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ON ANALYSIS OF THIN-WALLED SPATIAL SYSTEMS OF COMPLEX STRUCTURE WITH DISCONTINUOUS PARAMETERS BY METHOD OF LARGE BLOCKS

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1. INTRODUCTION

The state of the presented scientific direction issue is reflected in a number of review works [1, 2, 3, 4].

A study of stress concentration in adjacent of holes with application of considered in the work [5] shells theory was performed in the works [6, 7, 8, 9, 10].

The effect of transverse shear deformation on stress concentration parameters for tensioned and bent depressed shells with a small circular hole was studied in the work [11].

Among the numerical methods for analysis od depressed shells with holes, finite element methods and the finite-difference method are most widely applied. The presence of holes in the shell complicates the study of structures using the finite element method. Various methods are used to take into account the stress concentration: from the thickening of the element grid as it approaches the edge of the hole [12, 13, 14] to the introduction of special elements [15] or super elements [17]. So, in the work [16], plane and curvilinear quadrangular finite elements are used.

FEM in the form of displacements is used in the work [18] to study a cylindrical shell in the presence of various kinds of irregularities: geometric (cuts, thickenings, lobes), force (concentrated and local loads) and physical (heterogeneity and layering). Legendre polynomials are used to represent a shape function that maps a square onto an arbitrary quadrangular element.

In the work [19] is stated a variant of the finite element method based on the introduction of an auxiliary element, developed to take into account the influence of the system of local cuts on the parameters mode of deformation of the shells.

The work of E.S. Greben [20], G.O. Kipiani [21], B.K. Mikhailov [22], and A.P. Guz [8] are devoted to the problems of reinforcing of thin-walled shells weakened by holes. A sufficiently detailed review of the literature on these problems would be found in the works of D.V. Vainberg and in the work [24].

The following works are devoted to the study of shells with large rectangular holes. In the work [25] by authors is considered the application of the finite element method for the study of cylindrical shells with rectangular cuts, is analyzed the mode of deformation and compares the results of the study with solutions obtained by other methods.

To experimental studies are devoted the works [26, 27]. A method for studying the stress and strain state of structural elements based on the combined use of holographic interferometric and finite element methods is considered. By the polarization-optical method using the “freezing” of strains was studied in the work [28] the stress concentration in adjacent of the reinforced holes. In the work [29] are stated an analysis of experimental data and practical recommendations for the design of depressed ribbed shells with a lantern hole.

In the work [30], are considered depressed shells with taking into account physical and geometric nonlinearity within the framework of the classical theory of shells. The nonlinear task is solved using the generalized method of variable elastic parameters.

An analytical solution of the problem of residual stresses distribution of in an infinite elastic-plastic disk with a circular hole is presented in the work [31].

The small parameter method is used in the works [32, 33]. So in the work [32] the problem of finding elasto-plastic boundaries at variational-difference methods have been widely developed in the works of scientists of the Kiev school. In the work [12], based on the theory of thin shells and the deformation theory of plasticity, nonlinear decisive equations were obtained using the variational-difference approach, and a method for solving them was stated. In the work [16], the effect of the reinforcing element on the mode of deformation of the shell is taken into account.

The statement of the physically nonlinear problem of the statics of orthotropic conical shells with holes is stated in the work [11]. The derivation of the basic equations is based on the application of the nonlinear theory of elasticity and plasticity of anisotropic environment and the geometrically linear theory of thin shells in that the Kirghoff – Love hypotheses are realized by the method of undetermined Lagrange multipliers.

The joint application of the method of successive approximations and the variational-difference method for solving nonlinear two-dimensional problems was given in the works [31, 34].

The finite elementary method for calculating the elasto-plastic depressed shells and the plates is developed in the works [2, 3, 7].

A numerical method that gives the possibility to study the mode of deformation of shells of variable thickness shells weakened by cuts of various shapes is described in the work [96]. Geometric nonlinearity is taken into account in the quadratic approximation. For the numerical solution of the problem, the finite difference method is applied jointly with the determined method.

In the work [31] is stated the variational method for analysis the stress concentration at the adjacent of hole in the shell made from composite material for the case when the contour is reinforced by an elastic orthotropic cover plate (shell).

