Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 624.042

DOI: 10.34910/MCE.114.6

Forced vibrations of a box element of a multi-story building under dynamic impact

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Keywords: buildings, box- like structure, dynamic calculation, displacement, stress, deformation, equation of motion, boundary conditions, contact conditions.

Abstract. The article is devoted to the dynamic calculations of the elements of the box-shaped structure of buildings for seismic resistance, taking into account the spatial work of the elements of the box under the action of dynamic influences set by the movement of their lower part according to the sinusoidal law. The equations of motion are given for each of the plate and beam elements of the box-shaped structure of the building on the basis of the Kirchhoff-Love theory. Expressions are given for the forces, moments and stresses of the plate elements that equalize the movement of the box elements, and the boundary conditions, as well as the conditions for full contact in terms of displacements and force factors in the contact zones of plate and beam elements. The general solution of the problem is constructed by the method of decomposition of the movement of the elements of the box according to their own forms using the method of finite differences. The calculation results were obtained in the form of diagrams over the height of the box of bending moments, plate elements working in bending, as well as shear stresses of plate elements.

Citation: Usarov, M.K., Mamatisaev, G.I., Ayubov, G.T. Forced vibrations of a box element of a multi-story building under dynamic impact. Magazine of Civil Engineering. 2022. 114(6). Article No. 11406. DOI: 10.34910/MCE.114.6

1. Introduction.

The theory of beams, slabs and shells is widely used in the field of structural dynamics when calculating structural elements of buildings and structures. In [1-4], the spatial vibrations of a structure made of rod elements interacting with the surrounding soil under seismic influences are considered.

In [5], the problem of protecting a building or a group of buildings using a seismic barrier from seismic waves is considered. Various types of seismic barriers are available depending on the nature of the seismic waves.

In [6,7], the dynamic characteristics and vibrations of elements of various designs are considered, taking into account the dissipative properties of materials.

In calculations on earthquake resistance of underground and aboveground structures, an important role is played by consideration of physically nonlinear properties of the structure elements material and the soil base and the structure-soil interaction. Such studies include the works of the authors [8–10], who investigated the elastic-plastic behavior of structural materials under complex loading conditions, the studies in [11-14] devoted to the determination of elastic-plastic law of state of soils and soil structures.

In works [15-18], the problems of forced vibrations of boxes of a large-panel building and cells of frame buildings were solved, taking into account the interaction of their elements, and also a spatial box with a pinched lower end is considered as a design scheme. On the basis of the finite difference method, the numerical results of the stress and displacement in the box elements are obtained.

In a scientific study [19], oriented particle board (OSB) is considered as an element of a pitched roof structure with a soft roof, under the action of a vertical load from snow. The reasons for uneven deflections in OSB joints in the structures of inclined roofs and vertical walls are revealed, and recommendations for eliminating these reasons are justified.

The article [20] considers the impact of earthquakes of various intensity and frequency character on the seismic resistance of a wooden building. A computational and theoretical assessment of the frame building was carried out on simple and complex models under the influence of different intensities and frequency composition. It has been established that the frequency composition of the seismic effect significantly affects the seismic resistance of frame buildings.

The article [21] proposes methods for solving dynamic problems of the dynamics of soils and earth structures, as well as underground structures interacting with the soil.

Using the method of initial functions (ISF), a multilayer basic model was developed and the spatial problem of the theory of elasticity of compression of an isotropic layer by a normal load uniformly distributed over a bounded region of the boundary was solved [22].

In [23], the influence of displacements, fractures of the axes of wall panels during their installation on the operation of a large-panel structure is considered. A comparative analysis of design schemes, taking into account different types of installation errors, has been carried out. In the process of calculating structures, taking into account the installation error of parts, efforts were obtained in the structural elements that exceeded the permissible values prescribed in the regulatory documentation.

In [24], a multi-storey reinforced concrete frame-braced frame with prestressed girders is considered, subject to emergency impact in the form of a sudden removal of a column of the outermost row on the first floor of the building. Using the finite element method, a nonlinear quasi-static analysis of deformation and failure was carried out under the structure in the form of a two-storey two-span frame, separated from the building frame by the decomposition method.

In [25], the analysis of the process of changing the initial geometric parameters of the elements of the design scheme in the erection mode with various methods of installation of structures is carried out. Proposals are presented for performing a computational analysis within a computational experiment for a situation of structural degradation associated with various reasons (wear, corrosion, micro- and macro-destruction under load, etc.).

