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PLATE MODEL APPLICATION TO TASKS ABOUT LONGITUDINAL OSCILLATIONS OF MULTI-STOREY BUILDINGS AND STRUCTURES

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Abstract. The article is devoted to the development of a continual spatial plate model of a multi-story building, developed in the framework of the bimoment theory of thick plates. A technique for dynamic spatial calculation for the seismic resistance of buildings under longitudinal seismic impacts is proposed. Formulas are given for determining the reduced moduli of elasticity. Numerical results of eigenfrequencies and displacements are obtained.

Keywords: Multi-story building, plate model, seismic load, equations of motion, displacement, stress, force, moment, bimoment, grid method.

1. Introduction

Buildings are complex objects of study in a structural mechanics course. Today, there are no universal methods for dynamic calculation of deformation-stress state for them, due to the large number of elements and the complex structure of such structures as high-rise large buildings. The theory of seismic resistance of buildings and structures is developing as one of the current areas of structural mechanics. There are numerous studies devoted to the development of the theory of seismic resistance. Various methods have been developed for calculating buildings and structures for seismic impacts, taking into account important factors of seismic load, soil conditions of the area and design features of building structures. Note that the analysis of the consequences of many strong earthquakes has shown the shortcomings of existing methods for calculating buildings and structures for seismic resistance.

In [1], a method was developed for calculating the dynamic coefficient taking into account elastoplastic deformations of the reinforcement of a reinforced concrete structure. Examples of building calculations taking into account the destruction of columns are considered

The main issues of determining the parameters of reinforcement of reinforced concrete structures during their control are considered. The main ways to solve these problems are analyzed. The most reliable and accurate methods for determining the parameters of reinforcement are shown. In [2], [3], the dynamic characteristics and vibrations of various axisymmetric and flat structures are considered, taking into account various geometries, spatial factors and inelastic properties of materials.

Work [4] considers the analytical calculation of brickwork for a barrel-shaped vault, the material structure of which has a pronounced variability of elastic constants.

Article [5] presents a technology for the production of building ceramics based on anorthite using semi-dry powder pressing based on sintering of a raw material mixture consisting of low-melting clay and blast furnace sludge (BFS) in various proportions.

Article [6] examines the foundations of buildings and structures made of weakly viscoelastic soils and the features of the theoretical justification of their deformations. The need for this study is due to the discrepancy between the theory of filtration compaction and field and laboratory experiments.

Article [7-11] is devoted to the dynamic calculation of box-shaped building structures for seismic resistance, taking into account the spatial work of box-shaped elements under the influence of

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dynamic influence. A mathematical model and a numerical-analytical method for solving the problem of dynamics using the finite difference method and expanding the solution according to the modes of natural vibrations in the spatial formulation of elements of box-shaped structures under kinematic influence have been developed. Forced vibrations of box-shaped structures under harmonic influences applied to the base of the structure have been studied. The areas where the highest values of shearing forces and bending moments occur under harmonic influences are determined.

Article [12] is devoted to solving the problem of transverse vibrations of a multi-story building within the framework of a spatial model of multi-story buildings under seismic influence using an explicit scheme of the finite difference method. As a dynamic model of a multi-story building, a continuum model in the form of an orthotropic plate is proposed, the theory of which was developed within the framework of the three-dimensional theory of elasticity and takes into account not only traditional forces and moments, but also bi-moments [12].

This paper proposes a spatial continuum plate dynamic model, methods and programs for calculating multi-storey buildings for seismic resistance. Recommendations have been developed for the application of the bi-moment theory of flexural and longitudinal vibrations of plate building models[14-15].

A multi-story building is modeled as a continuous thick plate. Seismic vibrations of a building are modeled by the movement of a thick anisotropic cantilever plate, the deformation of which is described on the basis of the bi-moment theory of thick plates. This model is considered as the most suitable model of a multi-story building, suitable for dynamic spatial calculations of the seismic resistance of buildings under seismic impacts.

