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ANALYSIS OF EFFICIENCY OF THREE-LAYER WALL PANELS WITH A DISCRETE CORE

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Abstract

Introduction: The paper addresses thin-walled three-layer plates and panels with cutouts, reinforced with an orthogonal grid of stiffeners or rectangular reinforcement plates parallel to the coordinate lines. In this case, the thickness of the entire structure is taken into account analytically using unit column functions. **Purpose of the study:** We aimed to build a mathematical model of deformation and develop a method for the analysis of the stability of thin-walled elastic isotropic three-layer plates and wall panels with a discrete core. **Methods:** Based on the mathematical apparatus of generalized functions using the Bubnov–Galerkin method, an eigenvalue problem is solved to determine the critical parameters of a compressed three-layer wall panel with a discrete core. **Results:** According to the suggested method, we perform a stability analysis of three-layer wall panels with different values of core stiffness and study the impact of the discrete core parameters on the buckling load, consumption of materials, and efficiency of three-layer engineering structures.

Keywords

Three-layer plate, wall panel, discrete core, cutout, stiffener.

Introduction

Currently, to improve the weight and economic efficiency, specific strength, and stiffness of thin-walled structures, especially in construction, shipbuilding, mechanical engineering, and other technical industries, three-layer plates and shells are widely used. The heterogeneous layered structure of such shells provides the necessary strength and stiffness characteristics as well as soundproofing and heat and vibration isolation properties.

The used thin-walled structure analysis principles are common for bending flat three-layer panels, three-layer panels resisting compression and bending, and three-dimensional three-layer structures — shells.

Since three-layer structures have a core (solid or discrete, e.g., ribbed) offering relatively low resistance to shear, the bending strains in these structures are accompanied by mutual skin displacement. It is possible to perform three-layer panel and shell analysis either based on the precise methods of the elasticity theory or through the introduction of certain hypotheses that reflect the specifics of structure behavior and make it possible to significantly simplify the process of problem-solving with no considerable error.

The precise method of core element analysis uses an equation for a three-dimensional problem of the elasticity theory. This method was first used for thick slabs by Galerkin (1931).

In the case of cylindrical bending, Rzhanitsyn's theory of built-up columns (1986) can also be applied effectively for the analysis of three-layer panels. In this case, the panel skins are considered as built-up column laminations while the core is considered as transverse and shear connections evenly distributed along the column length.

Three-layer panels with low section height and, therefore, high flexibility are usually supported on four sides or secured on supports and calculated based on the non-linear theory with account for chain (membrane) forces acting in the middle surface.

The analysis of stiffened three-layer panels has a number of specific features. In three-layer wall panels (especially if there is a solid core), stiffeners are distributed relatively sparsely, therefore, in the analysis, it is necessary to account for the non-uniformity of the distribution of normal stresses in the skins along the width of the panel, caused by shear forces along the lines where the skins and the stiffeners come together (Aleksandrov et al., 1960; Davies, 2001).

The general theory of the analysis of three-layer plates and shells with a structural core was developed by Aleksandrov (1959), Aleksandrov et al. (1960), Bryukker (1965), Grigolyuk and Chulkov (1973), Grigolyuk and Kogan (1972), Levchuk (2008a, 2008b) as well as Dragan and L evchuk (2011).

Numerous researchers (Eremeev and Zubov, 2017; Kipiani, 2014; Kobelev et al., 1984; Kreja, 2011;

Pukhliy and Pukhliy, 2019) dealt with the development of new analytical models for three-layer plates and shells. The wide implementation of new materials that enable making structures with unique properties in engineering and construction has significantly complicated analytical models. Among the studies addressing methods for the analysis of thin-walled structures made of composite materials, we would also like to mention publications by Kaledin et al. (2014), Nguyen et al. (2019), and Solomonov et al. (2014).

Currently, numerical calculations of three-layer panels are usually performed using finite-element modeling packages. The skins are modeled by finite elements of the plates and the core is modeled by solid finite elements. The creation of powerful computing systems based on the finite element method (FEM) opens up opportunities for the development of new analytical models with regard to the analysis of the stress-strain state of multi-layer plates and shells with irregular structures (Baculin, 2018; Golovanov et al., 2006; Grishanov, 2018). Mathematical models for the analysis of modern thin-walled three-layer structures shall meet a lot of requirements. Among other things, they shall allow us to determine with high accuracy the stress-strain state, load-bearing capacity, and critical buckling values of such structures, taking into account the heterogeneity of layers and a wide range of external effects (Karpov, 2010; Karpov et al., 2002).