The purpose and task of the study is the dynamic calculation of elements of a box-shaped structure of buildings for seismic resistance, taking into account the spatial work of the elements of a box under the action of dynamic influences set by the movement of their lower part. according to the sinusoidal law.

2. Methods

This article deals with the problem of forced vibrations of elements of a spatial box-shaped structure of buildings, consisting of rectangular plate and beam elements, as shown in Fig. 1. It is believed that the bottom of the box is firmly pressed against the base.

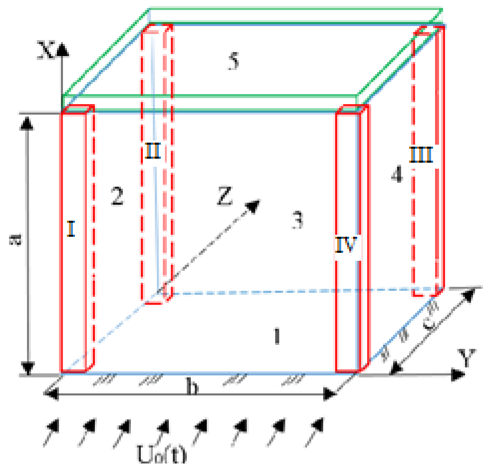

Figure. 1. Building space box [15, 16].

The dynamic problem of oscillation of the building box is considered, the base of which oscillates according to the law:

$$U_0 = A_0 \sin \omega_0 t , \tag{1}$$

where A_0 and ω_0 are amplitude, and frequency of forced oscillations.

Assume that the load-bearing walls of the building (plate elements 1. and 3.) are located perpendicular to the direction of seismic action and work only for lateral dynamic bending. The deflection function of the plate elements are denoted by $W(x,y,t)$. Parallel plate elements 2. and 4. in the direction of the external impact are subjected only to shear in the OXZ plane. The functions for moving plate elements, working on shear, are denoted $u(x,z,t)$, $\upsilon(x,z,t)$.

The overlap (plate elements 5.) is also considered deformable. The law of motion of its points is determined in accordance with the deformation forms of the upper edges of the vertical contacting plate elements.

Let us introduce the following designations for the plate elements of the spatial box-shaped structure of the building: E_b, ρ_b, h_b and v_b are the modulus of elasticity, density, width, thickness and Poisson's ratio of bent plate elements, E_c, ρ_c, h_c and v_c are the modulus of elasticity, density, width, thickness and Poisson's ratio of panels working in shear. E_n, ρ_n, h_n and v_n are modulus of elasticity, density, thickness and Poisson's ratio of the slab, G_n is slab shear modulus $G_n = \dfrac{E_n}{2(1+v_n)}$. Box height (dimensions of all plate elements and beams are the same) is *a*. The cross-sections of all the beam elements of the space box have a rectangular cross-section with the sizes h_b, h_c of the same material, with the same moduli of elasticity E and shear G, and Poisson's ratio v and density ρ. J and I_{kr} are moments of inertia of the beam section during bending and torsion.

Plate elements of the frame are rigidly connected to the beam elements, therefore, the beam elements are subjected to bending and torsion. The deflection functions and torsion angles of the beams are denoted $W^{(i)}(x,t)$ and $\alpha^{(i)}(x,t)$, where: *i*- I, II, III, IV (number of beams).

Let us introduce the forces and moments arising in the elements of the box and their butt joints.

The expressions for the bending and torque moments of the bending panels M_{xx}, M_{yy} and M_{xy} will be introduced by the formulas:

$$M_{xx} = -D\left(\frac{\partial^2 W}{\partial x^2} + \nu_b \frac{\partial^2 W}{\partial y^2}\right), \; M_{yy} = -D\left(\nu_b \frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2}\right),$$
$$M_{xy} = -D\frac{(1-\nu_b)}{2}\frac{\partial^2 W}{\partial x \partial y}, \tag{2}$$

where: $D = \dfrac{E_b h_b^3}{12(1-{v_b}^2)}$ is cylindrical stiffness in transverse bending.

The expressions for the longitudinal and tangential forces of the plate elements working in shear can be represented as:

$$P_z = B\left(\frac{\partial U}{\partial z} + \nu_c \frac{\partial V}{\partial x}\right), \; P_x = B\left(\frac{\partial V}{\partial x} + \nu_c \frac{\partial U}{\partial z}\right),$$
$$P_{zx} = B\frac{1-\nu_c}{2}\left(\frac{\partial V}{\partial z} + \frac{\partial U}{\partial x}\right), \tag{3}$$

where $B = \dfrac{E_c h_c}{1-v_c^2}$ is the cylindrical stiffness of the panels in tension and compression.