Determination of the reduced density and modulus of elasticity of the plate model according to the method [12] The reduced density of the building is determined by the following formula:

$$m_{\text{reduced}} = \rho_{\text{density}} V_1 = \rho_{\text{reduced}} V_0 . \quad (1)$$

Here V_1– volume of slabs forming one floor of a building. V_0– volume of one floor of a building. Then, to calculate these volumes, we obtain the following formulas:

$$V_0 = ab_1H,\ V_1 = 2ab_1h_1 + ab_1h_2 + 2Hb_1h_1 + \\ +(n-2)Hb_1h_2 + aHh_{overlap}, \quad (2)$$

Here a, H – building length and width; b_1 – one floor height of the building; n– number of interior walls of the building; h_1 - outer wall thickness; h_2 – interior wall thickness; $h_{overlap}$ – floor thickness.

In reduced, the elastic characteristics $E_1^{reduced}$, $E_2^{reduced}$, $E_3^{reduced}$, $G_1^{reduced}$, $G_2^{reduced}$, $G_3^{reduced}$, and densities $\rho_{reduced}$ of the spatial continuum model of a building are determined by the following formulas [1-4]:

$$E_1^{\text{reduced}} = \zeta_{11}E_0, E_2^{\text{reduced}} = \zeta_{22}E_0, E_3^{\text{reduced}} = \zeta_{33}E_0,$$
$$G_{12}^{\text{reduced}} = \zeta_{12}G_0, G_{13}^{\text{reduced}} = \zeta_{13}G_0, G_{23}^{\text{reduced}} = \zeta_{23}G_0,$$
$$\rho_{\text{reduced}} = \rho_0\varsigma_0. \quad (3)$$

Note that coefficient values $\xi_{11}, \xi_{22}, \xi_{33}, \xi_{12}, \xi_{13}, \xi_{23}, \zeta_0$ for each cell (room) of the discrete part of the building are defined as functions of two spatial variables, E_0, G_0– elastic and shear modulus of the strongest cell support panel of the discrete part of the building.

Write down formulas for determining coefficients $\xi_{11}, \xi_{22}, \xi_{33}, \xi_{12}, \xi_{13}, \xi_{23}, \zeta_0$ given moduli of elasticity of a discrete part of the building in the form [1-4]:

$$\xi_{11} = \alpha\frac{S_{11}}{S_{01}},\quad \xi_{22} = \alpha\frac{S_{22}}{S_{02}},$$
$$\xi_{33} = \alpha\frac{S_{33}}{S_{03}},\ \xi_{12} = \alpha\frac{S_{12}}{S_{01}},$$
$$\xi_{13} = \alpha\frac{h_{nep}}{b_1}\lambda^*,\quad \xi_{23} = \alpha\frac{h_2}{a_1},\quad \zeta_0 = \frac{V_1}{V_0}. \quad (5)$$

Here S_{01}, S_{02}, S_{03} – area of cross-sections of the building in three coordinate planes of one floor of the building; S_{11}, S_{22}, S_{33} – total area of the cross sections of the plates in the coordinate planes forming one floor of the building; λ^* – coefficient characterizing the hollow cross-section of the slab. Coefficient α is determined according to the cellular structure of the building structure.

Note that the above volumes and areas are determined depending on the size of the plates, rooms and the building itself, as follows:

$$S_{01} = E_0b_1H, S_{02} = E_0aH, S_{03} = E_0ab_1, \quad (6)$$
$$S_{11} = b_1h_2E_b^{(2)} + Hh_{\text{overlap}}E_{\text{overlap}}, S_{12} = b_1h_2E_b^{(2)},$$
$$S_{22} = ah_2E_b^{(2)} + (k-2)Hh_2E_b^{(2)},$$
$$S_{33} = ah_2E_b^{(2)} + (k-2)b_1h_2E_b^{(2)}. \quad (7)$$

Here $G_{\text{пер}}$– building slab displacement module; G_2– interior wall shear module; $E_b^{(2)}$– interior wall elastic module; $E_{reduced}$– floor elastic module.

Now let's define the given modules of elasticity and shear of external walls, taking into account window openings, using the method given in [5] as approximate formulas:

$$E_1^{reduced} = E_1\left(1-\frac{\eta}{\eta_0}\right), E_2^{reduced} = E_2\left(1-\frac{\eta}{\eta_0}\right),$$
$$G_{12}^{reduced} = G_{12}\left(1-\frac{\eta}{\eta_0}\right), G_{13}^{reduced} = G_{13}\left(1-\frac{\eta}{\eta_0}\right). \quad (8)$$

Here E_1, E_1, G_{12}, G_{13}– external wall flexibility and shear modules, η, η_0- constant coefficients.

