Сендвічеві багатовідсікові оболонкові конструкції з несучими обшивками із полімерних композиційних матеріалів і стільниковим заповнювачем знайшли широке застосування у виробах різних класів техніки. Цей тип конструкцій дозволяє реалізувати одні з найвищих показників питомої міцності і жорсткості при мінімальній масі, що є одним з визначальних критеріїв ефективності різних агрегатів. У зв'язку з тим, що дана конструктивно-силова схема містить дуже велику кількість параметрів, при зміні яких істотно змінюється маса виробу, до теперішнього часу відсутні загальноприйняті методики їх оптимального проектування.

Стаття присвячена розробці нової методики оптимізації сендвічевих оболонкових композитних конструкцій зі стільниковим заповнювачем. Змінними параметрами в методіці є товщини несучих обшивок, стільникового заповнювача і поясів шпангоутів, геометричні параметри стільників, а також враховувується технологічна механіка конструкцій.

Відмінною особливістю методики є облік при її реалізації технологічних (монтажних) і експлуатаційних поводок розглянутих оболонкових систем. У статті проведено аналіз взаємного впливу таких поводок, а також показана можливість дослідження їх залежності від параметрів навантаження для заданих амплітуд початкових прогинів технологічного походження. Отримані результати дозволяють визначити оптимальний вид армування несучих композитних обшивок при дії осьового стискання, поперечного тиску і згинального моменту з урахуванням технологічних і експлуатаційних прогинів сендвічевої оболонкової системи. Розроблена методика та її програмне забезпечення реалізували всі основні залежності механічних характеристик стільників від їх геометричних параметрів і матеріалу. Це дозволило процес оптимального проектування розглянутого класу конструкцій пов'язати з технологічними процесами формування виробу і можливостями конкретного виробництва за конструкційними матеріалами і номенклатурою стільників. Реалізація запропонованої методики для оптимізації параметрів багатовідсікової сендвічевої оболонкової композитної системи типу головного обтічника космічної ракети-носія виявила її ефективність, що виразилася в зниженні маси оптимального виробу. Показано, що застосування стільників неправильної шестигранної форми є досить ефективним засобом зниження маси системи

Ключові слова: сендвічеві оболонкові конструкції, композитні несучі обшивки, стільниковий заповнювач, оптимізація параметрів

UDC 629.7.01:539.4
DOI: 10.15587/1729-4061.2019.154928

WEIGHT-BASED OPTIMIZATION OF SANDWICH SHELLED COMPOSITE STRUCTURES WITH A HONEYCOMB FILLER

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1. Introduction

An analysis of existing practice in the development and operation of high-loaded units of different designs showed that sandwich structures with composite skin combined with the honeycomb filler (HF) are widely used today [1, 2]. This type of structural-power configuration (SPC) makes it possible to realize one of the highest indicators of specific strength and stiffness at minimal weight, which is the determining criterion of the effectiveness of units of different classes of equipment [3, 4]. The degree of implementation of these possibilities depends on the effectiveness of the accepted design-technological solutions, detectable as a result of the optimization in the process of product designing. The structures under consideration contain a very large number of parameters, at the change of which the weight of the product changes substantially. Thus, the character of changes in the thickness of composite load-bearing skin is associated with the need to take into account a change in their physical-mechanical characteristics (FMC) due to the reinforcement variations. Wide possibilities of variation in the FMC of HF with the change of geometrical parameters of its cell also complicate the possibility of setting and realization of the problem of optimal designing due to the increasing number of variable parameters. Until now, there have been no methods for optimal designing the sandwich shelled composite structures, where variable parameters would be the thicknesses of load-bearing skin, HF and bands of frames, and honeycomb geometric parameters [5, 6].

All the above testifies to the relevance of conducting the studies on the development of the methods for optimization, leading eventually to the product of the minimum weight, taking into consideration the regulated limits.

2. Literature review and problem statement

Paper [7] examines the problems of optimization of cylindrical shells of homogeneous and non-homogeneous thickness, forming an irregular periodic structure. The authors explored the package of the polymer composite material (PCM), composed of the layers of different types at fixed reinforcement angles, as load-bearing skins. The calculation programs, with the help of which the analysis of load-bearing capacity and optimization of load-bearing shells was performed, were developed. However, the given results were obtained by the action of isolated axial compression alone.