Write the bending and torque moments of the beams in the form:

$$M^{(i)} = -EJ\frac{\partial^2 W^{(i)}}{\partial x^2},\ M_{kr}^{(i)} = EI_{kr}\frac{\partial \alpha^{(i)}}{\partial x}, \quad (4)$$

where EI_{kr} is the torsional stiffness of the beam, EJ is the bending stiffness of the beam.

Write the expressions for bending moment and the reactive shear forces, the bending plate elements and the longitudinal force of the panel in the zone of joint between plate and beam elements as follows:

$$\begin{aligned}
&M_{yy}^{b} = \left(M_{yy}\right)_{y=b} = -D\left[\nu_b\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2}\right]_{y=b}, \\
&R_y^b = \left(R_y\right)_{y=b} = -D\frac{\partial}{\partial y}\left[\frac{\partial^2 W}{\partial y^2} + (2-\nu_b)\frac{\partial^2 W}{\partial x^2}\right]_{y=b}, \\
&R_x^a = \left(R_x\right)_{x=a} = -D\frac{\partial}{\partial x}\left[\frac{\partial^2 W}{\partial x^2} + (2-\nu_b)\frac{\partial^2 W}{\partial y^2}\right]_{x=a}, \\
&P_z^c = \left(P_z\right)_{z=0} = B\left(\frac{\partial U}{\partial z} + \nu_c\frac{\partial V}{\partial x}\right)_{z=0}.
\end{aligned} \quad (5)$$

An analytical-numerical method is proposed for solving the problem of oscillation of the building box, taking into account spatial deformations with full contact conditions in the zones of butt joints of plate and beam elements of the building box.

Based on representation (1), we will rewrite the kinematic laws of movement of the points of the plate elements. The general kinematic law of movement of the box is presented as the sum of the function of displacement of the base $U_0(t)$ and the relative displacements of the plate elements:

$$\begin{aligned}
&u_3 = U_0(t) + W(x,y,t), \\
&u_1 = U_0(t) + u(x,y,t), u_2 = \upsilon(x,z,t), \\
&u_3^i = U_0(t) + W^{(i)}(x,t).
\end{aligned} \quad (6)$$

Write down the displacements of plate and beam elements as follows:

$$\begin{aligned}
&W = W(x,y)\sin(\omega_0 t), \\
&u = u(x,z)\sin(\omega_0 t),\ \upsilon = \upsilon(x,z)\sin(\omega_0 t), \\
&W^{(i)} = W^{(i)}(x,y)\sin(\omega_0 t),\ \alpha^{(i)} = \alpha^{(i)}(x,y)\sin(\omega_0 t).
\end{aligned} \quad (7)$$

Consider the theoretical calculation of the box of a large-panel building under dynamic action, taking into account the spatial work of transverse and longitudinal walls.

As the equation of motion of the bending panel, Based on the findings/relations/formulations in [7, 8],and taking into account of (1) , the equation of motion of the bending panel can be written in the form:

$$D\left(\frac{\partial^4 W}{\partial x^4} + 2\frac{\partial^4 W}{\partial x^2 \partial y^2} + \frac{\partial^4 W}{\partial y^4}\right) + \rho h_b \ddot{W} = \rho h_b A_0 \omega_0^2 \sin\omega_0 t. \quad (8)$$

Two dimensional equations can be written as shown in [7,8]:

$$\begin{aligned}
&B\left(\frac{\partial^2 u}{\partial z^2} + \frac{1+\nu_c}{2}\frac{\partial^2 \upsilon}{\partial x \partial z} + \frac{1-\nu_c}{2}\frac{\partial^2 u}{\partial x^2}\right) = \rho h_c \ddot{u} - \rho h_c A_0 \omega_0^2 \sin\omega_0 t, \\
&B\left(\frac{\partial^2 \upsilon}{\partial x^2} + \frac{1+\nu_c}{2}\frac{\partial^2 u}{\partial x \partial z} + \frac{1-\nu_c}{2}\frac{\partial^2 \upsilon}{\partial z^2}\right) = \rho h_c \ddot{\upsilon}.
\end{aligned} \quad (9)$$