Thus, we have obtained formulas for representing the values of the reduced elasticity module of the plate model of the building.

Coefficient values ξ_{11}, ξ_{22}, ξ_{33}, ξ_{12}, ξ_{13}, ξ_{23}, ζ_0 for each cell (room) of the building are defined as functions of two spatial variables, E_0, G_0 – elastic and shear modulus of the strongest load-bearing panel of the building.

Formulas (1) – (8) determine the reduced elastic moduli of the discrete part of the plate model of the building. According to these formulas, the reduced elastic moduli are 8–30 times less than the elastic modulus of the panels, and the reduced density of the plate model of a discrete part of the building is 7–20 times less than the density of the panel material. This discrepancy between the modules is explained by the presence of a large number of voids and the cellular structure of the building.

2. Problem formulation.

Now let's consider the asymmetric problem of the bimomental theory. Movement of dots plate model of multi-storey building is considered in Cartesian coordinate system x_1, x_2 and z. The origin of the coordinates is located in the lower left corner of the median surface of the continuum plate model of a multi-storey building. Direct the *Ox1* and *Ox2* axes along the length and height, and the *Oz* axis along the thickness (building width) of the plate model.

The problem of longitudinal vibrations of a multi-storey bi-moment theory of plate structures consists of two equations regarding longitudinal and tangential forces and four additionally constructed bi-moment equations regarding nine unknown kinematic functions [12]:

$$\tilde{u}_k = \frac{u_k^{(+)} - u_k^{(-)}}{2}, \tilde{\psi}_k = \frac{1}{2h^2}\int_{-h}^{h} u_k z\, dz,$$
$$\tilde{\beta}_k = \frac{1}{2h^4}\int_{-h}^{h} u_k z^3\, dz, (k=1,2),$$
$$\widetilde{W} = \frac{u_3^{(+)} + u_3^{(-)}}{2}, \tilde{r} = \frac{1}{2h}\int_{-h}^{h} u_3\, dz,$$
$$\tilde{\gamma} = \frac{1}{2h^3}\int_{-h}^{h} u_3 z^2\, dz. \quad (9)$$

Forces N_{11}, N_{12}, N_{22} from stresses $\sigma_{11}, \sigma_{12}, \sigma_{22}$ are determined by the expressions:

$$N_{11} = E_{11}H\frac{\partial\overline{\psi}_1}{\partial x_1} + E_{12}H\frac{\partial\overline{\psi}_2}{\partial x_2} + 2E_{13}\overline{W},$$
$$N_{22} = E_{12}H\frac{\partial\overline{\psi}_1}{\partial x_1} + E_{22}H\frac{\partial\overline{\psi}_2}{\partial x_2} + 2E_{23}\overline{W},$$
$$N_{12} = N_{21} = G_{12}\left(H\frac{\partial\overline{\psi}_2}{\partial x_1} + H\frac{\partial\overline{\psi}_2}{\partial x_1}\right). \quad (10)$$

Bi-moments generated by longitudinal vibrations of a plate model of a building, T_{11}, T_{22}, T_{12} from stresses $\sigma_{11}, \sigma_{12}, \sigma_{22}$ are defined as:

$$T_{11} = H\left(E_{11}\frac{\partial\overline{\beta}_1}{\partial x_1} + E_{12}\frac{\partial\overline{\beta}_2}{\partial x_2} + E_{13}\frac{2\overline{W}-4\overline{r}}{H}\right),$$
$$T_{12} = T_{21} = HG_{12}\left(\frac{\partial\overline{\beta}_2}{\partial x_1} + \frac{\partial\overline{\beta}_1}{\partial x_2}\right),$$
$$T_{22} = H\left(E_{12}\frac{\partial\overline{\beta}_1}{\partial x_1} + E_{22}\frac{\partial\overline{\beta}_2}{\partial x_2} + E_{23}\frac{2\overline{W}-4\overline{r}}{H}\right). \quad (11)$$