Based on the theory of thin shells and the deformation theory of plasticity, using the variational-difference method, obtained in the work [34] a system of nonlinear decisive equations for an elastic-plastic cylindrical shell with a circular reinforced hole.

Based on the experimentally determined distribution of stress intensity, the stress concentration was studied in the work [26] at the holes of plastically deformed cylindrical shells loaded with internal pressure, depending on their geometry.

Despite the great development of theoretical studies in the field of analysis of shells with holes, there are still complexities in determining the stress state in adjacent of rectangular holes. Acceptable results were obtained only for the special case of the action of tensile and compressive forces on the shells.

2. BASIC PART

The objects by authors are considered as complex structure, when: a) an accurate functional record of physical and theoretical characteristics and boundary conditions does not stated in a single coordinate system; b) they are consisting from several sub-domains (large blocks) of simple structure, within each of them such functional record is possible possible. As example of such blocks are considered shells and plates weakened by holes.

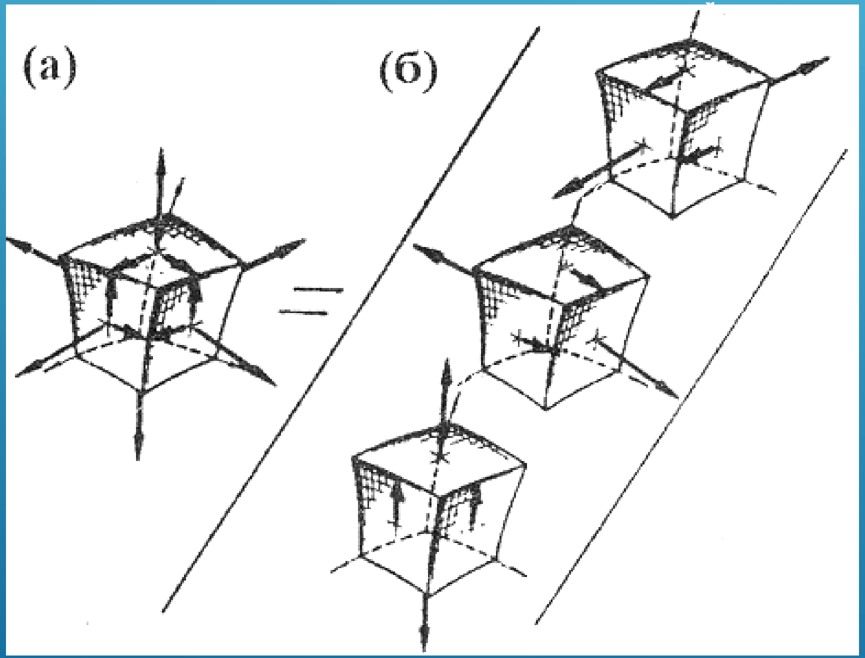

Fig. 1

To solve this problem, is applied large block method, based on the theory of elasticity in ordinary differential equations [1]. It is based on the original analytical model that is a new interpretation of the essence of the analytical model of the classical theory of elasticity on the infinitesimal element.

Namely, the work of an infinitesimal element of a given body in tension (compression) in three orthogonal directions α, β, γ (Fig. 1,a) is represented in the form of joint work of geometrically adequate three fictitious elements, each of that is capable of working in tension only in one of these options (Fig. 1,b). In this case, the following two main requirements must be met: 1) ensuring the full adequacy of the joint work of three fictitious elements (Fig. 1,b) with the work of a real infinitesimal element of a given elastic body (Fig. 1,a); 2) reduction of the problems of the theory of elasticity to integrated system equations.

