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DYNAMIC CHARACTERISTICS OF SHELL STRUCTURES

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ABSTRACT

The algorithm of dynamic calculation of the coating shell is presented. The frequencies of natural oscillations for smooth, ribbed and prefabricated shell structures are determined. Using the spectral method, the values of horizontal and vertical seismic loads are found. The influence of the structural features of the shell structure on its dynamic characteristics and seismic load values is estimated. It should be noted that in some cases, the construction of facilities using shell structures requires special responsibility, high qualifications, the use of advanced methods of control and monitoring, modern achievements of science and technology, construction and operation experience.

Keywords: Shell, elasticity, structure, stiffeners, curvature fractures, reactive forces, frequency and period of natural oscillations, seismic load.

Introduction

Modern buildings and structures are complex in their architecture and design solutions. In the process of design and construction, many problems arise regarding the seismic resistance and reliability of buildings (1-8). Insufficient accuracy and reliability of the seismological forecast is fundamentally unavoidable in the near future, since the nature of seismic activity is extremely complex, not fully understood and insufficiently investigated, despite the undoubted and significant achievements of world and domestic seismology in recent decades. Therefore, in the future, not only earthquakes within the intensity predicted by the maps of General Seismic Zoning are possible, but also earthquakes of higher intensity, i.e. above the calculated seismic impacts on structures.

Let's consider some results of research on earthquake resistance of buildings and structures close to this topic. Basically, all of them are based on the maximum reduction of seismic impacts, taking into account the rigidity, multi-connectivity of the spatial constructive solution of a continuous spatial platform and structures and buildings of a closed type erected on it. The building together with the foundation is a "closed box" (1).

The design of earthquake-resistant buildings and structures is based on the following conditions: load-bearing structures of buildings and structures must have a reserve of seismic resistance sufficient for repeated perception of the calculated seismic load without significant damage; load-bearing structures of buildings and structures must have a reserve of seismic resistance sufficient for a single perception of the seismic load exceeding the calculated one point, without the collapse of the structure as a whole or its individual parts. One of the ways to ensure these conditions is to regulate the dynamic characteristics of the load-bearing structural elements, which contribute to reducing the vibrations of buildings and structures, and thereby increase reliability under seismic impacts of any intensity. In the future, in this work, a spectral method was used to study the seismic resistance of buildings and structures, which is based on the consideration of a model of a linear elastic system (2). As a result of this method, the oscillation of the system consists of the sum of oscillations in their own forms multiplied by resonant dynamic coefficients determined by the norms and rules developed for a given area and the provisions of the Eurocode RK. Regulation of these characteristics can reduce fluctuations and thereby increase the reliability of buildings and structures.

Methods

In contrast to the spectral theory, some field studies speak of the inconsistency of the spectral theory. The basis for such an assertion was that those who had to personally conduct full-scale tests of buildings and their foundations for seismic resistance by a resonant method using vibrating machines know how much attention and experience is needed to continuously reduce the excitation frequency following the continuously falling frequency of natural vibrations of the test object, i.e. it is almost impossible to achieve resonance (3). The earthquake itself is a chaotic movement of the earth's crust and the true reason for its destructive impact is that the seismic impact initiates destructive transverse waves running upwards in the foundation of the structure, the speed and shape of which depend on the nature of the seismic disturbance, physical and geometric characteristics of the structure.

In the authors considered a decomposition approach to modeling the seismic resistance of building structures (4). A number of problems of oscillation of flat rectangular elements under arbitrary boundary conditions along the edges of the element are considered in order to determine the frequencies of natural oscillations by decomposition method. The material of the element is considered as elastic, in the future an element made of viscoelastic material is considered. In the case of a flat element made of elastic material, the approximate equation of the transverse oscillation of the fourth order is written as:

$$\Delta^2 W - D_0 \frac{\partial^2}{\partial t^2} \Delta W + D_1 \frac{\partial^4 W}{\partial t^4} + D_2 \frac{\partial^2 W}{\partial t^2} = 0, \qquad (1)$$

Where the coefficients D0, D1, D2 are determined by the geometry and material properties of the flat element, W are the deflections of the rigid plate (5). The paper shows that for a pivotally fixed rectangular flat element, the decomposition method gives an exact solution to the problem in comparison with the result obtained by the direct method. Solutions of a number of problems are considered. The results of the study show that the approximate decomposition method makes it possible to find the frequencies of natural vibrations of the plate at given mechanical and geometric characteristics. Mechanical and geometric characteristics are the main elements of earthquake resistance of many building structures (6).