The equation of bending and torsional vibrations of beams will be written as:

$$\frac{\partial^2}{\partial x^2}\left(EJ\frac{\partial^2 W^{(i)}}{\partial x^2}\right)+\rho F\ddot{W}^{(i)}=R_y^b-P_z^c-\frac{h_b}{2}\frac{\partial P_{zx}^c}{\partial x}-\rho F\ddot{U}_0,$$
$$\frac{\partial}{\partial x}\left(GI_{kr}\frac{\partial \alpha^{(i)}}{\partial x}\right)=\rho I_{kr}\ddot{\alpha}^{(i)}+M_{yy}^b+\frac{h_c}{2}R_{y,}^b \quad (10)$$

where GI_{kr} is the torsional stiffness of the beam.

Write the boundary conditions at the base of the building box ($x=0$) as for rigid clamping. The lower part of the building moves with the base and there is no turn

$$u_1=u_3=u_3^{(i)}=U_0(t),u_2=0,\ \frac{\partial W}{\partial x}=0,\ \frac{\partial W^{(i)}}{\partial x}0,\ \alpha^{(i)}=0. \quad (11)$$

Boundary conditions (11) with allowance for (6) will be rewritten as:

$$W=0,\frac{\partial W}{\partial x}=0,u=0,\upsilon=0,\ W^{(i)}=0,\frac{\partial W^{(i)}}{\partial x}=0,\ \alpha^{(i)}=0. \quad (12)$$

The boundary conditions at the upper ends of the building box elements at $x=a$ are the following contact conditions between these elements and the floor.

Contact conditions in the zones of butt joints (at) beam and plate elements working in shear will be written in the form:

$$u(x,z,t)=W^{(i)}(x,t),\ \ \upsilon(x,z,t)=\pm\frac{h_b}{2}\frac{\partial W^{(i)}(x,t)}{\partial x},$$
$$W(x,y,t)==W^{(i)}(x,t),\ \left(\frac{\partial W(x,y,t)}{\partial y}\right)=-\alpha^{(i)}, \quad (13)$$

The displacements of the top points of beam and plate elements operating bending and shear are denoted by:

$$W_a(y,t)=W(a,y,t),u_a(y,t)=u(a,z,t),\upsilon_a(z,t)=\upsilon(a,z,t). \quad (14)$$

Based on the notation (13), the distribution law of the displacement of overlap points will be given by:

$$u_n(z,y,t)=W_a(y,t)+u_a(z,t)-W^{(i)}(a,t)$$
$$\upsilon_n(z,y,t)=\upsilon_a(z,t). \quad (15)$$

The contact conditions at the joints of the floor and the wall working in bending have the form:

$$-R_x^a+\eta_0\rho_n h_b h_n\left(\ddot{W}_a+W^{(i)}(a,t)\right)=h_b h_n\frac{\partial \tau_{zy}^n}{\partial y}-\eta_0\rho_n h_b h_n\ddot{U}_0,$$
$$M_{xx}=0, \quad (16)$$

where $\tau_{zy}^n=G_n\left(\frac{\partial W_a}{\partial y}\right)$ is the tangential stress of the floor at its edge $z=a$, $\eta_0=\frac{2(bh_b+ch_c)}{bc}$.

The contact conditions at the joints of the floor and the wall working in shear, with respect to the contact tangential and normal stresses, will be written in the form:

$$\begin{aligned} -ch_c\tau^c_{zx} + \eta_0 m_{mc}\ddot{u}_a &= ch_c h_n \frac{\partial \sigma^n_{zz}}{\partial z} - \eta_0 m_{nc}\ddot{U}_0, \\ -ch_c\sigma^c_{xx} + \eta_0 m_{nc}\ddot{\upsilon}_a &= ch_c h_n \frac{\partial \sigma^n_{xz}}{\partial z} \end{aligned} \quad . \tag{17}$$

where $\sigma^n_{zz} = E_n\left[\frac{\partial u_a}{\partial z}\right]$, $\sigma^n_{zx} = G_n\left[\frac{\partial \upsilon_a}{\partial z}\right]$ are normal and shear stresses of the floor at its edge $y = b$, $\sigma^c_{xx} = E_c\left[\frac{\partial \upsilon}{\partial x} + \nu_c \frac{\partial u}{\partial z}\right]_{x=a}$, $\tau^c_{zx} = G_c\left[\frac{\partial \upsilon}{\partial z} + \frac{\partial u}{\partial x}\right]_{x=a}$ are normal and shear stresses of the shear plate elements at its upper edge $x=a$.