The fulfillment of the first of these requirements is achieved almost exactly due the application of necessary and sufficient reactive forces of interaction of fictitious elements , the desired functions of that are interpolated building using infinite series of the following general form:

$$Y_i^* = \sum_m^{\infty} \sum_n^{\infty} \sum_k^{\infty} A_{mnk}^i \varphi_m^i(\alpha) \psi_n^i(\beta) f_k^i(\gamma) +$$

$$+\sum_{j=1} \left[\xi_j^i(\alpha) B_j^i(\beta,\gamma) + \eta_j^i(\beta) C_j^i(\alpha,\gamma) + \lambda_j^i(\gamma) D_j^i(\alpha,\beta) \right]$$

where

Y_i^* – are some of the ways to use fictitious elements (Fig. 1,b),

$\varphi_m^i(\alpha)\psi_n^i(\beta)f_k^i(\gamma)$ – are the arbitrary interpolating functions that with their derivatives in the required number of times, are continuous within the area occupied by an elastic body of domain,

A_{mnk}^i – are the desired constant coefficients of an infinite series; in one, some of the three specified conditions for the fulfillment of some of the boundary conditions, as a rule, only one holds certain problems, or all of them are considered equal to zero (depending on the boundary conditions specified in the problem).

The fulfillment of the second of these two main requirements performs due the following o less important feature of applied analytical model (Fig. 1,b), according to that internal shear stresses $\tau_{\alpha\beta}$ $\tau_{\alpha\gamma}$ $\tau_{\beta\gamma}$ are arisen, taking into account the nature of their origination (they are originated only in two-dimensional and three-dimensional problems), are related to interaction forces of mentioned above fictitious elements, and therefore their desired functions are also preliminary interpolated using series of the form (1). The only difference is that internal shear stresses $\tau_{\alpha\beta}^*$ $\tau_{\alpha\gamma}^*$ $\tau_{\beta\gamma}^*$ considered in such a new role are not reactive forces. In addition, when choosing interpolating functions of the corresponding series of form (1), the difference is only that conditions in such new way in addition to to select the interpolating function corresponding to them series in the form (1), beside the fulfilment of above specified requirements is preliminary achieved the exact satisfaction of task for internal shear stresses for all boundary conditions that sharply ensures the solution of arbitrary problems in the theory of elasticity.

Developed on the basis of the above mentioned new analytical model (Fig. 1,b) of elasticity in ordinary differential equations [1] leads to system of differential equations in partial derivatives that due to a special structure of their recording and belonging of internal shear stresses to the interaction forces of fictitious elements equations always are integrating as ordinary equations at determining internal stresses from the equilibrium equations and the components of the displacement of arbitrary point $M(\alpha,\beta,\gamma)$

The above-mentioned theory of shells in ordinary differential equations, presented in monograph [1], in addition to drastically simplifying the mathematical side of solving problems, gives the possibility to us to ensure that all five independently specified boundary conditions are satisfied in general, and in the case of a free boundary, in the form of equalities (2). The fact is that, according to the essence of this theory, the desired functions for the interaction forces of fictitious elements of the shell, including internal shear forces (T^*) and torques (H^*), are preliminary interpolated by application of series of the following forms:

from the equations of deformation, obtained as a result of excluding the components of deformation from the Cauchy equations and the dependences of Hooke's law. At the same time, it always ensures the exact fulfillment of the first of the above mentioned requirements that is indicated by the fact that the proven system of equations, after excluding all reactive relations of force functions from it, is reduced to the systems of differential equations and relations known from the classical theory of elasticity.

From the above mentioned theory, as a special case, follow the theory of shells and plates in ordinary differential equations and the corresponding method of large blocks [1] that were used by the authors in solving the problems considered in the report. We should especially note the effectiveness of this theory of shells and, in particular, in the corresponding method of large blocks when considering shells of a complex structure in the above mentioned sense, i.e. shells with holes. The fact is that along the contour line of the hole, when there is no external influence along this line (as is most often found, for example, in the shells of the stadium overlap), there are five exact boundary conditions. So, for example, on the segment of the contour line of the hole, in this case, there will be the following five boundary conditions:

$$S_a = 0 \quad M_a = 0 \quad Q_\alpha = 0 \quad T^* = 0 \quad H^* = 0$$

where

$$T^* = T_{\alpha\beta} = T_{\beta\alpha}; \qquad H^* = M_{\alpha\beta} = M_{\beta\alpha}$$

