various points shifted in time.

With the use of the results of experimental and theoretical studies, proposals have been developed to determine the magnitude of the seismic load, taking into account the possibility of the manifestation of symmetrical and skew-symmetric forms of support vibrations depending on the length of the shell in
plan, the length of the seismic waves and the duration of operation corresponding to \( i, j \) - the tone of natural vibrations:

\[
S_{ij}(\alpha, \beta) = q(\alpha, \beta)A\mu(\alpha, \beta)\beta_{ij}(l, \gamma, c)K_{\psi}\eta_{ij}(\alpha, \beta)
\]

(3)

where \( ij \) - the number of half-waves corresponding to the forms of vibrations, \( \mu(\alpha, \beta) \) is the distribution function of the portable movement over the coverage area; \( l \) – is the length of the building; \( \gamma \) – is the damping coefficient of the oscillations of the system; \( c \) – is the speed of propagation of a seismic wave in the soil; \( \eta_{ij}(\alpha, \beta) \) is the coefficient of the spatial form of shell vibrations;

To prevent brittle fracture of spatial structures that are in operational condition and subjected to seismic influences of various intensities, in order to control the fracture mechanism, criteria have been developed that limit the magnitude of the ultimate static and seismic load [3, 4, 8]:

\[
q = q_{l} + q_{s} \leq kq_{u}
\]

(4)

where \( q_{l} \) is the long operational load; \( q_{s} \) is the seismic component of the load, determined from expressions (3); \( q_{u} \) is the static breaking load, taking into account the operational state of the structure, determined by the solution of system (1).

The research results showed that for earthquakes with an intensity of 7, 8 and 9 points, the magnitude of the ultimate long-term static and seismic load, in accordance with expressions (4), can be taken, respectively:

\[
q = 0.7q_{u}; \quad q = 0.65q_{u}; \quad q = 0.6q_{u}
\]

Thus, the results of the carried out researches of long-loaded shell models by creating high-intensity dynamic loads showed that the seismic resistance of spatial structures to vertical effects can be ensured by the use of discretely located edges (grids) necessary to strengthen the shell field, as well as by limiting the size of one of the spans of the constituent elements. For the perception of horizontal seismic loads, the development of special design solutions is required.

4. Constructive solution of spatial structures of coatings for seismic areas

The increasing of seismic resistance of composite shells for large-span buildings was made by increasing spatial stiffness with the introduction of special spatial stiffening elements (Figure 2).
Spatial stiffener elements are made of a wavy or folded profile. They are provided from three or more sides of the shell, depending on the geometric shape in plan and the length of a span. These elements, perceiving the horizontal components of seismic effects, transmit them directly to the foundations of the structure.

The carried out numerical evaluations of the results of experimental researches showed the need to limit the minimum size of the span of one of the directions of the component of the shell element and take them no more than 36 m. The dimensions in the other direction are not limited and can be taken based on technological requirements and taking into account the regional characteristics of the construction areas.

5. Conclusions
Based on the conducted researches, modeling the staged construction and operation of unique large-span buildings and structures using spatial constructions, the following conclusions can be drawn:
- at the present stage, for the development of the construction of unique large-span buildings and structures with the use of spatial structures, the consideration of regional features, the use of experimental methods, modeling with the subsequent scientific and technical support of the facilities in operation is relevant;
- proposed to provide coatings with operational safety of structures, accounting for changes in time of the structural properties of materials and dynamic parameters of spatial systems;
- for long-loaded models and full-scale spatial structures according to the test results, the influence of climatic conditions, the flexibility of the contour structures and foundations, the change in initial imperfections, local damage and failure of the most stressed elements, ways of erecting the structure into operation, ensuring the further operational safety, were identified and evaluated;
- it is proposed to assign maximum levels of external loads for different intensities of seismic effects, the introduction of spatial stiffeners, the inclusion of which helps to exit the resonance state of the spatial systems of buildings and structures during an earthquake of high intensity.

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