The author presented the development of methods of the wave theory of seismic resistance of building structures (7). The description of a wave pattern close to the real one at the earth's surface becomes an independent difficult task. The advance of a traveling seismic wave under the foundation can lead to rocking and torsional vibrations (three-dimensional rotations) of the structure. In this case, even at small rotation angles, there is a redistribution and an increase in internal forces in the structure, and at large angles the problem becomes geometrically nonlinear. To account for the wave motion under the foundation and to enter into the calculation of rotations, integral dilation-rotational and differentiated models of seismic motion of the soil are used.

Results and discussion

In the integral dilation-rotation model, the volume of soil under the foundation moves as a solid with three angular and three linear degrees of freedom. A differentiated model of seismic ground motion is given by a vector field of kinematic parameters defined at each point of the ground. Engineering analysis, taking into account wave effects, should provide for the selection of a suitable model of seismic motion and the determination of the calculated parameters of seismic impact. The rocking of the structure can lead to the separation of the foundation from the ground base, as a result of which the overall rigidity of the system will change, the centers of mass and stiffness will shift relative to each other, plastic areas with a reduced deformation modulus may appear in the ground base. Differential equations of motion of a system with partial disconnection of connections become nonlinear or with variable coefficients; complete loss of stability is possible. Waves approaching the foundation of the structure pass through it in the same way as on the ground. Various models of buildings and various models of their interactions with the soil base are considered.

In (4-8), the authors considered various models reflecting the three stages through which the structure passes in the process: A - the elastic stage for calculating the design earthquake (PZ). The design works elastically during the entire impact, internal forces do not exceed the limit. The physical and mechanical characteristics of the system are constant and the same as before the earthquake. The calculation is carried out by the linear spectral method. B stage - the elastic-plastic stage for calculating the maximum calculated earthquake (MRZ). Internal forces in some elements exceed the limit, they are subjected to plastic deformation, it is possible to turn off the connections (8). The physical and mechanical characteristics change from cycle to cycle, and the rigidity degrades over time. The impact is set in the form of extreme scenario accelerograms. The calculation is carried out by integrating nonlinear equations of motion in the time domain. C is the elastic stage of the carrier core for calculation on the MRZ. It is assumed that some of the peripheral elements are damaged or destroyed, but the main load-bearing elements have not reached the limit state and are deformed elastically. The physical and mechanical characteristics of the structure have been changed, but are constant over time; stiffness has been reduced, damping properties have increased. The symmetry of space-planning solutions may be broken, which will lead to bending-torsional vibrations. The calculation is carried out by the linear spectral method. The general criteria of seismic resistance are formulated: a structure is considered earthquake-resistant if its structure retains its load-bearing capacity under a given damage pattern (reaching a given limit state) during the calculated seismic impact. The seismic impact vector is the result of averaging the field of seismic displacements under the foundation of the building and generally consists of three translational and three rotational components. Assuming that the base of the structure moves as an absolutely solid body with six degrees of freedom, its motion is described by three-component vectors of translational and angular (rotational) displacements X0, α0, velocities X0, α0 and accelerations X0, α0 (9).

As a result of the analysis of the presented studies, it is possible to see a range of different directions for the development of the theory of earthquake-resistant construction, the reliability of buildings and structures. Basically, all directions are related to the study of the nature of an earthquake, the determination of seismic effects on buildings and structures, considering it as a wave process and the seismic response of a building to these impacts. Despite the existing norms and rules of earthquake-resistant construction, there are many questions about the accuracy of the presented coefficients and models. Another task is to take into account non-linearity. The problem of calculating nonlinear dynamical systems of large dimension is complex both mathematically and computationally, especially with respect to the dynamics of systems with structural changes. All this requires further development of the theory using new computational models, more advanced mathematical apparatus, the use of modern computer and construction technologies (10).

The aim of the study is to improve models and design schemes in order to preserve the bearing capacity of buildings and structures at possible maximum seismic loads.

The objective of this study is to assess the influence of the structural features of the shell structure on its dynamic characteristics and seismic load values.

A single shell structure in the elastic stage of work with various design features is considered: smooth, ribbed, possible curvature fractures for a prefabricated structure. The coating shell itself is considered as a system with a uniformly distributed mass. The influence of dynamic characteristics on seismic loads is investigated. Dynamic characteristics are determined using variationalmethods, seismic loads are determined by the spectral method.