In papers [8, 9], the techniques for rationalization of the problems of designing the composite load-bearing shells were explored. Based on the examples of actual structures, the methodology for determining the areas of rational use of different SPC of cylindrical composite shells was shown. The optimum structures, designed for taking up compressive loads of the shells with a fixed number of layers, were obtained and explored. However, the methods for solving optimization problems presented in these papers indicate substantial idealization of representation of the considered objects and external influences that influence them.

In papers [10, 11], the developed methods for determining the limit loads for the shelled composite structures were systematized. The papers studied stability of the shells for different types of loading, as well as the influence of the configurations of reinforcement of load-bearing skins on the limit loads and deformation of shells. The common drawback of the papers is that the authors paid significant attention to the theory of calculation of extreme loads, based on the use of generalized PCM characteristics, which can be obtained only for separate samples of the structure.

Paper [12] addresses problems of optimization of parameters of honeycomb filler [12]. The authors developed the concept, the essence of which is the proposed method for analytical prediction of the maximum possible reduction of the weight of composite structures for space purposes, taking into consideration the technological possibilities for their manufacturing. However, this work uses a simplified calculation scheme, which is the reason of predictably approximate results. Such simplification is also used in the studies by other authors, for example [13].

Study [14] deals with the optimization of load-bearing skin, taking into consideration the design-technological restrictions for the thickness of PCM package. The study proposed the algorithms that allow taking into account discreteness of a change in layers' thickness and limitations on angles of laying. Although the proposed algorithms are direct selection of all possible integer options of PCM reinforcement for a plate with the structure [0; $\pm\varphi$], they allow reducing significantly the optimization procedure, as it discards non-optimal decisions beforehand. However, the application of the obtained results to sandwich shells with honeycomb fillers in combined loading requires corresponding generalization of the proposed algorithms.

The approach [15, 16] is based on the implementation of the analytical mathematical model that makes it possible to establish the total loss of stability of the conical and cylindrical sandwich shell under the action of compressive force, uniform external pressure and torque.

The common feature of the selected above papers is that most of the approaches proposed in them are based on some heuristic additional assumptions, such as equal strength, equal deformation and so on. Realization of these assumptions, according to the authors, guarantees the improvement of the product parameters. However, the errors that are brought in by this idealization can not only neutralize the advantages of the original analytical models, but also cause the mismatch of the actual and predicted load-bearing capability of products. It should also be noted that a characteristically small number of variable parameters is usually considered during optimization calculations. Given that actual composite honeycomb structures have quite a large number of design parameters, generalization of the approaches proposed in the considered papers looks problematic.

Consideration of the HF design parameters, given technological mechanics of its manufacture, was implemented in [17]. However, the proposed procedure only with some adjustment can be used to optimize by weight the parameters of honeycomb shells during separating them into cylindrical panels that are attached to each other.

At present, information technologies lie at the base of the scientific and technological support of the effectiveness of optimal designing and manufacturing composite structures with HF [18, 19]. Great capabilities of these technologies make it possible to abandon analytical models for determining the stressed-strained state (SSS) in favor of the simulation of an object. The undeniable advantage of using these technologies is the possibility to exclude a number of errors during determining the SSS pertaining to or related to the use of analytical models. However, the labor consumption of such approaches is obviously justified only in cases when it is necessary to conduct verification calculation of SSS.

The possibility of optimization with the help of information technologies using different types of restrictions for a large number of simultaneously varied parameters makes it possible to realize more fully hidden reserves of the designed structure. An attempt to solve the problem of reducing the weight of composite honeycomb structures for space purposes by optimizing their parameters, based on the synthesis of information technologies of finite-element analysis and analytical models was undertaken in study [20]. Different conceptual approaches to the weight-based optimization of multi-compartment sandwich shelled structures with the HF were analyzed in it. The integrated approach to the optimization of shelled structures that can extend the range of the considered optimization parameters was proposed. The authors obtained the results that include the concept of minimizing the weight of multi-compartment composite shells with HF with the multi-stage algorithm of implementation, which was developed and implemented on the example of actual products – the nose fairing of the launch vehicle. This enabled the authors to reach a rather deep level of simultaneous optimization within each compartment of the configuration of laying load-bearing skin, geometric parameters of honeycomb and frames when applying virtually the entire range of external influences to the unit. However, this approach to optimization, as well as the other approaches based on information technologies makes it possible to solve only a specific task. Such approaches usually do not make it possible to generalize the obtained results in the light of technological and other restrictions.

