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OPTIMIZATION OF RIBBED PLATE OF FREE VIBRATIONS MADE OF COMPOSITE MATERIAL

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The thin-walled systems intensified with ribs of stiffness are one of the most common structural elements found in various fields of technology.

They have been widely used in civil, industrial and hydraulic engineering, road transport construction, mechanical engineering, shipbuilding and aircraft construction. For designing ribbed structures their comprehensive study is important by taking into account working conditions, the creation of new calculation models, the development and application of modern calculation methods.

The issues of optimal design of ribbed plates are of particular interest due to which it is possible to significantly increase their characteristics of strength, stiffness and stability providing maximum material savings. Moreover, a greater effect can be achieved by manufacturing structures from composite materials (CM). The use of these materials is conditioned by several advantages over traditional materials used in production.

For a plate made of a composite material pivotally supported along two opposite edges and reinforced by a stiffener in the middle of the span or along one of the free edges of the plate, the optimal geometric and physical parameters of the structure are determined which ensure the largest low frequency value for a given overall dimensions and constant weight of the vibrations of the structure.

Key words: optimization, material, plate, rib, oscillation, frequency, the greatest value.

Introduction: The optimal design of thin-walled structural elements is one of the leading directions in the mechanics of a solid deformable body. When designing them, an important problem is to increase the characteristics of strength and stiffness of the structure while ensuring maximum material economy. One way to achieve this goal is to optimally distribute the material of the structure over its volume.

Conflict setting

Free vibrations of a rectangular plate are considered with the dimensions of a, b, h_2, jointed around the edges $y = 0, y = b$ free around the edges $x = \pm a/2$ and reinforced in the middle of the span $x = 0$ with ribs of stiffness of rectangular section ($\alpha h_1 \times h_1$). The case when the edge is located on the edge is also considered $x = a$, and the edge $x = 0$ is free.

It is assumed that the plate is composed of monolayers of fibrous composite material (FCM), stacked alternately at angles $\pm \varphi$ to axis x, and in the ribs the monolayers are oriented along the axis y.

The task is to determine the optimal geometric and physical parameters of the structure h_1, h_2, α, φ, providing the maximum value of the lowest frequency of eigen oscillations of the plate with constant weight and specified overall dimensions of the structure $\xi = (a + \alpha h_1)/b$.

The design problem, reinforced along two edges with stiffeners of a rectangular plate of composite material of the highest lowest frequency of eigen oscillations was considered in [1].

The constancy of the weight of the structure corresponds to the following condition:

$$a(h_0 - h_2) = \alpha h_1 (h_1 - h_0) \tag{1}$$

where h_0 - is the corresponding thickness of a solid plate of a given weight.

The problem of eigen oscillations of a plate is solved which satisfies the conditions of pairing with stiffeners working in bending and torsion. Moreover, in the case when the edge of the plate is located in the middle of the plate due to symmetry half of the plate is considered ($0 \le x \le a/2$) using the study of cases of symmetric and antisymmetric modes of vibration.

The adopted structure of the plate package allows us to consider it orthotropic for which the equation of eigen oscillations is written in the form as follows

$$D_{11}\frac{\partial^4 w}{\partial x^4} + 2(D_{12} + 2D_{66})\frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22}\frac{\partial^4 w}{\partial y^4} + \rho h_2 \frac{\partial^2 w}{\partial t^2} = 0, \qquad (2)$$

where D_{ik} stiffness of the plate is determined by the following formula:

$$D_{ik} = \frac{B_{ik} h_2^3}{12} \qquad (i, k = 1, 2, 6),$$

B_{ik} - the elastic characteristics of the FCM in the main geometric directions of the plate, determined through its characteristics in the main physical directions according to the known rotation formulas [2].