However, as it is known, the classical theory of shells does not gives the possibility to satisfying all five boundary conditions (2), and therefore they are replaced by four “boundary” conditions that are obtained by replacing the last three equalities (2) with the following two equalities:

$$Q_\alpha + \frac{1}{B} \cdot \frac{\partial H^*}{\partial \beta} = 0 \qquad T^* + \frac{H^*}{R_\beta} = 0$$

that are obtained on the basis of the well-known Kirchhoff assumptions.

$$Y_i^* = \sum_m^\infty \sum_n^\infty A_{mn}^i \psi_m^i(\alpha) \psi_n^i(\beta) + \sum_{j=1} \lambda_j^i(\alpha) \eta_j^i(\beta)$$

Moreover, when expression (4) is used for internal forces T^*, H^* $\varphi_m^i(\alpha)\psi_n^i(\beta)$

the interpolating functions and are selected so that they preliminary satisfy the last two boundary conditions (2). As a result, even when using the above-mentioned writing of the four Kirchhoff-Love boundary conditions, accepted in monograph [3] similarly to the classical theory of shells, the exact fulfillment of all five boundary conditions (2) is easily achieved. Consequently, the theory of shells used in the article, considering it in the above sense, is also contradictory.

Let's consider another method leading to a simpler algorithm. This method is based on representing the deflection in terms of functions that satisfy the boundary conditions along all four edges. Let us represent the functions W and $\Delta\gamma_1$ as [21]

$$W = \sum\sum W_{mn}(1-\cos 2\alpha_m x)(1-2\beta_n y)$$

$$\Delta\gamma = \sum \Delta\gamma_{1(n)} \sin \beta_n y_1 H_{yy}$$

Let's multiply both its parts on $(1-\cos 2\alpha_m x)(1-\cos 2\beta_n y)$

and make it's integration in the range from 0 up to b and from 0 up to a, we will obtain the simultaneously differential equations

$$W_{mn} = 32\left[B\left(h+\frac{t}{2}\right)^2\left(2a_m^4 + 2\beta_n^4 + (a_m^2+\beta_n^2)^2 + \right.\right.$$

$$+D\left(\left(2a_m^4 + 2\beta_n^4 + (a_m^2+\beta_n^2)^2\right) + \right.$$

$$\left.+\frac{Bh}{G_3}2D\left(\left(2a_m^6 + 2\beta_n^6 + (a_m^2+\beta_n^2)^3\right)\right] =$$

$$= P_{kp}\left[1 + \frac{Bh}{G_3}8D\left(\left(2a_m^8 + 2\beta_n^8 + (a_m^2+\beta_n^2)\right)\right]\cdot\right.$$

$(m = 1,2)$
$(n = 1,2)$

where

$$a_{mn} = \frac{8}{ah}\int_0^a\int_0^b \left\{\left[B\left(h+\frac{t}{2}\right)^2 + D\right]\left[(\delta_x'' -\right.\right.$$

$$\left. -\bar{\beta}_i^2\delta_x)H_{yy}\sin\bar{\beta}_i\gamma_1 + \delta_x\delta_{yy}\cos\bar{\beta}_i\gamma_1\right] +$$

$$+\frac{Bh}{G_3}D\left[(\delta_x''' - 2\delta_x'')H_{yy}\sin\bar{\beta}_i y +\right.$$

$$+\left(\bar{\beta}_i^4 H_{yy} - 3\bar{\beta}_i^2\delta_{yy}'\right)\delta_x\sin\bar{\beta}_i y +$$

$$\left.\left. +\left(\bar{\beta}_i\delta_{yy} - \bar{3}_i^3\delta_{yy}''\right)\delta_i\cos\bar{\beta}_i y\right]\right\}$$

$$\cdot(1-\cos 2a_m x)(1-\cos 2\beta_m y)dxdy$$

In the first approximation would be accepted $= n = i = 1$ $m \cdot n \cdot i = 1$

then from (7) we will obtain one equation with two unknowns W_{1i} and $\Delta\gamma_{1(i)}$

The second equation we will obtain from the condition to equality to zero of bending moments on line of cut

$$M_1 = D\left(W_x^{*\prime\prime} + \mu W_y^{*\prime\prime}\right) = 0$$

$x = x_1 \qquad b_1 < y < b_2$

This condition accordingly of stating of angle of rotation γ_1 with taking into account that

$$W_x^{*\prime\prime} = (\gamma_1^{*})'_x$$

will be as $M_1 = D\left(W_x'' + \mu W_y''\right) + D\Delta\gamma_1\delta_x H_{yy} = 0$