The intensities of transverse bi-moments generated during longitudinal vibrations of the plate model of the building, $\overline{p}_{13}$, $\overline{p}_{23}$ and $\overline{\tau}_{13}$, $\overline{\tau}_{23}$ from tangential stresses σ_{13}, σ_{23}, are constructed in the form of the following expressions:

$$\overline{p}_{k3} = G_{k3}\left(\frac{\partial\overline{r}}{\partial x_k} + \frac{2(\overline{u}_k - \overline{\psi}_k)}{H}\right),$$
$$\overline{\tau}_{k3} = G_{k3}\left(\frac{\partial\overline{\gamma}}{\partial x_k} + \frac{2(\overline{u}_k - 3\overline{\beta}_k)}{H}\right), \quad (k=1,2). \quad (12)$$

For the intensity of bi-moments 1 and 2 from normal voltage we have the following equations:

$$\overline{p}_{33} = E_{31}\frac{\partial\overline{\psi}_1}{\partial x_1} + E_{32}\frac{\partial\overline{\psi}_2}{\partial x_2} + E_{33}\frac{2\overline{W}}{H},$$
$$\overline{\tau}_{33} = E_{31}\frac{\partial\overline{\beta}_1}{\partial x_1} + E_{32}\frac{\partial\overline{\beta}_2}{\partial x_2} + E_{33}\frac{2\overline{W}-4\overline{r}}{H}. \quad (13)$$

The system of equations of motion of a plate model of a building relative to longitudinal and tangential forces generated by longitudinal vibrations of a plate model of a building is constructed in the form:

$$\frac{\partial N_{11}}{\partial x_1}+\frac{\partial N_{12}}{\partial x_2}=\rho H\ddot{\overline{\psi}}_1$$
$$\frac{\partial N_{21}}{\partial x_1}+\frac{\partial N_{22}}{\partial x_2}=\rho H\ddot{\overline{\psi}}_2 \quad (14)$$

It should be noted that the system of two equations (14) contains three unknown functions $\overline{\psi}_1,\ \overline{\psi}_2,\ \overline{W}$

To determine the longitudinal and tangential bi-moments generated by longitudinal vibrations of the plate model of the building, two equations of motion were also constructed in the form:

$$\frac{\partial T_{11}}{\partial x_1}+\frac{\partial T_{12}}{\partial x_2}-4\overline{p}_{13}=\rho H\ddot{\overline{\beta}}_1,$$
$$\frac{\partial T_{12}}{\partial x_1}+\frac{\partial T_{22}}{\partial x_2}-4\overline{p}_{23}=\rho H\ddot{\overline{\beta}}_2. \quad (15)$$

Two more equations of motion of plates relative to the intensity of transverse bi-moments, which are absent in the traditional theory of plates, were constructed in the following form:

$$\frac{\partial\overline{p}_{13}}{\partial x_1}+\frac{\partial\overline{p}_{23}}{\partial x_2}-\frac{2\overline{p}_{33}}{H}=\rho\ddot{\overline{r}},$$
$$\frac{\partial\overline{\tau}_{13}}{\partial x_1}+\frac{\partial\overline{\tau}_{23}}{\partial x_2}-\frac{6\overline{\tau}_{33}}{H}=\rho\ddot{\overline{\gamma}}\ , \quad (16)$$

Three missing kinematic equations of motion of a plate model during longitudinal vibrations of a multi-story building, which determine generalized displacements, $\overline{u}_1,\ \overline{u}_2,\ \overline{W}$ which will be rewritten in the following form:

$$\overline{u}_k=\frac{1}{4}\left(21\overline{\beta}_k-3\overline{\psi}_k\right)-\frac{1}{20}H\frac{\partial\overline{W}}{\partial x_k},\quad (k=1,2), \quad (17)$$

$$\overline{W}=\frac{1}{2}\left(21\overline{\gamma}-7\overline{r}\right)-\frac{1}{30}H\left(\frac{E_{31}}{E_{33}}\frac{\partial\overline{u}_1}{\partial x_1}+\frac{E_{32}}{E_{33}}\frac{\partial\overline{u}_2}{\partial x_2}\right). \quad (18)$$

