Dynamic calculation of boxed design of buildings

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Abstract. A method for dynamic calculation of a box-like structure, consisting of interconnected longitudinal and transverse plate and beam elements is developed. The problem is posed of spatial vibrations of the box-like structure of a building under dynamic impact determined by its base motion according to a sinusoidal law. It is assumed that the external load-bearing walls of the building, perpendicular to the direction of the seismic effect, work on transverse bending only. The interior panels, located in the direction of external impact, are subjected to tension-compression and shear in their planes. Equations of vibrations of the points of panels, box beams, boundary and initial conditions of the problem are given. In the areas of butt joints of panels, full contact conditions are set to ensure the equality of displacements and stresses. Within the framework of the finite difference method, a methodology was developed for dynamic calculation of box-like structures. Numerical results of stresses over time in the hazardous areas of the box were obtained. The laws of changes in the maximum stress values in characteristic sections of the panels are graphically presented as a function of time.

1. Introduction
The theory of beams, plates, and shells has been widely used in the field of the dynamics of structures in the calculation of structural elements of buildings and structures.

In studies [1, 2], the problems of parametric resonance were solved for forced vibrations of structural elements made of isotropic material under the action of a uniformly distributed dynamic load.

In [3, 4], using the dynamic model, the problems of forced vibrations of the box-like structure of a building were solved taking into account the conditions of continuity of movements and stresses in the contact zones of the beam and plate elements. Using the finite difference method, numerical results of stresses and displacements in the hazardous areas of the box-shaped building are obtained.

The studies in [5, 6] are devoted to the numerical solution of the problem of oscillations of the plate model of buildings and structures under seismic impacts using the finite difference method. Solutions to the problem of transverse and longitudinal vibrations of buildings and structures were obtained using the model developed in the framework of the bimoment theory of plates [7].

The study in [8] is devoted to the calculation of oriented wood-particle boards of structures under vertical load from the snow. The aim of the study is to identify the causes of non-uniform deflections at the joints of the wood-particle boards in the structures of sloping roofs and vertical walls. Recommendations are given to address these causes.
In [9] the external impact of varying intensity and frequency on buildings was examined. The forces in structural elements exceeding the permissible values were given. It should be noted that the dynamic problems of earthquake resistance of underground and ground hydro-technical structures interacting with a soil base, taking into account the real rheological factors of the materials of structural elements of structures and soil foundation, remain relevant and difficult tasks of structural mechanics and theory of structures. The authors of [10–13] proposed methods for solving the dynamic problems of the dynamics of soils and earth structures, as well as under-ground structures interacting with soil.

A multilayer base model was developed in [14], using the initial function method and solving the spatial problem of the elasticity theory of an isotropic layer compression under normal load. The studies in [15–17] are devoted to the experimental study of elastic-plastic behavior of structural materials elements under complex loading. In [15], reliability regions of plasticity theories are shown for some variants of complex loading. In [16, 17], it was revealed that in calculations with the appearance of plastic strains, the law of external force application and the anisotropic properties of the structural material should be taken into account.

The problem of protection against the influence of seismic waves of a building or group of buildings was studied in [18, 19] using a seismic barrier. Various types of seismic barriers available to protect structures were listed, depending on the nature of seismic waves. In [20], the dynamic problem of building structures vibration under the influence of a harmonic load was considered. It was found that displacements and internal forces in the nodes of structural elements depend on various parameters of harmonic influence.

A method for dynamic calculation of one box (room) of buildings, called the box-like structure, consisting of an interconnected plate and beam elements has been developed in the paper.

2. Methods

Buildings in their geometrical structure are close to the box-shaped systems consisting of interconnected panels and beam elements, subjected to compression, transverse shear and bending under oscillations. Each element of the box model and the entire model as a whole is an object of study of the mechanics of a deformable rigid body, structural mechanics, and several other disciplines. The problem is formulated on the basis of a box-like structure of buildings with a fixed lower end (Fig.1).

Introduce the following notation for the panels of the spatial box-like structure of a building: $E_i, \nu_i, \rho_i$ are the elastic modulus, Poisson's ratio, and density of i-wall, respectively.
A theoretical calculation of the box structure of large-panel buildings on dynamic effects in the form of (1) was carried out in the paper taking into account the spatial work of internal transverse and external longitudinal walls

\[ U_0 = A_0 \sin \omega_0 t, \quad V_0 = 0 \]  

(1)

Where: \( A_0 \) and \( \omega_0 \) are the amplitude and frequency of the forced oscillations.