Set the boundary conditions on the contour of the window opening as for the free edge (Figure. 2):

$M_{xx} = 0, R_x = 0,$ at $x = const$, (on the AB and CD circuit), (18)

$M_{yy} = 0, R_y = 0,$ at $y = const$, (on the AC and BD circuit). (19)

At each interior corner points of the opening A, B, C, D, we have five boundary conditions:

$M_{xx} = 0, R_x = 0, M_{yy} = 0, R_y = 0, M_{xy} = 0,$ at $x = const, y = const$ (20)

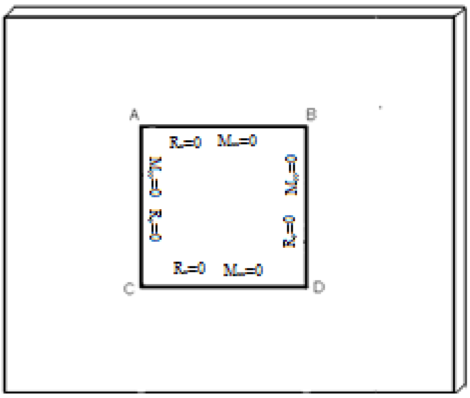

Figure. 2. Bending plate element with cut out.

The initial conditions of the problem are taken to be zero.

The vibration modes (7) must satisfy the equations of motion (8–10), boundary conditions (12), contact conditions (13) and (16–20).

The general solution to the problem of forced vibrations of the bending box plate element is described by a function represented as the sum of the solution to the problem of forced and natural vibrations:

$$W(x,y,t) = A_0 W_v(x,y)\sin\omega_0 t + \sum_{i=1}^{N} C_i W_i(x,y)\sin p_i t, \tag{21}$$

The solution to the problem of forced vibrations of bending plate elements are expressed through the main vibration modes:

$$W_v(x,y) = \sum_{i=1}^{N} A_i W_i(x,y), \tag{22}$$

where $A_i(i = 1.2.3...)$ expansion coefficients.

In the calculations, it was enough to restrict ourselves to the one-term approximation. The general solution to the equation of bending vibrations of the panels is:

$$W(x,y,t) = A_0 W_v(x,y)\sin\omega_0 t + C_1 W_1(x,y)\sin p_1 t\,, \tag{23}$$

Let express the solution to the problem of forced vibrations in terms of the main vibration mode:

$$W_v(x,y) = A_1 W_1(x,y), \tag{24}$$

where p_1 is the first natural frequency, $W_v(x,y)$ is the form of forced oscillations, C_1 is constant to be determined.

A_1 is the decomposition coefficient, the value of which is obtained by the formula.

$$A_1 = \frac{\iint f_0(x,y) f_1(x,y) dxdy}{\iint f_1^2(x,y) dxdy} = 0.1739.$$

Here $f_0(x,y)$ and $f_1(x,y)$ are the forced and main natural modes of oscillations.

Substituting (24) into (23) and subjecting to zero initial conditions, we obtain $C_1 = -A_0 A_1 \frac{\omega_0}{p_1}$.

By virtue of this expression and taking into account (24), we obtain a general solution to the problem for a bending plate element in the form [15-16]:

Solution method. The general solution given by previous studies [17, 18] is:

$$W(x,y,t) = A_0 (\sin \omega_0 t - \frac{\omega_0}{p_1} \sin p_1 t) W_v(x,y). \tag{25}$$

The expressions for moving the shear plate elements are:

$$\begin{gathered} u(x,z,t) = A_0 \left(\sin \omega_0 t - \frac{\omega_0}{p_1} \sin p_1 t \right) u_v(x,z), \\ \upsilon(x,z,t) = \left(\sin \omega_0 t - \frac{\omega_0}{p_1} \sin p_1 t \right) \upsilon_v(x,z). \end{gathered} \tag{26}$$

The kinematic functions of the beams are written as:

$$\begin{gathered} W^{(i)}(x,t) = A_0 \left(\sin \omega_0 t - A_1 \frac{\omega_0}{p_1} \sin p_1 t \right) W_v^{(i)}(x), \\ \alpha^{(i)}(x,t) = A_0 \left(\sin \omega_0 t - A_1 \frac{\omega_0}{p_1} \sin p_1 t \right) \alpha_v^{(i)}(x). \end{gathered} \tag{27}$$

The problem of determining the unknown coordinate functions in expressions (25–27) was solved using the “fortran” software by the finite difference method.