Despite the fact that current computational resources make it possible to build and analyze complex finite element models in a comparatively short time, the very development of an analytical model that would reliably take into account the stress-strain state of an irregular structure requires the involvement of a highly qualified computing engineer and significant programming efforts. The creation of a method for stability analysis of three-layer panels with a discrete core, based on the mathematical apparatus of generalized functions and variational analysis methods, is quite an important task.

The paper builds a mathematical model and develops an algorithm for the analysis of three-layer wall panels with a discrete core in the form of some inner cutouts, which is equivalent to a core in the form of a system of wide cross stiffeners.

Mathematical model for the analysis of plates and wall panels

The paper addresses plates and panels reinforced with an orthogonal grid of stiffeners parallel to the coordinate lines. The height and location of the stiffeners are specified according to Karpov (2010) using unit column functions $\bar{\delta}(x-x_j)$ $\bar{\delta}(y-y_i)$ as follows:

$$H(x,y)=\sum_{j=1}^{m}h^j\bar{\delta}\left(x-x_j\right)+\sum_{i=1}^{n}h^i\bar{\delta}\left(y-y_i\right)-\sum_{i=1}^{n}\sum_{j=1}^{m}h^{ij}\bar{\delta}\left(x-x_j\right)\bar{\delta}\left(y-y_i\right), \tag{1}$$

where h^j, h^i — the height of the stiffeners parallel to the y and x axes, respectively; $h^{ij}=\min\left\{h^i,h^j\right\}$;

$\bar{\delta}(x-x_j)$, $\bar{\delta}(y-y_i)$ — the unit column functions equal to 1 at points where the stiffeners are located or 0 outside those locations. If $h^j=h^j(y)$, $h^i=h^i(x)$, then $h^{ij}=\min\left\{h^i(x_j);h^j(y_i)\right\}$.

Therefore, the thickness of the entire structure is equal to $h+H$. If $H>0$, then the plate is reinforced with stiffeners or reinforcement plates. If $H<0$, then it is weakened by cutouts.

Let us consider a wall panel with thickness h with a rectangular cutout reinforced with eccentric stiffeners in the direction of the x axis.

If a slab, reinforced with stiffeners, the size and location of which are specified by function $H(x,y)$ in the form of Eq. (1), also has cutout holes, the location of which is specified by function $H_2(x,y)$ in the following form:

$$H_2\left(x,y\right)=-h\sum_{j_2=1}^{m_2}\sum_{i_2=1}^{n_2}\bar{\delta}\left(x-x_{j_2}\right)\bar{\delta}\left(y-y_{i_2}\right),$$

then the total thickness of the slab will be $h+H(x,y)+H_2(x,y)$.

The internal forces in the panel can be represented as follows:

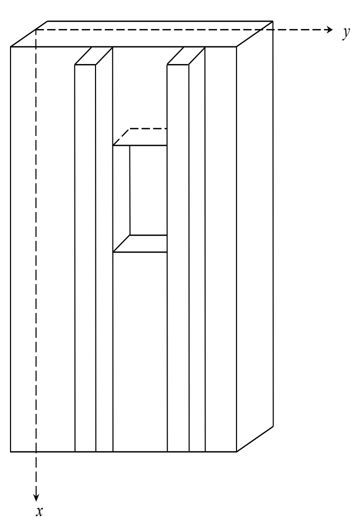

Fig. 1. Wall panel with a rectangular cutout reinforced with stiffeners

$$M_x = \frac{E}{1-\mu^2}\left(\frac{h^3}{12} + J_x + \bar{J}\right)\left(\chi_1 + \mu\chi_2\right),$$

$$M_y = \frac{E}{1-\mu^2}\left(\frac{h^3}{12} + J_y + \bar{J}\right)\left(\chi_2 + \mu\chi_1\right),$$

$$M_{xy} = \frac{E}{2(1+\mu)}\left(\frac{h^3}{12} + J_y + \bar{J}\right)\chi_{12},$$

$$M_{yx} = \frac{E}{2(1+\mu)}\left(\frac{h^3}{12} + J_x + \bar{J}\right)\chi_{12},$$