Suppose that the bearing walls of a building (panels 1,3) are located perpendicular to the direction of seismic impact and work only on transverse dynamic bending (Fig. 1). Panels 2 and 4 located parallel to the direction of external impact are subjected only to shear in the \( OXZ \) plane. Based on this assumption, bending force factors disappear in the area of the butt joints of panels 4, 2, and beams. Only longitudinal contact forces remain (Fig. 2).

**Figure 2. Spatial Box-type Cell of a building**

Overlapping is also considered deformable. The law of motion of its points is determined following the forms of strains of the upper edges of vertically contacted panels. Box panels are supported by elastic beams. Therefore, the movements of panel edges are not equal to zero, but to the beam deflection; the angle of rotation of the panel edge is equal to the angle of beam twist. The bending of a beam is caused by the shear force of the edge of the bending panel attached to it (panel 1 or 3) and the longitudinal force of the edge of the other attached beam (panel 2 or 4).

An analytical-numerical method is proposed for solving the vibration problem of a building box taking into account spatial strains. In the areas of butt joints of panels, full contact conditions are set to ensure the equality of displacements and stresses.

The general kinematic law of a box motion is represented as the sum of the base displacement \( U_0(t) \) and the relative displacements of the panels \( u(x, z, t) \), \( v(x, z, t) \):

\[ u_1 = U_0(t) + u(x, z, t), \quad u_2 = v(x, z, t) \]  

(2)

Here \( u, v \) are the displacements of shear panels.

The law of normal displacements of the points of bent panels are taken in the form:

\[ u_3 = U_0(t) + W(x, y, t) \]  

(3)

where \( W(x, y, t) \) is the deflection of flexible panels.

When constructing the equation of motion, the panels are considered as thin elastic plates obeying the Kirchhoff-Love hypothesis, and each beam is subjected to bending and torsion.

As the equation of motion of the bending panel \([3, 4]\), taking into account (3), can be written in the form
The equation of the bending and torsional oscillations of the beams can b
\[
E J \frac{\partial^4 W}{\partial x^4} + \rho F \frac{\partial \ddot{W}}{\partial t} = R_y^{(b)} - P_{(b)} - \rho F \ddot{U}_0.
\]

where \( R_y^{(b)} \) and \( P_{(b)} \) are the values of the reactive shear force, bending panel and longitudinal
force of the panel working on shear in the area of the butt connection of panels and beam, \( W^{(b)}(x,t) \) is
the deflection of the beam, \( \alpha = \left( \frac{\partial W}{\partial x} \right)_{x=a} \) is the beam twist angle, \( M_{kr} = E I_{kr} \frac{\partial \alpha}{\partial x} \) is torque, \( E I_{kr} \) is
the beam torsional rigidity, \( E J \) is the beam flexural rigidity.

The equation of motion of the floor slab is derived based on the following considerations. For
simplicity, we assume that the floor displacement field is determined by the law:
\[
\begin{align*}
\{u_n(y,t)\} &= W(H, y, t) \\
\{v_n(y,t)\} &= \nu(H, t)
\end{align*}
\]

Where: \( u_n(y,t) \) and \( v_n(y,t) \) are the horizontal and vertical displacements of floor slab points;
\( W(H, y, t) \) and \( \nu(H, t) \) are the deflection and displacement of the upper points of panels working on
bending and shear.

Write the equations of motion of the overlap according to representation (8).

The contact conditions at the joints of the floor and the bending wall have the form
\[
-R^b_x + \eta_0 \rho_n h_n h_n \ddot{W}_n = \dot{h}_n h_n \frac{\partial \tau_{zy}^b}{\partial y} - \eta_0 \rho_n h_n h_n \ddot{U}_0.
\]

Where: \( \tau_{zy}^b = \zeta \frac{\partial W}{\partial y} \), \( \eta_0 = \frac{bc}{2(bh_b + ch_c)} \) is the ratio of the floor slab area in the plan to the cross-
sectional areas of the walls working on bending and shear, \( \rho_n \) is the floor slab density, \( h_n, h_b, h_c \) are the
thickness of the floor slab and bending and shear panels, \( b \) and \( c \) are the box length and width.

In the areas of butt joints of panels and beam elements, full contact conditions regarding kinematic
and force factors are accepted.
Now consider the contact conditions between the elements of the box and the boundary conditions at the base and in the upper part of the building. At the junction of panels and beams, we have contact kinematic conditions.

\[ W(x,0,t) = U(x,c,t) = W^{(b)}(x,t), \quad V(x,c,t) = \pm H_1 \frac{\partial W^{(b)}}{\partial x}. \]  

(10)

Where: \( W(x,0,t) \) is the displacement of the bendable panel, \( u(x,c,t) \) is the displacement of the side panel, \( W^{(b)}(x,t) \) is the displacement of beams, \( V(x,c,t) \) is the vertical displacement of the tank panel. The minus sign is taken when the beam is connected to the panels with concave sides.