Let us write down the boundary conditions for the considered problem of oscillations of multi-story buildings. When describing the boundary conditions for the equations of longitudinal vibrations of buildings (16) - (17), we introduce the intensities of bi-moments [12] $\overline{\sigma}_{11},\ \overline{\sigma}_{22},\ \overline{\sigma}_{12},\ \overline{\sigma}^*_{11},\ \overline{\sigma}^*_{22}$, which are determined by the following formulas:

$$\overline{\sigma}_{11}=\left(E_{11}-\frac{E_{13}}{E_{33}}E_{31}\right)\frac{\partial\overline{u}_1}{\partial x_1}+\left(E_{12}-\frac{E_{13}}{E_{33}}E_{32}\right)\frac{\partial\overline{u}_2}{\partial x_2},$$
$$\overline{\sigma}_{22}=\left(E_{21}-\frac{E_{23}}{E_{33}}E_{31}\right)\frac{\partial\overline{u}_1}{\partial x_1}+\left(E_{22}-\frac{E_{23}}{E_{33}}E_{32}\right)\frac{\partial\overline{u}_2}{\partial x_2},$$
$$\overline{\sigma}_{12}=G_{12}\left(\frac{\partial\overline{u}_1}{\partial x_2}+\frac{\partial\overline{u}_2}{\partial x_1}\right). \quad (19)$$

Based on Hooke's law and expressions (19), we obtain the following expressions for bi-moments: $\overline{\sigma}^*_{11},\ \overline{\sigma}^*_{22}$

$$\overline{\sigma}^*_{11}=-E_{11}H\frac{\partial^2\overline{W}}{\partial x_1^2}-E_{12}H\frac{\partial^2\overline{W}}{\partial x_2^2}+$$
$$+E_{13}\frac{60\left(7\overline{W}+42\overline{r}-105\overline{\gamma}\right)}{H},$$
$$\overline{\sigma}^*_{22}=-E_{12}H\frac{\partial^2\overline{W}}{\partial x_1^2}-E_{22}H\frac{\partial^2\overline{W}}{\partial x_2^2}+$$
$$+E_{23}\frac{60\left(7\overline{W}+42\overline{r}-105\overline{\gamma}\right)}{H}. \quad (20)$$

At the base of the plate model of a multi-story building, the boundary conditions for flexural-shear vibrations have the form:

$$\overline{\psi}_1=u_0(t),\ \overline{\psi}_2=0,\ \overline{\beta}_1=\frac{1}{3}u_0(t),\ \overline{\beta}_2=0,$$
$$\overline{u}_1=\frac{1}{3},\ \overline{u}_2=0,\ \overline{r}=0,\ \overline{\gamma}=0,\ \overline{W}=0. \quad (21)$$

where $u_0(t)$ -is the law of motion of the base.

On the free side faces of the building we have the conditions for forces, moments and bi-moments and force factors to be zero:

$$N_{11}=0,\quad N_{12}=0,\quad T_{11}=0,$$
$$T_{12}=0,\quad \overline{p}_{13}=0,\quad \overline{\tau}_{13}=0,$$
$$\overline{\sigma}_{11}=0;\quad \overline{\sigma}_{12}=0\ \ \overline{\sigma}^*_{13}=0. \quad (22)$$

On the free upper face of the building we have the following conditions:

$$N_{12}=0,\ \ N_{22}=0,\ \ T_{12}=0,\ \ T_{22}=0,$$
$$\overline{p}_{23}=0,\ \ \overline{\tau}_{23}=0,\quad \overline{\sigma}_{12}=0;\ \ \overline{\sigma}_{22}=0\ \ \overline{\sigma}^*_{23}=0. \quad (23)$$

It is assumed that the seismic movement of the soil occurs in the direction of the OZ axis (the width or thickness of the building). Based on

considerations, the external seismic impact is given as the acceleration of the base $\ddot{u}_0(t)$ in the form:

$$\ddot{u}_0(t) = a_0 \cos(\omega_0 t), \qquad (24)$$

where $a_0 = k_c g$ and $\omega_0 = 2\pi\nu_0$ - respectively, the maximum acceleration and circular frequency of the soil base, k_c and ν_0 коэффициент балльности землетрясения и собственная частота внешнего воздействия.