$$\tilde{M}_{xy} = \frac{1}{2}\left(M_{xy} + M_{yx}\right),$$

where expressions for the moments of inertia have the following form:

$$\bar{J} = -\frac{h^3}{12}\sum_{j_1=1}^{m_1}\sum_{i_1=1}^{n_1}\bar{\delta}\left(x - x_{j_1}\right)\bar{\delta}\left(y - y_{i_1}\right),$$

$$J_x = \sum_{i=1}^{n} J^i \bar{\delta}(y - y_i) + r_a \sum_{j=1}^{m} J^j \bar{\delta}(x - x_j) -$$

$$r_a \sum_{i=1}^{n}\sum_{j=1}^{m} J^{ij} \bar{\delta}(x - x_j)\bar{\delta}(y - y_i),$$

$$J_y = \sum_{j=1}^{m} J^j \bar{\delta}(x - x_j) + r_b \sum_{i=1}^{n} J^i \bar{\delta}(y - y_i) -$$

$$r_b \sum_{i=1}^{n}\sum_{j=1}^{m} J^{ij} \bar{\delta}(x - x_j)\bar{\delta}(y - y_i),$$

$$r_a = r_j / a, \;\; r_b = r_i / b.$$

The equilibrium equation for the slab compressed in the direction of the x axis will be as follows:

$$\frac{\partial^2 M_x}{\partial x^2} + \frac{\partial^2 M_y}{\partial y^2} + 2\frac{\partial^2 \tilde{M}_{xy}}{\partial x \partial y} - N_x \frac{\partial^2 W}{\partial x^2} = 0. \quad (2)$$

Let us consider a wall panel in the form of a three-layer slab with a discrete core. Such a structure can be specified according to Karpov et al. (2002) if a slab of thickness h with internal cutouts of depth $h/3$ is considered. Let us assume that the cutouts have the same size and are rectangular with side a_1 along the x axis and side b_1 along the y axis. In the direction of the x axis, there will be m_1 cutouts, and in the direction of the y axis, there will be n_1 cutouts (Fig. 2).

The reduced area of the cutouts will be equal to the following:

$$K_1 = \frac{a_1 m_1 b_1 n_1}{b}.$$

The moment of inertia of such a slab with the zero stiffness of the cutouts "smeared" along the entire plate will be equal to the following:

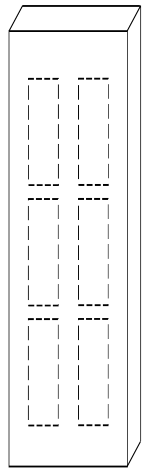

Fig. 2. Wall panel with inner cutouts

$$\tilde{J} = J - J_1 K_1,$$

where:

$$J = h^3/12, \; J_1 = \int_{-h/6}^{h/6} z^2 dz = \frac{h^3}{324} = \frac{h^3}{12 \cdot 27}.$$

Then the moments in Eq. (2) will be as follows:

$$M_x = \frac{E}{1-\mu^2}\tilde{J}\left(\chi_1 + \mu\chi_2\right),$$

$$M_y = \frac{E}{1-\mu^2}\tilde{J}\left(\chi_2 + \mu\chi_1\right),$$

$$\tilde{M}_{xy} = \frac{E}{2(1+\mu)}\tilde{J}\chi_{12}.$$

Analysis of the efficiency of three-layer wall panels with a discrete core

Let us study the stability of wall panels in the form of three-layer plates with a discrete core compressed in the direction of the *OX* axis with force N_x uniformly distributed along the middle plane of the slab ($N_x = -\,const$). The equilibrium equation for such a slab has the form of Eq. (2).

Let us assume that the edges of the slab have pin support. We need to find such value of N_x where deflection $W(x,y)$ is other than 0. This value of N_x will be critical. Let us present $W(x,y)$ in the following form:

$$W_{mn} = \sum_{j=1}^{m}\sum_{i=1}^{n} A_{ij} \sin\frac{i\pi x}{a}\sin\frac{j\pi y}{b}. \quad (3)$$

To find the A_{ij} coefficients according to the Bubnov–Galerkin method, we will derive a system of homogeneous linear algebraic equations.