Due the introduction in these expressions of W and $\Delta\gamma_1$ by formulae (4), and then multiply them on function

$(1 - \cos 2\alpha_m x)(1 - \cos 2\beta_n y)$

and make its integration in the range from 0 up to a and from 0 up to b, we will obtain the simultaneously algebraic equations

$$12W_{mn}\left(\alpha_m^2+\mu\beta_n^2\right)=\sum_i \Delta\gamma_{1(i)}\bar{a}_{imn}$$

$(m=1,2\ldots)$ $(n=1,2\ldots)$

where

$$a_{mn}=\frac{4}{ah}\int_0^a\int_0^b \delta_x H_{yy}\sin\bar{\beta}_i\,\gamma_1(1+$$

$$+\cos 2a_m x)(1-\cos 2\beta_m y)dxdy\,.$$

Then from (9) is obtained one equation that accordingly to equation (5) at $m=n=i=1$

creates the homogeneous system from two equations. By introducing from (9) the value

$$\Delta\gamma_{1(i)}=W_{11}\frac{12(\alpha_1^2+\mu\beta_1^2)}{\bar{a}_{ni}}$$

in the equation (5) and by reducing on W_{11}, we obtain the formula for critical loading

$$P_{kp} = \frac{32\left[\left(B\left(h+\frac{t}{2}\right)^2 + D\right)\left(\left(2a^4 + 2\beta^4 +\right.\right.\right.}{\left[1 + \frac{Bh}{G_3}2D\left(\left(2a_m^2 + 2\beta_n^2 + (a_m^2 + \beta_n^2)\right)\right]\right.}$$

$$\frac{+(2a^2 + 2\beta^2)\big) + \frac{Bh}{G_3}2D(2a_1^6 + 2\beta_1^6 +}{(k_1 a_m^2 + k_2\beta_n^2)\left[1 + \frac{Bh}{G_3}2D(2a_1^2 + 2\beta_1^2 +\right.}$$

$$\frac{-(a_m^2 + \beta_n^2)^3)\big] - 12(a_1^2 + \beta_1^2)\, a_m/a_{11i}}{(a_m^2 + \beta_n^2)\big)\big]\,(k_1 a_m^2 + k_2\beta_n^2)}.$$

At consideration of other terms of series in expansion (4) in the equations (5) and (9) would be accepted corresponding values for m, n and i. As result is obtained homogeneous system of equation.

The critical loading is determined from condition of equality to zero of determinant of this system

$$\det\left|l_{ij}\right| = 0$$

where l_{ij} – is the coefficient of unknowns $\Delta\gamma_{1(n)}$ and W_{mn}

The parameter of critical loading is included in the diagonal elements of determinant.

Is recommended the following algorithm of analysis

1. Will be computed a_{imn} due the formulae (6).

2. Based on the values of coefficients are generated and solved the systems (5) and (9).

3. Is determined the value $\Delta\gamma_{1(1)}$ by formula (11).

4. Is determined the critical value of contour loading (12).

As case is considered the rectangular plate with various length cut. The results of analysis are following (with consideration of second approximation).

$T_{kp} = 0,82T_{kp}^0$ при $b' = b/2$

$T_{kp} = 0,75T_{kp}^0$ при $b' = b/3$

$T_{kp} = 0,66T_{kp}^0$ при $b' = b/4$

where b′is the relative length of cut.

Are stated the algorithm and program of analysis.

3. CONCLUSIONS

In the analysis of thin-walled lamellar systems of complex structure by the large blocks method is applied analytical method developed by grounded on the theory of elasticity in ordinary differential equations.

Based on the Bubnov-Galerkin variation ,method is solved the equation of critical state of compressed plate with cut and are obtained simple approximate formula for determination of critical loading.

Is obtained the possibility of determination of value of drctrasing the critical loading with respect on dimensions and arrangement of cut i/e/ thr drsree of weakening of load bearing capability of plate at caused due cut buckling.

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Thank You for attention