Из выражения ускорения определяются выражения перемещения основания здания в виде:

$$u_0(t) = \frac{A_0}{2}(1 - \cos(\omega_0 t)). \qquad (25)$$

where A_0 – amplitude of movement of the base.

Amplitude of external influence A_0 depends on the magnitude of the earthquake, which is determined from the condition $A_0\omega_0^2 = 2k_c g$, where k_c, g - seismicity coefficient and free fall acceleration.

Solution method.

To solve the problem numerically, the finite difference method was chosen. To approximate the derivatives of displacements along spatial coordinates, we will use the formulas of central difference schemes. In this case $\Delta x_1 = \frac{a}{N}$, $\Delta x_2 = \frac{b}{M}$ – the calculation step, N, M – the number of divisions, Δt – the time step. We select the calculation steps based on spatial coordinates and time as follows:

$$\Delta x_1 = \frac{a}{N},\ \Delta x_2 = \frac{b}{M},\quad c\Delta t \le \min(\Delta x_1, \Delta x_2)$$

where $c = \sqrt{E/\rho}$.

Analysis of numerical results.

Calculations were performed for nine-, twelve-story buildings under seven-, eight- and nine-magnitude earthquakes, which are specified through the corresponding seismicity coefficients k_c. In this case, internal and external walls, floors and coverings are considered to consist of reinforced concrete.

For a magnitude 7 earthquake $k_c = 0.1;\ \nu_0 = 2.7\,Hz$. Then the amplitude of the external influence will be equal to $A_0 = \frac{2k_c g}{\omega_0^2} = \frac{2 \cdot 0.1 \cdot 9.8}{16.95^2} = 0.68\,sm \cdot$

For a magnitude 8 earthquake $k_c = 0.2;\ \nu_0 = 2.4\,Hz$. Then the amplitude of the external influence will be equal to $A_0 = \frac{2k_c g}{\omega_0^2} = \frac{2 \cdot 0.2 \cdot 9.8}{15.07^2} = 1.74\,sm \cdot$

For a magnitude 9 earthquake $k_c = 0.4;\ \nu_0 = 2\,Hz$. Then the amplitude of the external influence will be equal to $A_0 = \frac{2k_c g}{\omega_0^2} = \frac{2 \cdot 0.4 \cdot 9.8}{12.56^2} = 4{,}97\,sm \cdot$

The mechanical and geometric characteristics of the materials of the room panels and the external dimensions of the buildings must be specified as initial data. To obtain numerical results, the following initial data were used for the structures of the considered plate model of a multi-story building.

We assume that the external walls consist of reinforced concrete with an elastic modulus $E = 20000$ Mpa density $\rho = 2500$ kg/m^3, Puasson's ratio. $\nu = 0.3$. We consider the internal walls to consist of expanded clay concrete with the following physical characteristics: modulus of elasticity $E = 7500$ MPa density $\rho = 2500$ kg/m^3, Puasson's ratio. $\nu = 0.3$. Let us introduce the following notation for the plate model of a multi-story building: b_1 – the height of one floor of the building; k – the number of internal transverse walls of the building; h_1 – thickness of external load-bearing walls; h_2 – thickness of internal walls; $h_{overlap}$ – floor thickness.

The results of calculations of forced vibrations of a building within the framework of a thick plate model are presented for the following sizes of building slabs:

$h_1 = 0.40\,m,\ h_2 = 0.25\,m,\ h_{\text{overlap}} = 0.2\,m,\ a_1 = 5\,m,\ b_1 = 3\,m,$

The height and length of a multi-story building are assumed to be equal, respectively $\mathrm{b} = \mathrm{nb}_1$ and $\mathrm{a} = 30\,\mathrm{m}$, and the width of the building H varies.