To determine the spectrum of natural vibrations of a flat reinforced concrete shell, the technical theory of flat shells was used, the following equations were used as initial equations (9-12):

$$\Delta_{\kappa}^{2}\varphi + D\Delta^{2}\Delta^{2}w\text{-}(F_3 + \frac{\partial m_x}{\partial x} + \frac{\partial m_y}{\partial y}) = 0,$$

$$\frac{1}{Eh}\Delta^{2}\Delta^{2}\varphi - \Delta^{2}{}_{k}w = 0,$$

$$\Delta_{k}^{2} = \frac{\partial}{\partial x}(\kappa_2 \frac{\partial}{\partial x}) + \frac{\partial}{\partial y}(\kappa_1 \frac{\partial}{\partial y}), \qquad (1)$$

Where (x,y,t) is the stress function– - normal displacements– -cylindrical stiffness, E is the elastic modulus of the shell, - the thickness of the shell, - the main curvatures, mx ,my - external linear moments (11).

The dynamic problem of shell theory can be reduced to the corresponding static one if inertia forces are added to the values of the external load components in the static equations (F=-ma, where m is the mass of the entire system). In the future, we consider the shell together with the stiffeners and contour elements as a single system, the mass of which is summed up from the masses of its individual elements. Since the stiffness of the shell in the direction of the median surface is much higher than the stiffness in the direction of the normal to it, the tangential components of the inertial forces are assumed to be zero. Taking into account the interaction of the shell with the ribs , when considering free transverse vibrations, the external load can be represented as:

$$F_1 = F_2 = 0,$$

$$\tilde{F}_3 = F_3 + \sum_{i=1}^{m} q_i + \sum_{j=1}^{n} q_j, \qquad (2)$$

where F1, F2 are the tangential components of the inertial forces, F3 is the normal component of the inertial forces– is the total normal component of the external load, m, n is the number of edges, respectively, along the i-th and j-th directions, qi, qj are the reactive forces replacing the action of the edges that are applied along the contact line with the shell. Thenormalcomponentofinertialforceshastheform:

$$\tilde{F}_3 = -\frac{1}{g}\left[\gamma h^0 + \sum_{j=1}^{\kappa}\gamma_j h_j \delta(x - a_j) + \sum_{i=1}^{t}\gamma_i h_i \delta(y - b_i)\right]\frac{\partial^2 w}{\partial t^2}$$

(3)

In (3) g - acceleration of a free-falling body /9.81 m/sec2/– - specific gravity of the shell material– - specific gravity of the rib material, hi, hj – height of the rib cross-section, h0 - thickness of the shell,

$$\delta(x - a_j) = \begin{cases} 0, x \neq a_j \\ 1, x = a_j \end{cases}$$

$$\delta(x - b_i) = \begin{cases} 0, y \neq b_i \\ 1, y = b_i \end{cases}$$

–Dirac function.

The expression for F3 also takes into account the masses of contour elements and side elements along the interface line of adjacent shells (11).

When considering longitudinal vibrations, expressions for inertial forces in the longitudinal direction are written by analogy, where the displacement function is denoted by u(x,y,t) in the direction of the x axis or v(x,y,t) in the direction of the axis. The most dangerous is the transverse direction of the building, which has a lower stiffness value than in the longitudinal direction.

Considering the contact problem, we represent the shell structure as a single system consisting of various elements interacting with each other. The action of the ribs is replaced by an equivalent system of reactive moments and normal forces applied to the median surface of the shell along the contact line. The elastic resistance of the ribs to bending, stretching (compression) and twisting is taken into account.

The action of the contour elements is replaced by a system of reactive moments and forces (shifting and normal) applied along the contact line of the shell with the contour element. The elastic resistance of the contour element to bending in two directions, shear, stretching and torsion is taken into account.

The action of the columns is replaced by reactive forces representing concentrated vertical and tangential forces. The elastic resistance of the columns to compression caused by the vertical displacement of the supports due to the malleability of the soil base and the weight of the overlap, as well as bending caused by the longitudinal displacement of the supports, is taken into account. The local action of these loads is expressed in terms of δ-functions. The vertical forces are combined with the normal load acting on the surface of the coating shell and the weight of the overlap. Since the shell itself has great rigidity in the longitudinal direction, it can be considered in the first approximation as a single-mass cantilever system (12).