The boundary conditions are written in the form:

-of hinged support

$$w = 0, \qquad \frac{\partial^2 w}{\partial y^2} = 0 \quad \text{when} \quad y = 0, \quad y = b, \qquad (3)$$

- of elastic support, when the stiffener is located in the middle of the span:

in the case of a symmetrical oscillation shape

$$\frac{\partial w}{\partial x} = 0, \; B\frac{\partial^4 w}{\partial y^4} + \rho A\frac{\partial^2 w}{\partial t^2} = -2\left(D_{11}\frac{\partial^3 w}{\partial x^3} + (D_{12} + 4D_{66})\frac{\partial^3 w}{\partial x \partial y^2}\right) \quad \text{when } x = 0, \qquad (4)$$

in case of an antisymmetric oscillation shape

$$w = 0, \quad C\frac{\partial^3 w}{\partial x \partial y^2} - \rho J_k \frac{\partial^3 w}{\partial x \partial t^2} = -2\left(D_{11}\frac{\partial^2 w}{\partial x^2} + D_{12}\frac{\partial^2 w}{\partial y^2}\right) \quad \text{when} \quad x = 0, \qquad (5)$$

- of free edge when the stiffener is located in the middle of the span

$$D_{11}\frac{\partial^2 w}{\partial x^2} + D_{12}\frac{\partial^2 w}{\partial y^2} = 0, \; D_{11}\frac{\partial^3 w}{\partial x^3} + (D_{12} + 4D_{66})\frac{\partial^3 w}{\partial x \partial y^2} = 0, \text{ when } x = a/2 \qquad (6)$$

- of free edge when the stiffener is located on the edge of the plate

$$D_{11}\frac{\partial^2 w}{\partial x^2} + D_{12}\frac{\partial^2 w}{\partial y^2} = 0, \; D_{11}\frac{\partial^3 w}{\partial x^3} + (D_{12} + 4D_{66})\frac{\partial^3 w}{\partial x \partial y^2} = 0, \text{ when } \quad x = 0, \qquad (7)$$

- of elastic support when the stiffener is located on the edge of the plate

$$B\frac{\partial^4 w}{\partial y^4} + \rho A\frac{\partial^2 w}{\partial t^2} = D_{11}\frac{\partial^3 w}{\partial x^3} + (D_{12} + 4D_{66})\frac{\partial^3 w}{\partial x \partial y^2},$$

$$C\frac{\partial^3 w}{\partial x \partial y^2} - \rho J_k \frac{\partial^3 w}{\partial x \partial t^2} = D_{11}\frac{\partial^2 w}{\partial x^2} + D_{12}\frac{\partial^2 w}{\partial y^2}, \quad \text{when} \quad x = a, \qquad (8)$$

where $B = E\alpha h_1^4/12$ is rib stiffness at bending, $A = \alpha h_1^2$ is rib cross-sectional area, C is rib stiffness torsion determined by the following formula:

$$[3]\; C = G_{23} J_k, \quad J_k = \alpha h_1^4 \beta, \quad \beta = d^2\left[\frac{1}{3} - \frac{64}{\pi^5} d \sum_{1,3,\ldots} \frac{1}{n^5} th \frac{\pi n}{2d}\right], \quad d = \alpha\sqrt{\frac{G_{23}}{G_{13}}},$$

G_{13}, G_{23} - shear module of rib material in planes xoz and yoz.

The second terms in the left-hand sides of conditions (5) and (8) take into account the influence of inertial forces during torsional vibrations of the rib. In further numerical calculations, it is shown that the influence of these members is insignificant and when solving the tasks they may be omitted:

The solution of equation (2) satisfying conditions (3) is taken in the form

$$w=\begin{pmatrix} C_{1m}ch\mu_{1m}\lambda_m x + C_{2m}sh\mu_{1m}\lambda_m x + C_{3m}\cos\mu_{2m}\lambda_m x + \\ + C_{4m}\sin\mu_{2m}\lambda_m x \end{pmatrix}\sin\omega_m t\sin\lambda_m y, \tag{9}$$

where

$$\mu_{1m}=\sqrt{\frac{\sqrt{D_3^2+D_{11}D_{22}\left(k_m^2-1\right)}+D_3}{D_{11}}},\quad \mu_{2m}=\sqrt{\frac{\sqrt{D_3^2+D_{11}D_{22}\left(k_m^2-1\right)}-D_3}{D_{11}}},$$

$$\lambda_m=\frac{m\pi}{b},\quad D_3=D_{12}+2D_{66},\quad k_m^2=\omega_m^2\frac{\rho h_2}{D_{22}\lambda_m^2}, \tag{10}$$

ω_m - is the frequency of eigen oscillations of the plate.