Then the calculated coefficients ξ_0, ξ_{11}, ξ_{22}, ξ_{33}, ξ_{12}, ξ_{13}, ξ_{23} according to the corresponding formulas are equal:

$\xi_{11} = 0.11,\ \xi_{22} = 0.137, \xi_{33} = 0.09,\ \xi_{12} = 0.077,$

$\xi_{13} = 0.067,\ \xi_{23} = 0.04,\ \xi_0 = 0.142$

The given elastic characteristics of the building are determined by the following formulas:

$$E_1^{red} = \xi_{11}E_0,\quad E_2^{red} = \xi_{22}E_0,\quad E_3^{red} = \xi_{33}E_0,$$
$$G_{12}^{red} = \xi_{12}G_0,\quad G_{13}^{red} = \xi_{13}G_0,\ G_{23}^{red} = \xi_{23}G_0.$$

Modulus of elasticity and density of concrete. Then, according to the formulas, the given characteristics of the building turned out to be equal.

$$E_1^{reduced} = 1323.08\ MPa,\quad E_2^{red} = 1643.08\ MPa,$$
$$E_3^{red} = 1120.00\ MPa,$$
$$G_{12}^{red} = 369{,}23\ MPa,\quad G_{13}^{red} = 320.00\ MPa,$$
$$G_{23}^{red} = 192{,}00\ MPa,\ \rho_{red} = 351.02\ kg/m^3.$$

The length for nine-story, twelve-story and sixteen-story buildings is assumed to be the same, equal to $a = 30\ m$.

Let us present the numerical results of stresses obtained during transverse vibrations of a 9-story building during a magnitude 9 earthquake. Calculations were performed at the following values: frequency of external influence $\nu_0 = 2.8$ Hz period of the fundamental tone of oscillations - $T_0 = 1/\nu_0 = 0.36$ s.

Calculation results for a 9-story building. Calculations were performed at the following values: frequency of external influence $\nu_0 = 2.8$ Hz period of the fundamental tone of oscillations - $T_0 = 1/\nu_0 = 0.36$ s. Amplitude of external influence A_0 determined for a nine-story building during an eight-magnitude earthquake $(k_c = 0.2)$ equal to $A_0 = 0.0174$ m.

Figure 1 shows graphs of changes in the values of horizontal longitudinal displacement $\bar{u}_1$ at the highest point of a nine-story building from time τ.

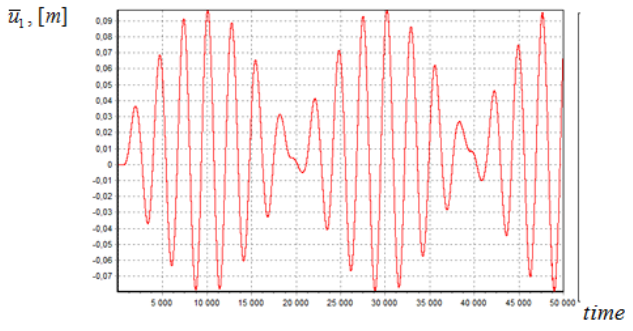


Figure 1. Graphs of changes in longitudinal displacement over time in the middle upper level of a nine-story building

It has been established that the dynamic behavior of a nine-story building is close to a beating state, since the values of its natural frequency are close to the value of the frequency of the external influence.

From the graph (Figure 1) it is clear that in the middle of a nine-story building the maximum longitudinal displacement is equal to $\bar{u}_1 = 9\ sm$.

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Using the resonance method, the values of the natural frequency of longitudinal vibrations of a nine-story building were calculated depending on two values of the building width $H = 11$ m and $H = 13$ m, which are equal p_1=8.917 Hz and p_1=8.608 Hz, for and the period of the fundamental tone of oscillations $T_1=1/p_1$=0.112 s and $T_1=1/p_1$=0.116 s

Calculation results for a 12-story building. Calculations were performed at the following values: frequency of external influence $\nu_0 = 2.8$ Hz period of the fundamental tone of oscillations - $T_0 = 1/\nu_0 = 0.36$ s. Amplitude of external influence A_0 determined for a nine-story building during an eight-magnitude earthquake $(k_c = 0.2)$ equal to $A_0 = 0.0174$ m.

Figure 2 shows graphs of changes in the values of longitudinal horizontal displacements u1 at the edges of a twelve-story building versus time t.

From the graph (Figure 2) it is clear that in the middle of a twelve-story building the maximum longitudinal displacement is equal to $\bar{u}_1 = 12\ sm$.