The solution of equations (1) is obtained using the variational method. For various connections of the shell with contour elements, a characteristic equation is obtained with respect to the values of the natural frequencies and the corresponding oscillation forms of the shell. These equations are a system of homogeneous algebraic equations with respect to the amplitude values of displacements, revealing its determinant, we obtain an algebraic equation with respect to unknown values of natural frequencies of oscillations. The natural frequencies and the corresponding oscillation periods depend on the physical and geometric characteristics, design features and rigidity of the internal and external connections of the building or structure. The influence of torsion deformation of the reference contour, the influence of ribs, fractures of the curvature of the surface and connections of elements of the shell structure on the dynamic characteristics is investigated.

Using the spectral method, seismic horizontal and vertical loads are determined and compared with various structural features of the shell.A shell structure consisting of a coating shell, contour elements and columns rigidly connected to the base is considered. The flat shell, square in plan 24x24m, has the following characteristics: γ = 2500 kg / m3 - specific gravity of the shell material; E= 26x108 kg/ m2; a= b = 24 m; μ= 0.2 - Poisson's ratio; R1 = R2 =23.4 m - radius of curvature; h=0.03 m – thickness (13).

The shell is reinforced with cross ribs of trapezoidal cross-section with the following characteristics: Ix=0.000791m4 - moment of inertia of the rib section; F=0.0462 m2 - the area of the rib section; n= -0.115m - the eccentricity of the center of gravity of the section; yp= 2500 kg/m3 - the specific weight of the rib material; Sx= F.n= -0.00531 m3 - the static moment of the rib section.

The columns are reinforced concrete with dimensions of 40x40 cm in increments of 6 m.

Two types of connection of the coating shell with connecting elements are considered: hinged and rigid. Table 1 shows the values of the natural frequencies of the shell 24x24 m in plan for a hinge joint with contour elements.

Table 1. Values of natural frequencies (Hz)

Number of fractures along the axis	Number of fractures along the axis	Number of edges along the axis	Number of edges along the axis	The number of half-waves in the x-axis direction				Number of half-waves in the direction of the y axis			
x	y	x	y	1	2	3	4	1	2	3	4
Smoothshell											
0	0	0	0	30,9	30,9	30,9	31,0	31,0	31,0	31,0	31,0
Ribbedshell											
0	0	0	1	30,0				30,2			
0	0	0	2	29,2	29,2			29,5	29,6		
0	0	0	3	28.3	28,4	28,5		28,8	29.0	29,2	
0	0	0	4	27,6	27,7	27,8	27,8	28,2	28,5	28,6	28,8
0	0	0	5	27,0	27,1	27,1	27,2	27,7	28,0	28,1	28,3
0	0	0	6	26,0	26,5	26,5	26,6	27,5	27,7	27,9	28,0
0	0	1	1	29,2							
0	0	2	4	26,4	26,5	27,0	28,3	26,9	27,3	28,0	29,0
Shellwithcurvaturefractures											
0	2	0	0	33,6	26,8			40,0	33,7		
0	2	0	2	31,3	25,0			38,0	32,8		
0	2	3	0	30,0	24,9			36,0	31,2		
0	2	3	1	29,0	24,2			35,0	30,0		
0	2	3	2	28,4	23,6			35,1	30,7		
0	2	3	3	27,7	23,0	24,0		34,6	30,5	30,3	41,0
0	2	3	3	27,7	23,0	24,0		34,6	30,5	30,3	41,0
0	2	4	0	29,2	24,4			35,2	30,6		

Table 1 shows that the presence of massive stiffeners slightly reduces the values of the natural frequencies of vibrations, and with an increase in the number of half-waves, the values of the natural frequencies increase by about 3-6%. The most significant influence on the values of natural frequencies is played by curvature fractures. The presence of curvature fractures for a composite shell in comparison with a smooth one increases the values of natural frequencies by almost 8-30%. With a rigid connection to the stiffness diaphragms, the values of natural frequencies increase by 7-10%. Taking into account the torsion resistance of the ribs reduces the values of natural frequencies by 10-15% (14). Table 2 shows the maximum values of the oscillation periods. Tables 1-2 show that low frequencies do not always correspond to the first tone of vibrations, sometimes they correspond to the 2nd tone of vibrations.

Table 2. Maximum values of oscillation periods (sec)

Number of fractures along the axis	Number of fractures along the axis	Number of edges along the axis	Number of edges along the axis	Number of half-waves	
x	y	x	y	1	2
Smoothshell					
0	0	0	0	0,2	
Ribbedshell					
0	0	0	2	0,21	
0	0	0	4	0,22	
0	0	0	5	0.23	
0	0	0	6	0.24	
Shellwithcurvaturefractures					
0	2	0	0		0.23
2	2	0	0	0,3	
0	2	0	2		0.25
0	2	3	1		0.26
0	2	3	2		0.27

Tables 3-4 show the values of periods and natural frequencies for major earthquakes in Bukhara and Gazli, which caused significant damage to buildings.