In the case when the rib is located in the middle of the plate, the satisfaction of conditions (4), (6) leads to a homogeneous linear system of equations with respect to the coefficients C_{im} $(i=1,2,3,4)$. From the condition for the existence of a nontrivial solution of this system, we obtain the following transcendental equation with respect to the coefficient k_m for the case of a symmetric form of oscillations

$$\begin{aligned} H_1(k_m)=&\left[f_1 ch\mu_{1m}\lambda_m \tfrac{a}{2}-f_0f_5\right]\times\left[\mu_{2m}f_4\sin\mu_{2m}\lambda_m\tfrac{a}{2}-f_0f_6\right]-\\ &-\left[f_2\cos\mu_{2m}\lambda_m\tfrac{a}{2}+f_0f_5\right]\times\left[\mu_{1m}f_3 sh\mu_{1m}\lambda_m\tfrac{a}{2}-f_0f_6\right]=0, \end{aligned} \tag{11}$$

where

$$f_0=\frac{B_{22}m\pi\alpha\, h_1^2}{B_{11}h_2 b}\left(\frac{E_1}{B_{22}}\frac{h_1^2}{h_2^2}-k_m^2\right),\quad f_1=\frac{B_{11}\mu_{1m}^2-B_{12}}{B_{22}},\quad f_2=\frac{B_{11}\mu_{2m}^2+B_{12}}{B_{22}},$$

$$f_3=\frac{B_{11}}{B_{22}}\mu_{1m}^2-\frac{B_{12}+4B_{66}}{B_{22}},\qquad f_4=\frac{B_{11}}{B_{22}}\mu_{2m}^2+\frac{B_{12}+4B_{66}}{B_{22}},$$

$$f_5=\frac{1}{2\left(\mu_{1m}^2+\mu_{2m}^2\right)}\times\left(\frac{f_1}{\mu_{1m}}sh\mu_{1m}\lambda_m\tfrac{a}{2}+\frac{f_2}{\mu_{2m}}\sin\mu_{2m}\lambda_m\tfrac{a}{2}\right),$$

$$f_6=\frac{1}{2\left(\mu_{1m}^2+\mu_{2m}^2\right)}\times\left(f_3 ch\mu_{1m}\lambda_m\tfrac{a}{2}+f_4\cos\mu_{2m}\lambda_m\tfrac{a}{2}\right)$$

In the case of the antisymmetric form, the satisfaction of conditions (5), (6) leads to the following transcendental equation with respect to the coefficient k_m

$$\begin{aligned} H_2(k_m)=&\left[f_1 sh\mu_{1m}\lambda_m\tfrac{a}{2}+\mu_{1m}f_7f_9\right]\times\left[-\mu_{2m}f_4\cos\mu_{2m}\lambda_m\tfrac{a}{2}+\mu_{2m}f_8f_9\right]+\\ &+\left[f_2\sin\mu_{2m}\lambda_m\tfrac{a}{2}-\mu_{2m}f_7f_9\right]\times\left[\mu_{1m}f_3 ch\mu_{1m}\lambda_m\tfrac{a}{2}+\mu_{1m}f_8f_9\right]=0, \end{aligned} \tag{12}$$

where

$$f_7=\frac{1}{2\left(\mu_{1m}^2+\mu_{2m}^2\right)}\times\left(f_1\, ch\mu_{1m}\lambda_m\tfrac{a}{2}+f_2\cos\mu_{2m}\lambda_m\tfrac{a}{2}\right),$$

$$f_8 = \frac{1}{2\left(\mu_{1m}^2 + \mu_{2m}^2\right)} \times \left(\mu_{1m} f_3 sh\mu_{1m}\lambda_m \, a/2 - \mu_{2m} f_4 \sin\mu_{2m}\lambda_m \, a/2\right),$$

$$f_9 = \frac{B_{22} m^3 \pi^3 \alpha h_1^4 \beta}{B_{11} b h_2}\left(\frac{12 G_{23}}{B_{22} h_2^2 m^2 \pi^2} - k_m^2\right).$$