Represent the frequency of forced oscillations in the form:

$$\omega_0 = \frac{\beta}{H^2} \sqrt{\frac{D}{\rho h_b}},$$

where β is the frequency parameter of the external influence.

In the problems being solved, with the values of the frequency parameter of the external influence $\beta = 2.0$ then the frequency and amplitude of external influence were obtained as $\omega_0 = 81.03 \text{sec}^{-1}$ and $A_0 = 2.0 \text{cm}$.

3. Results and Discussion

The following parameters are set as the initial data [7–9]. The ratio of the height to the width of the bending plate elements $H / b = 3.25 / 6.0$, the ratio of the height to the width of the shear plate elements $H / c = 3.25 / 6.0$. The ratio of the thickness to the width of the bending plate element $h_b / b = 0.5 / 6.0$

, and the ratio of the thickness of the bending plate element to the thickness of the shear plate element $h_c / h_b = 0.25 / 0.5$.

Moduli of elasticity of flexible and shear plate elements $E_c = 7500\text{Mpa}$ and $E_b = 20000\text{Mpa}$. Poisson's ratio of plate element materials is $v_b = v_c = v_n = 0.3$.

Figure 3 shows a graph of the change in the bending moment M_{yy} on the upper and lower parts of bending plate elements, from the middle of the plate element to one of its edges. As you can see, the moments of the panels increase as they approach the edge of the plate element (at $A_0 = 2.0\text{cm}$).

In the figures, the blue lines represent the values obtained when solving stationary problems. The red lines show the numerical results obtained taking into account the window openings.

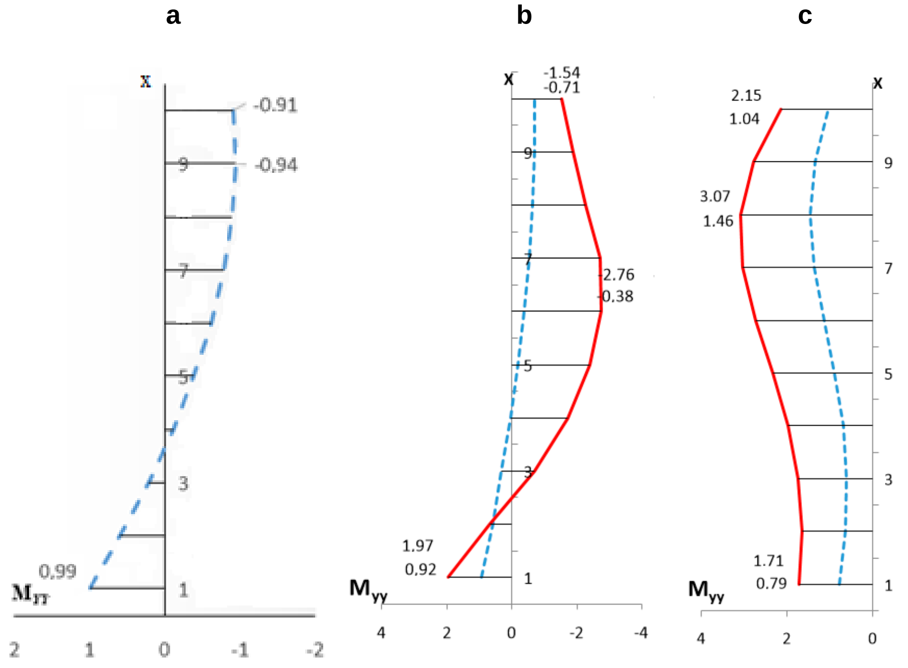

Figure. 3. Changes in the bending moment M_{yy} of bending plate element.
a) edge opening b) middle c) panel edges.

Calculations show that the bending moment M_{yy} values in the middle of the plate elements are less than at the edges of the plate element. The maximum value of the bending moment M_{yy} is found in the middle of the second half of the contact zone of the bending plate and beam elements. Note that at the contact zones of the plate element, the bending moment M_{yy} twists the beams and plays the role of the torque.

In Fig. 4 the graphs of the vertical change of the dimensionless maximum bending moment of the plate element working in bending are shown.

The maximum values of the bending moment (Fig. 4.a) are achieved at the lowest points of the bending plate elements.

In Fig. 4 it can be seen that the bending moment of the vertical edge of the bending plate element is several times greater than the moment of the middle part, since the edges of the plate elements are held by transverse plate elements that work in shear.