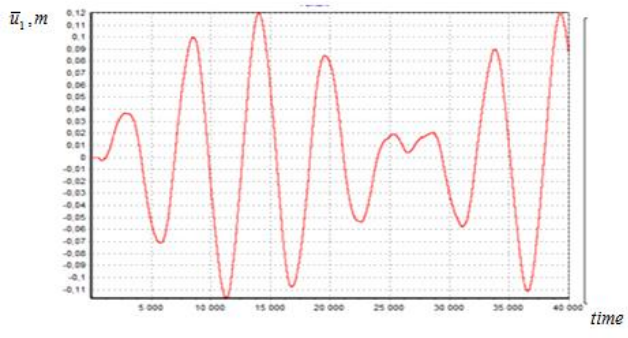


Figure 2. Graph of changes in displacement u1 over time in the middle of a twelve-story building

Own constructions of multi-storey buildings. Calculations were performed for nine-, twelve- and sixteen-story buildings under seven-, eight- and nine-magnitude earthquakes, which are specified through the corresponding seismicity

№	Number of floors	*H*, metr	p_1, Hz	T_1, second
1	9	11	8,917	0,112
2	12	11	4,863	0,205
		13	5,178	0,193
3	16	13	3,086	0,323

coefficients ks. In this case, internal and external walls, floors and coverings are considered to consist of reinforced concrete.

Let us present the results of calculations of the natural frequency, periods of oscillation and movement of points for nine- and twelve-story buildings, near the resonant mode. The dynamic characteristics of a multi-story building during longitudinal vibrations are also determined by the resonance method. The frequency values of the external influence, starting from a certain small value, gradually increase and for each frequency value the displacements and stresses are determined. With an increase in the frequency of external influence, a state of beating is observed in the oscillatory process of the building. As the value of the dimensionless frequency of external influence approaches. ω_0 dimensionless natural frequency p_1 values of displacements, forces and moments increase sharply, which indicates a gradual transition to the resonant mode.

Table 1 shows the values of natural frequencies p_1 and periods of natural vibrations T_1 of longitudinal vibrations of nine- and twelve-story buildings, depending on the value of the width of the building H.

Values of proper frequency of longitudinal oscillations of a nine-storey building at the value of the width of the building $H = 11\ m$ was equal p_0=3.4 Hz. The base tone period of the proper oscillations will be T0=1/p0=0.294 s. (Table 1).

The values of the proper frequency of longitudinal oscillations of the twelve-storey building have been calculated depending on the two values of the width of the building $H = 11$ m and $H = 13$ m which are p1=4.863 Hz and p1=5.178 Hz for, and the base tone period is T1=1/p1=0.205 s and T1=1/p1=0.193 c (table 1).

Values of proper frequency of longitudinal oscillations of sixteen-story building depending on two values of width of the building were found $H = 13$ m are equal to p1=3.086 Hz, and the base tone period is T1=1/p1=0.323 (Table 1).

Table 1 - Custom frequencies ν_1 and p_1 and periods of self fluctuation T_1 nine-, twelve-, sixteen-story buildings, depending on the width of the building H

In conclusion, note that the plate model of the building correctly reflects the form of vibration of the building at seismic impacts. In the calculations, the number of steps dividing the differential schemes by dimensionless coordinates is assumed as follows: for nine-story $N = 30,\ M = 30$ twelve-storey $N = 30,\ M = 42$. Stability of calculation by dimensionless time is ensured by an explicit scheme at a step $\Delta\tau = 0.01$.

Conclusions.

1. A spatial continuum plate model of longitudinal vibrations of multi-story buildings is proposed, developed within the framework of the bimoment theory of thick plates. Formulas are given for determining the elastic characteristics of a plate model of multi-story buildings, taking into account design features.

2. A methodology, algorithm and program for the numerical calculation of displacements of a multi-story building within the framework of a plate model using an explicit finite difference method scheme have been developed.

3. Numerical results were obtained for the maximum values of displacements at the upper level of nine and twelve storey buildings, for which the first frequencies and periods of natural oscillations were determined. The laws of changes in displacement over time have been established in the form of graphs in the state of beating and resonant mode.

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