In the case when the rib is located on the edge of the plate, the satisfaction of conditions (7) and (8) leads to the following transcendental equation with respect to the coefficient k_m

$$\begin{aligned} H_3(k_m) = &\left(-\mu_{2m} q_0 \sin\mu_{1m}\lambda_m a + q_5 \cos\mu_{2m}\lambda_m a + q_1\right)\times \\ &\times\left(f_0 \sin\mu_{2m}\lambda_m a + \mu_{2m} f_4 \cos\mu_{2m}\lambda_m a + q_4\right) - \\ &-\left(\mu_{2m} q_0 \cos\mu_{2m}\lambda_m a + q_5 \sin\mu_{2m}\lambda_m a + q_3\right)\times \\ &\times\left(f_0 \cos\mu_{2m}\lambda_m a - \mu_{2m} f_4 \sin\mu_{2m}\lambda_m a + q_2\right) = 0, \end{aligned} \tag{13}$$

where

$$q_0 = \frac{m^3 \pi^3 \alpha h_1^4 \beta}{b h_2}\left(\frac{12 G_{23}}{B_{22} h_2^2 m^2 \pi^2} - k_m^2\right), \quad q_1 = \frac{f_2}{f_1}\left(\mu_{1m} q_0 sh\mu_{1m}\lambda_m a - f_1 ch\mu_{1m}\lambda_m a\right),$$

$$q_2 = \frac{f_2}{f_1}\left(f_0 ch\mu_{1m}\lambda_m a - \mu_{1m} f_3 sh\mu_{1m}\lambda_m a\right),$$

$$q_3 = \frac{\mu_{2m} f_4}{\mu_{1m} f_3}\left(\mu_{1m} q_0 ch\mu_{1m}\lambda_m a - f_1 sh\mu_{1m}\lambda_m a\right),$$

$$q_4 = \frac{\mu_{2m} f_4}{\mu_{1m} f_3}\left(f_0 sh\mu_{1m}\lambda_m a - \mu_{1m} f_3 ch\mu_{1m}\lambda_m a\right), \quad q_5 = \frac{B_{11}\mu_{2m}^2 - B_{12}}{B_{22}}.$$

After determining the coefficient k_m, from equations (11) - (13) the value of the frequency of eigen oscillations according to (9) is determined by the following formula, respectively

$$\omega_m = \lambda_m^2 k_m \sqrt{\frac{D_{22}}{\rho h_2}}. \tag{14}$$

The optimization task is to redistribute the material of the ribbed structure between the rib and the plate in such a way as to ensure the highest value of the lowest frequency of eigen oscillations at given overall dimensions ξ and the condition of constant weight of the structure (1). Determination of the optimal design parameters is limited to the following nonlinear programming problem:

To find:

$$\omega_o = \max_{\bar{x}} \min_m \omega_m, \qquad \bar{x} = \{\alpha, h_1, h_2, \varphi\}, \tag{15}$$

under restrictions

$$H_i(k_m) = 0 \quad (i = 1,2,3), \;\; h_2 = h_0 - \frac{3\alpha h_1}{2a}(h_1 - h_0), \tag{16}$$

$$h_0 \le h_1 \le 0.2b, \quad 0.2 \le \alpha \le 5, \quad \delta \le h_2 \le h_0. \tag{17}$$

The first of the restrictions in the form of equation (16) corresponds to equations (11) - (13) with respect to k_m, the second follows from the condition that the weight of the structure (1) is constant. Limitations in the form of inequalities (17) are due to the limits of applicability of the classical theory of beams and plates. For δ $\delta = 0.01b$ is accepted when $a \ge b$, $\delta = 0.01a$, when $a \le b$.

The problem is solved by the method of deformable polyhedron in combination with the direct search method [4].