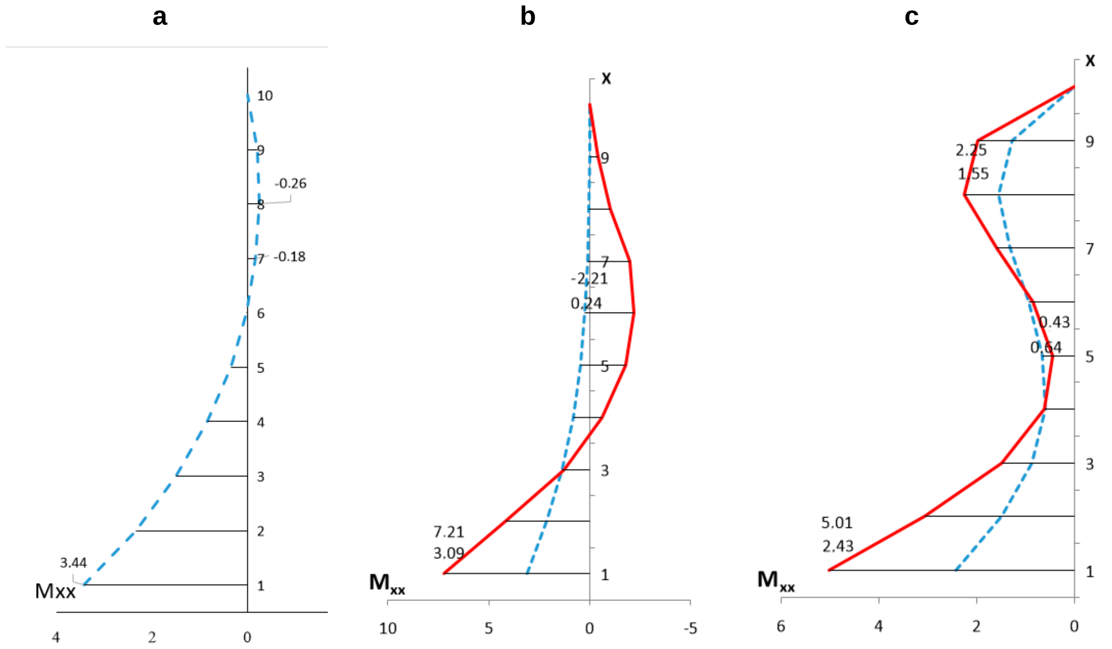

Figure. 4. Changes in the bending moment along the height of the plate element operating in bending) of the edge of the opening b) the middle c) the edge of the plate element.

In Fig. 5 graphs are presented that characterize the changes in the maximum normal stress in the lower vertical sections of plate elements and in the zones of butt joints of plate and beam elements. Consequently, in plate element working in bending, the middle of the plate element is compressed and the edges of the plate elements are stretched.

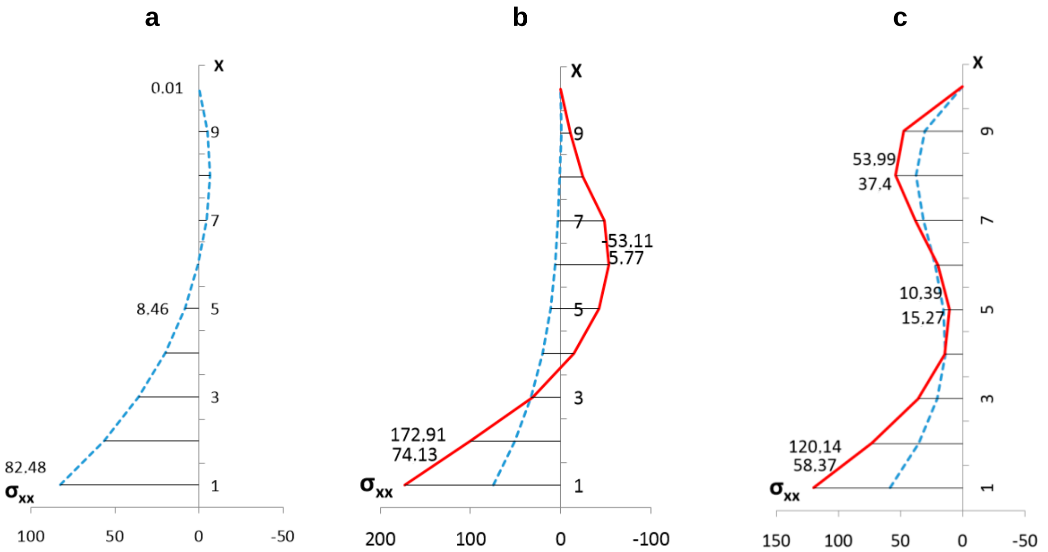

Figure. 5. Changes in the stresses of bending plate elements:

a) the edge of the window opening; b) middle; c) plate elemet edge.