Table 3. Maximum displacements, velocities, accelerations with free mfluctuations (Bukhara)

Period (sec)	Frequency (Hz)	Displacement (m)	Time	Speeds	Time	Acceleration	Time	Absolute acceleration	Time
0,20	31,40	-2,600	2,764	86,407	2,612	2619	2,764	2567	2,764
0,22	28,50	0,584	3,379	-14,857	3,442	-384	3,379	-475	3,379
0,24	26,16	1,455	2,580	37,352	2,643	959	2,580	996	2,580
0,26	24,15	1,142	3,411	-25,720	3,472	-596	3,400	-666	3,400
0,28	22,42	0,641	3,411	-12,800	3,472	-274	1,187	-322	3,400

Table 4. Maximum displacements, velocities, accelerations with free mass fluctuations (Gazli)

Period (sec)	Frequency (Hz)	Displacement (m)	Time	Speeds	Time	Acceleration	Time	Absolute acceleration	Time
0,20	31,40	-0,046	1,958	-1,455	1,084	72,90	1,110	46,40	1,960
0,22	28,50	-0,094	1,616	02,566	1,570	94,78	1,623	76,65	1,616
0,24	26,16	-0,073	1,675	-1,710	1,728	71,49	1,912	50,00	1,675
0,26	24,15	-0,076	1,958	-1,674	1,899	-62,80	1,840	44,40	1,958
0,28	22,42	-0,081	1,478	-!.938	1,945	-86,40	1,880	40,97	1,478

Tables 3-5 show that frequencies and periods close to our results can cause significant seismic loads and displacements.

Determinationofseismicloads

We use the simplest console model. The values of seismic loads are determined according to the norms and rules of earthquake-resistant construction, reflected in the Eurocodes of the Republic of Kazakhstan. To determine the horizontal and vertical calculated seismic loads by the Fik spectral method, we use the following formula:

$$F_{ik} = \gamma_{Ih} \cdot S_d(T_i) \cdot m_{ik},$$

where F_ik is the seismic load on the building or structure in the considered horizontal direction for the i-th form of its own vibrations applied to the point k; γ_Ih is the coefficient that takes into account the responsibility of the building or structure in determining horizontal seismic loads; S_d (T_i) is the value of the spectrum of calculated reactions in accelerations on the period Ti,); Ti is the period of vibrations of the building or structure in the i-th form in the considered horizontal direction; m_ik is the effective modal mass assigned to the point k, corresponding to the i-th form of oscillations, determined by the expression:

$$\boldsymbol{m_{ik} = m_k \cdot \eta_{ik}}$$

Table 5 shows the values of horizontal and vertical seismic loads corresponding to the obtained maximum values of natural oscillation periods.

Table 5. Values of seismic loads Kn

Number of fractures along the axis	Number of fractures along the axis	Number of edges along the axis	Number of edges along the axis	Seismic load values in 2 directions button	
x	y	x	y	horizontal	vertical
Smoothshell					
0	0	0	0	106,5	85,7
Ribbedshell					
0	0	0	2	104	82,13
0	0	0	4	102	
0	0	0	5	98,5	
0	0	0	6	94,4	78,5
Shellwithcurvaturefractures					
0	2	0	0		78,5
2	2	0	0	90,8	
0	2	0	2		75,3
0	2	3	1		73,8
0	2	3	2		72,4

Conclusion

Summarizing the data obtained, the following conclusions can be drawn:

1. To reduce the seismic load and enhance the reliability of buildings and structures, it is possible to adjust the dynamic characteristics of the structure under study using its design features, internal connections and methods of construction.

2. The seismic load for a ribbed shell in comparison with a smooth one can be reduced by up to 10% using the resistance of the stiffeners to compression, bending and torsion.

3. The use of a prefabricated shell with minor changes in the angle of inclination of tangents at the boundary of adjacent plates reduces seismic loads by up to 12 percent or more.

4. Regulation of the rigidity of the shell connections with contour elements and changes in the stiffness of individual load-bearing elements of the shell structure leads to a decrease in seismic load and a decrease in oscillation amplitudes, thereby increasing the bearing capacity of buildings and structures under seismic influences.

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