Numerical calculations are made for a design with overall dimensions $\xi = 1, 2$ when $\bar{h}_0 = h_0 / b = 0.015,\ 0.02,\ 0.03$. The FCM with the following characteristics was adopted as a material

$$\bar{B}^0_{11} = 1; \bar{B}^0_{22} = B^0_{22} / B^0_{11} = 0.0818; \bar{B}^0_{12} = B^0_{12} / B^0_{11} = 0.0196; \bar{B}^0_{66} = B^0_{66} / B^0_{11} = 0.04297;$$

$$G_{23} / G_{13} = 1; \quad \bar{E}_1 = E_1 / B^0_{11} = 0.995; \quad \bar{G}_{23} = G_{23} / B^0_{11} = 0.0497.$$

The optimal parameter values α, $\bar{h}_1 = h_1 / b,\ \bar{h}_2 = h_2 / b,\ \varphi$ and corresponding values of the reduced frequency of eigen oscillations $\bar{\omega}_o = \omega_o / \sqrt{\rho b^2 / B^0_{11}}$ are calculated.

Research results

The results of calculation for the case when the rib is located in the middle of the span of the plate are shown in Table 1. For comparison, the corresponding frequency values for equilibrium plates with two stiffeners located along its edges $\bar{\omega}^*_o$ and in the absence of ribs $\bar{\omega}^0$ are also given there.

Table 1

ξ	$\bar{h}_0$	α	$\bar{h}_1$	$\bar{h}_2$	φ	$\bar{\omega}_o$	$\bar{\omega}^*_o$	$\bar{\omega}^0$
1	0.015	0.2	0.0935	0.0120	45°	0.0512	0.0624	0.0427
	0.020	0.2	0.1127	0.0157	45°	0.0669	0.0869	0.0569
	0.030	0.2	0.1469	0.0229	45°	0.0974	0.1350	0.0854
2	0.015	0.2	0.0434	0.0147	90°	0.0429	0.0430	0.0427
	0.020	0.2	0.0516	0.0197	90°	0.0571	0.0574	0.0569
	0.030	0.2	0.0662	0.0295	90°	0.0855	0.0859	0.0854

Calculations show that in all studied cases optimal projects are obtained when $m = 1$, while in the case $\xi = 1$ asymmetric form of oscillations takes place and when $\xi = 2$, symmetric form of oscillations takes place. Comparison of the results shown in Table 1 shows that the value of the lowest frequency of eigen oscillations for an optimal project $\bar{\omega}_o$ when $\xi = 1$ almost 1.2 times greater than the corresponding values for continuous plate $\bar{\omega}^0$ and as much less than for a plate with two ribs $\bar{\omega}^*_o$. Obviously, as the parameter ξ increases, the vibrating effect decreases.

For the case when the stiffener is located on the right edge of the plate, the calculation results are shown in Table 2.

Table 2

ξ	$\bar{h}_0$	α	$\bar{h}_1$	$\bar{h}_2$	φ	$\bar{\omega}_o$
1	0.015	0.2	0.0354	0.0148	90°	0.0427
	0.020	0.2	0.0431	0.0198	90°	0.0572
	0.030	0.2	0.0561	0.0297	90°	0.0857
2	0.015	0.2	0.0273	0.0150	90°	0.0428
	0.020	0.2	0.0339	0.0199	90°	0.0570
	0.030	0.2	0.0427	0.0299	90°	0.0855

Here, the optimal projects are obtained when $m = 1$, and the values $\bar{\omega}_o$ are close to the corresponding values $\bar{\omega}^0$ for a solid plate.

Conclusion

Thus, the location of the stiffener in the middle of the span of the plate leads to a greater increase in the lower frequency of eigen oscillations than its location on the edge of the plate. It should also be noted that the increase in the number of ribs while maintaining the total weight of the structure, according to Table 1, also leads to an increase in its lowest frequency of eigen oscillations.