$$\int_0^a\int_0^b \left(\frac{\partial^2 M_x(W_{mn})}{\partial x^2} + \frac{\partial^2 M_y(W_{mn})}{\partial y^2} + 2\frac{\partial^2 \tilde{M}_{xy}(W_{mn})}{\partial x \partial y} \right) \sin\frac{i_1 \pi x}{a} \sin\frac{j_1 \pi y}{b} dxdy =$$

$$= N_x \int_0^a\int_0^b \frac{\partial^2 W_{mn}}{\partial x^2} \sin\frac{i_1 \pi x}{a} \sin\frac{j_1 \pi y}{b} dxdy,$$

$$i_1 = 1, 2, ..., m,\ j_1 = 1, 2, ..., n.$$

Having determined the integrals of known functions, we will obtain the following:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} C_{iji_1j_1} A_{ij} = N_x \sum_{i=1}^{m}\sum_{j=1}^{n} B_{iji_1j_1} A_{ij},$$

$$i_1 = 1, 2, ..., m,\ j_1 = 1, 2, ..., n.$$

As a result, we have an eigenvalue problem. We need to find such values of N_x where this system has a non-zero solution.

If small deflections are considered, the first approximation of the Bubnov–Galerkin method can be considered, i.e., $W(x,y)$ can be adopted in the following form:

$$W_1(x, y) = C_1 \sin\frac{\pi x}{a} \sin\frac{\pi y}{b}.$$

For a slab of constant thickness h, we will obtain the following:

$$C_1 \frac{\pi^4}{a^4}\frac{ab}{4}\left(1 + 2\frac{a^2}{b^2} + \frac{a^4}{b^4}\right) = -N_x \frac{C_1}{D}\frac{\pi^2}{a^2}\frac{ab}{4},$$

where:

$$D = \frac{Eh^3}{12(1-\mu^2)}.$$

Therefore:

$$N_x = -\frac{D\pi^2}{a^2}\left(1 + 2\frac{a^2}{b^2} + \frac{a^4}{b^4}\right). \quad (4)$$

For a rectangular slab at $a=b$, we will obtain the following:

$$N_{xcr} = -3.615\frac{Eh^3}{a^2}.$$

Let us consider a wall panel in the form of a three-layer slab with a discrete core. The thickness of such a structure can be specified if we consider a slab of thickness h with inner cutouts of depth $h/3$ (Fig. 3).

Let us assume that the cutouts have the same size and are rectangular with side a_1 along the x axis and side b_1 along the y axis. In the direction of the x axis, there will be m_1 cutouts, and in the direction of the y axis, there will be n_1 cutouts. The reduced area of the cutouts will be equal to the following:

$$K_1 = \frac{a_1 m_1 b_1 n_1}{ab}.$$

The moment of inertia of such a slab will be equal to $J–J_1K_1$ where:

$$J = \int_{-h/2}^{h/2} z^2 dz = \frac{h^3}{12}, \quad J_1 = \int_{-h/6}^{h/6} z^2 dz = \frac{h^3}{324} = \frac{h^3}{12 \cdot 27}.$$

Therefore:

$$D = \frac{Eh^3}{12(1-\mu^2)}\left(1 - \frac{K_1}{27}\right),$$

and the critical load will be as follows:

$$N_x = -\frac{D\pi^2}{a^2}\left(1 + \frac{a^2}{b^2}\right)^2.$$

Let us consider a specific example. Let us assume that the width of a cutout is two times larger than the width of the connection between the cutouts. Then, if there are four cutouts and five connections in the direction of the x axis, then 13 units of length will correspond to the distance a and the distance $a/13$ will correspond to each unit of length.

Since two units of length are required per one cutout, then $8a/13$ will correspond to four cutouts. There will be five cutouts in the direction of the y axis, i.e., $b/16$ per one unit of length, and $10b/16$ per five cutouts. Let us find K_1 for this case:

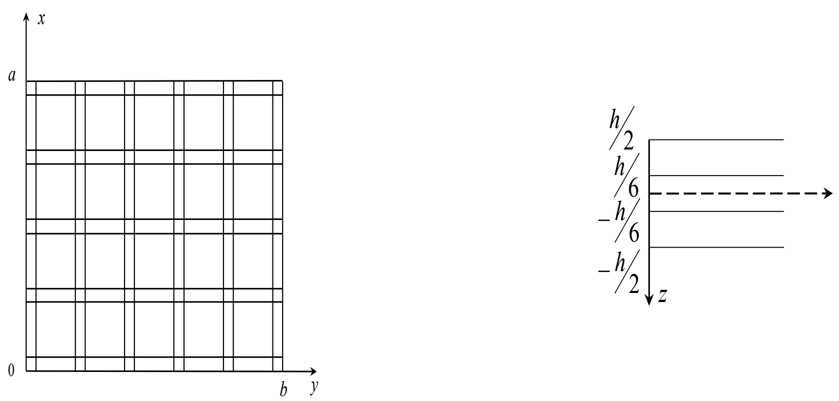

Fig. 3. Slab with inner cutouts

$$K_1 = \frac{ab \cdot \frac{8}{13} \cdot \frac{10}{16}}{ab} = 0.3846.$$

Therefore, $\left(1 - \frac{K_1}{27}\right) = 0.9858$. The value of the critical load N_x almost has not changed, but the volume of the slab has decreased and become as follows:

$$V = abh - \frac{2a}{13} \cdot 4 \cdot \frac{2b}{16} \cdot 5 \cdot \frac{h}{3} = abh \cdot 0.8718 \text{ m}^3.$$

Let us increase the area of the cutouts. Let us assume that the width of a cutout is three times larger than the width of the connection between the cutouts. The number of cutouts in the direction of the x axis will remain the same, i.e., four. We assume that in the direction of the y axis, their number is 10. In this case:

$$K_1 = \frac{12}{17} \cdot \frac{30}{41} = 0.5165, \left(1 - \frac{K_1}{27}\right) = 0.981.$$

The volume of the slab will be equal to the following:

$$V = abh \cdot 0.8278 \text{ m}^3.$$

If a reinforced concrete panel with the dimensions $a = 3m,\ b = 6m,\ h = 0.3m$, (E=$3.25 \cdot 10^4$ specific density ρ= 200 kg/m^3) is weakened by the above cutouts, then its dead weight will be as follows:

$$S_b = V \cdot \rho = 8940.24 \text{ kg}.$$

The dead weight of a solid panel with the same dimensions will be as follows:

$$S_b = abh\rho = 10800 \text{ kg},$$

i.e., such a panel will be heavier than a panel with cutouts by more than 1 ton.

Therefore, for the panel with cutouts, the critical load has decreased by 1.9%. Meanwhile, its weight has decreased by 17.2%. The example above shows that it is economically efficient to use three-layer panels with a discrete core, providing the required design stability parameters at reduced consumption of materials in construction.

Conclusion

We have built a mathematical model for the deformation of thin-walled elastic isotropic three-layer plates and wall panels with a discrete core in the form of a system of cross stiffeners, taking into account their width. The thickness of the entire structure is taken into account analytically by means of unit column functions.

To determine critical parameters of a compressed three-layer wall panel using the Bubnov–Galerkin method, the eigenvalue problem has been solved. According to the method suggested, we have performed stability analysis of three-layer wall panels with different values of core stiffness and studied the impact of the discrete core parameters on the buckling load, consumption of materials, and efficiency of three-layer engineering structures.

The reliable mathematical model and relative simplicity of the analysis algorithm make it possible to recommend the suggested method for the assessment of efficiency of three-layer wall panels with a discrete core.

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АНАЛИЗ ЭФФЕКТИВНОСТИ ТРЕХСЛОЙНЫХ СТЕНОВЫХ ПАНЕЛЕЙ С ДИСКРЕТНЫМ ВНУТРЕННИМ СЛОЕМ

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Аннотация
Рассматриваются тонкостенные трехслойные пластины и панели с вырезами, подкрепленные ортогональной сеткой ребер или прямоугольных накладок параллельных координатным линиям. Толщина всей конструкции при этом учитывается аналитически с помощью единичных столбчатых функций. **Целью работы** было построение математической модели деформирования и создание методики расчета на устойчивость тонкостенных упругих изотропных трехслойных пластин и стеновых панелей с дискретным внутренним слоем. **Методы:** На основе применения математического аппарата обобщенных функций методом Бубнова – Галеркина решена задача на собственные значения для определения критических параметров сжатой трехслойной стеновой панели с дискретным внутренним слоем. **Результаты:** По предложенной методике проведены расчеты трехслойных стеновых панелей на устойчивость при различной жесткости внутреннего слоя и исследовано влияние параметров дискретного внутреннего слоя на величину критической нагрузки, материалоемкость и эффективность трехслойных строительных конструкций.

Ключевые слова
Трехслойная пластина, стеновая панель, дискретный внутренний слой, вырез, ребро жесткости.