Note that the equations of motion (6) and (7) are taken as the contact force conditions in the butt joints of panels and beams.

The mass of the floor slab and the portion of the mass of the floor slab on the walls are written as follows:

\[ M_0 = \rho_b bc h_n, \quad m_{nb} = \eta_b \rho_b bh_p h_n, \quad m_{nc} = \eta_b \rho_b bh_p h_n, \]

where: \( M_0 \) is the mass of the floor slab, \( m_{nb} \) and \( m_{nc} \) are the portion of the mass of floor slab on the walls, working on bending and shear.

Based on the accepted assumption that the floor is not deformable, the boundary conditions on the upper part of the box are written in the form of kinematic and force conditions

\[ W = u_p(y,t), \quad U = W^{(b)} = u_p(b,t), \quad V = \partial_p(b,t), \quad M_{xx} = 0, \quad M_0 = 0, \]

(11)

where: \( M_0 \) is the mass of the floor slab, \( H \) is the thickness of shear panels, \( \tau_{xc} \) and \( R_x \) are the shear stress and reactive force of panels working on shear and bend, \( u_p(t) \) is the horizontal displacement of the rigid floor.

The boundary conditions at the base of the building are similar to the rigid fixing. The lower part of the building moves with the base;

\[ W = U = W^{(b)} = u_0(t), \quad V = 0, \]

and the rotation angle is absent

\[ \frac{\partial W}{\partial x} = 0, \quad \frac{\partial W^{(b)}}{\partial x} = 0. \]

(13)

The contact conditions at the joints of the floor and wall working on shear relative to contact shear stress are written as

\[ h_n \tau_{xy} + h_c \tau_{zx} - \rho h_n h_n h_{n_k} = \rho h_n h_0. \]

(14)

The contact conditions at the joints of the floor and the shear wall relative to the contact normal stress are written as

\[ \sigma_{xx} - \rho h_n \dot{h}_n x_k = \rho h_n \dot{V}_0(t). \]

(15)

Where \( \tau_{zx} = G_c \frac{\partial \varphi}{\partial z} \bigg|_{z=x}, \quad \sigma_{xx} = E_n \frac{\partial \varphi}{\partial z} \bigg|_{z=x}. \)

The modes of oscillations (2) and (3) must satisfy the equations of motion (4-7), boundary, and contact conditions (9-15). The problem is solved by the method of finite-difference schemes.

The solution to the problem of forced vibrations of the spatial box of a building, consisting of interacting beams and rectangular panels under dynamic influences, we obtain the method of separation of coordinates.

The deflection of the flexible panels, which satisfies the equation (3), following the law of movement of the soil (1), we will present in the form:

\[ W = W(x,y) \sin(\omega t), \]

and the displacement of panels working in shear, which satisfies the law of movement of the soil (1), we write in the form:
The deflection and the twist angle of the beams (6) and (7), following the law of movement of the soil (1), we will present in the form:

\[ u = u(x, z)\sin(\alpha t), \quad \nu = \nu(x, z)\sin(\alpha t). \]  

(17)

Substituting solutions (16), (17) and (18) into equations (4), (5), (6) and (7), we obtain partial differential equations for spatial coordinates, which are solved by the numerical method of finite differences.

3. Results and Discussion

The following parameters are set as initial data. The ratio of the height to the width of the bending panel is \( H/b = 3.25/6 \), the ratio of the height to the width of the panel working on shear is \( H/c = 3.25/4 \). The ratio of the thickness to the width of the bending panel is \( h_b/b = 0.5/6 \), and the ratio of the thickness of the bending panel to the thickness of the shear panel is \( h_c/h_b = 0.25/0.5 \).

The ratio of the elastic moduli of bending and shear panels is \( \frac{E_1}{E_2} = \frac{3}{8} \). Poisson's ratio of panel materials is \( \nu = 0.3 \).

Proceed to discuss the obtained numerical results of the stress calculation taking into account the initial conditions.

Graphs of the change in the time between normal and shear stresses in shear panels are shown in Figure 3 and Figure 4.
Figure 4. Graphs of shear stress variation at the midpoint of the left edge of shear panels

In Figure 5 the law of change in normal stress in a bending panel is shown.

Figure 5. Graph of normal stress change at the top of the right edge of the panel, working on bending

Note that the values calculated on each vertical section $\tau_{zx}$ are the contact stresses between the panels and the beams.

4. Conclusions
1. The equations of motion of the points of the panels and beams of the box of buildings, the boundary, contact, and initial conditions of the problem of forced vibrations are presented.
2. Graphically presents the laws of variation of the maximum voltage values in the characteristic sections of the panels depending on time
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