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ԿՈՄՊՈԶԻՑԻՈՆ ՆՅՈՒԹԻՑ ՊԱՏՐԱՍՏՎԱԾ ԿՈՂԱՎՈՐ ՍԱԼԻ ՕՊՏԻՄԱԼԱՑՈՒՄԸ ԱԶԱՏ ՏԱՏԱՆՈՒՄՆԵՐԻ ԴԵՊՔՈՒՄ

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Հայաստանի ազգային պոլիտեխնիկական համալսարան

Կոշտության կողերով ուժեղացված բարակապատ համակարգերը տեխնիկայի տարբեր բնագավառների կառույցների հաճախակի հանդիպող տարրերից են: Դրանք լայն կիրառություն են գտել արդյունաբերական, քաղաքացիական, հիդրոտեխնիկական, ճանապարհային շինարարությունում, նավաշինության, մեքենաշինության, ինքնաթիռաշինության մեջ: Կողավոր կառուցվածքների նախագծման ժամանակ կարևոր նշանակություն ունի տարբեր աշխատանքային պայմաններում դրանց համակողմանի ուսումնասիրությունը, հաշվարկային նոր մոդելների ստեղծումը, ժամանակակից մեթոդների կիրառումը և մշակումը:

Առանձնակի հետաքրքրություն են ներկայացնում կողավոր սալերի օպտիմալ նախագծման հարցերը, որոնց շնորհիվ կարելի է էապես մեծացնել դրանց ամրության, կոշտության և կայունության բնութագրերը՝ ապահովելով նյութի առավել տնտեսումը:

Առավել մեծ արդյունավետության կարելի է հասնել, երբ կառուցվածքները պատրաստված են կոմպոզիցիոն նյութերից /ԿՆ/: Ժամանակակից տեխնիկայի բնագավառներում այդ նյութերի կիրառումը պայմանավորված է մի շարք կարևոր առավելություններով արտադրությունում օգտագործվող ավանդական նյութերի նկատմամբ: Դիտարկվում է երկու հանդիպակած կողմերով հոդակապորեն ամրացված կոմպոզիցիոն նյութից պատրաստված ուղանկյուն սալը, որը թռիչքի մեջտեղում կամ ազատ եզրերից մեկում ուժեղացված է կոշտության կողով: Որոշվում են սալի օպտիմալ երկրաչափական և ֆիզիկական պարամետրերը, որոնք հաստատուն կշռի դեպքում ապահովում են նրա սեփական տատանումների ստորին հաճախության առավելագույն արժեքը:

Բանալի բառեր. օպտիմալացում, նյութ, սալ, կող, տատանում, հաճախություն, կոմպոզիցիոն նյութ, առավելագույն արժեք:

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ОПТИМИЗАЦИЯ РЕБРИСТОЙ ПЛАСТИНКИ ИЗ КОМПОЗИЦИОННОГО МАТЕРИАЛА ПРИ СВОБОДНЫХ КОЛЕБАНИЯХ

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Тонкостенные системы, усиленные ребрами жесткости, являются одним из наиболее распространенных конструктивных элементов, встречающихся в различных областях техники. Они получили широкое применение в гражданском, промышленном, гидротехническом, дорожно-транспортном строительстве, машиностроении, судостроении, самолетостроении.

При проектировании ребристых конструкций важное значение имеет их всестороннее изучение с учетом условий работы, создание новых расчетных моделей, разработка и применение современных методов расчета. Особый интерес представляют вопросы оптимального проектирования ребристых пластин, благодаря чему можно значительно увеличить их характеристики прочности, жесткости и устойчивости, обеспечивая максимальную экономию материала. При этом большего эффекта можно добиться путем изготовления конструкций из композиционных материалов (КМ). Использование этих материалов обусловлено рядом их преимуществ по сравнению с применяемыми в производстве традиционными материалами.

Для пластинки, изготовленной из композиционного материала, шарнирно опертой по двум противоположным краям и усиленной ребром жесткости в середине пролета или по одному из свободных кромок пластинки, определяются оптимальные геометрические и физические параметры конструкции, обеспечивающие при заданных габаритных размерах и постоянном весе конструкции наибольшее значение низшей частоты собственных колебаний.

Ключевые слова: оптимизация, материал, пластинка, ребро, колебание, частота, наибольшее значение.

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