Figure 6 shows the diagrams of the maximum compressive and tensile stresses of bending panels. The maximum stress values are found at the top of the bending panel. In the contact zones of the panel, the stresses are tensile.

The maximum value of the normal stress in plate elements operating in bending without taking into account the window opening is obtained equal to: -- $\sigma_{yy} = -7.37\text{MPa}$.

The method for calculating the box-shaped structure of a building proposed in the article makes it possible to estimate the maximum stresses in the internal transverse and external longitudinal bearing panels, as well as in the butt joints of these elements. This means that our proposed method for calculating the box-like structure complements the calculation method developed within the framework of the continuous plate model [17, 18].

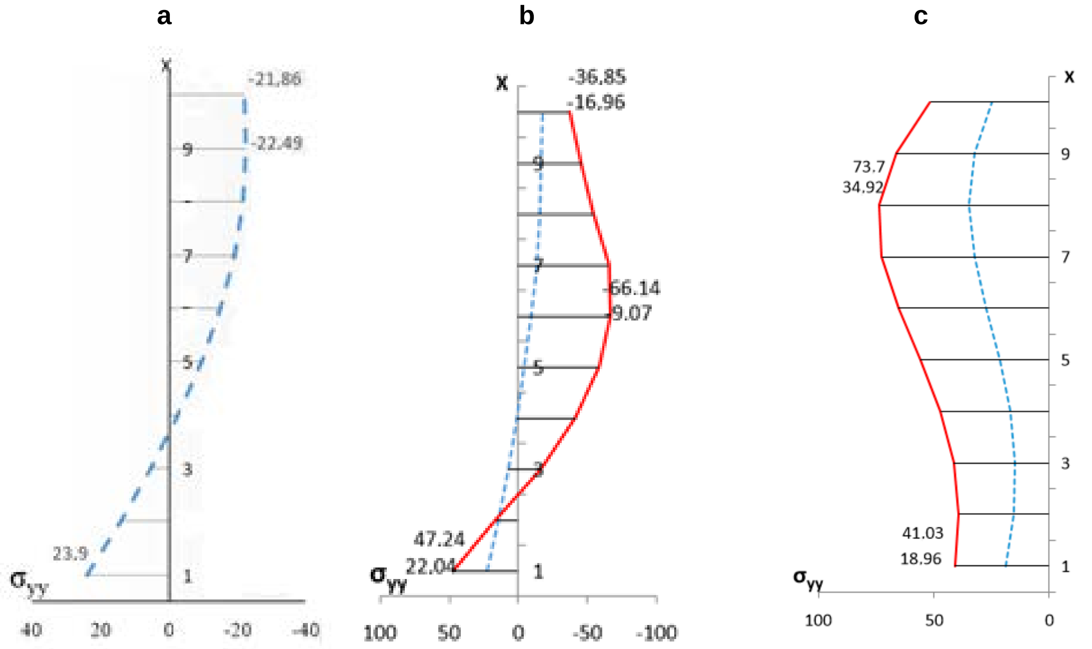

Figure. 6. Changes in the stress of panels working in bending in height: a) the edge of the window opening; b) middle; c) panel edge.

4. Conclusions

1. The method of dynamic calculation of the box-shaped structure of buildings under dynamic influences has been developed. Equations of motion of points of plate and beam elements, boundary and contact conditions of the box of buildings of the problem of forced vibrations are constructed.

2. Within the framework of the finite-difference method, a method for dynamic calculation of the bending moments of plate elements of box-shaped structures of buildings has been developed.

3. The laws of change in the maximum values of moments and stresses in the characteristic sections of plate elements with and without window openings are graphically presented.

4. From the graphs it can be seen that the maximum values of the normal stress when taking into account the window openings are obtained by 25–30% more than the values of the normal stress obtained when solving the problem without taking into account the window openings.

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Received 29.09.2020. Approved after reviewing 28.09.2021. Accepted 29.09.2021.