Research of some authors, generalized in [21], resulted in finding that critical compressive force, for example, of the cylindrical thin composite shell, decreases insignificantly if technological deflection of the shell does not exceed 0.1 of its thickness. Similar results were obtained for sandwich shells with the light filler [22]. In addition to random (usually neo-symmetric) shell deflections, related to the technology of their manufacturing, it seems necessary to take into consideration the actual neo-symmetric deflection. Such deflections occur when load of even perfectly constructed shell with operational loads, resulting in bending and compression. Calculations show that this deflection may exceed significantly a non-symmetric accidental deflection of technological origin [23]. The technological method for manufacturing cylindrical or conical shells from two or four shrouds with their subsequent attachment during assembly can be a vivid example of this kind of technological deflections [24]. Regardless of the nature of initial deflections, it is difficult to consider their impact on the stability of the orthotropic shell under the action of axial compression and transversal pressure when setting this problem taking into account geometrical non-linearity [25].

Analysis of mutual influence of this deflection and regular neo-symmetric (or axially-symmetric) deflection of technological origin, which is the inevitable consequence of implementing a particular technology of manufacturing and subsequent assembly of the shell structure, seems rather informative.

Based on the performed review of the problem, it can be concluded that most of the currently available results were obtained with very significant limitations and mainly for ideal calculation configurations. This requires further in-depth studies in this direction taking into consideration the structures of combination of external influences that are characteristic for the considered class. It is also necessary to take into account the capabilities of specific manufacturing by structural materials and nomenclature of HF as the weakest link of the sandwich composite when optimizing by weight the parameters of this type of structures.

All the above testifies to the need to develop a procedure to optimize by weight the sandwich shelled composite structures with HF.

3. The aim and objectives of the study

The aim of this research is to minimize the weight of multi-compartment sandwich shelled composite structures with honeycomb filler by optimizing their parameters, taking into consideration the regulated limits.

To accomplish the set goal, the following tasks were solved:

– to develop the procedure for optimization of sandwich shelled composite structures with the honeycomb filler. In this case, the variable parameters in the procedure should include thicknesses of load-bearing panels, honeycomb filler and bands of frames, honeycomb geometric parameters, taking into account technological mechanics of the structure;

– to implement in practice the developed procedure for minimizing the weight of the multi-compartment sandwich shelled structure of the nose fairing type.

4. Materials and methods of research

Determining critical forces is based on the general assumptions of the theory of slope shells. The hypothesis of Kirchhoff-Love for external load-bearing skin, made of PCM, is thought to be valid. For the filler, the linear law of cross-section distributions along the height is accepted, while deformations in the transverse direction are not taken into account. Reinforcing fibers of PCM are laid symmetrically relative to the median surface of the package and skin curvature lines. The initial stressed state of the shell until stability is lost is supposed to be moment-free. The solution of the original system is carried out by the Bubnov-Galerkin method, which leads to the system of linear equations that describe bulging of shells. The obtained equations make it possible to determine the optimal type of reinforcement under the action of axial compression and transversal pressure given the symmetrical and asymmetrical deflections at specified elastic properties of a unidirectional monolayer. The critical load is determined by the inflection point, or limit point on the curves of equilibrium states. During optimization, the method of coordinate-by-coordinate descent for the three coordinates was used.

5. Procedure for weight-based optimization of multi-compartment sandwich shelled composite structures with honeycomb filler

The following sets out the procedure for solving the problem of optimization of multi-compartment sandwich systems, in which the optimized parameters include characteristics of orthotropic HF with the cell of the generalized form (Fig. 1). In this case, the system consisting of conical and cylindrical composite shells was explored considering their deformability.

Regarding the shell, the following assumptions were accepted. The sandwich shell consists of two thin external load-bearing skins of equal thicknesses δ_{cl} and significantly thicker HF having height h_{hc}. The external skin of the shell is considered to be monolithic, homogeneous and orthotropic. HF is easy, orthotropic and homogeneous, that is, it exists in the estimated model of listed mechanical properties ρ_{hc}, G_{xz}^{hc} and G_{yz}^{hc} as an orthotropic body. The values of HF depend on the honeycomb material and cell parameters t_c, a_c, K and β [26]. The optimization cycle implies using the parameters of honeycomb cell as structural variables. At the same time, in the FMC unit implies the use of analytical dependences $\rho_{hc} = f(a_c, t_c, K, \beta)$, $G_{xz}^{hc} = f(a_c, t_c, K, \beta)$; $G_{yz}^{hc} = f(a_c, t_c, K, \beta)$, adjusted with regard to the technological factors [27] (Fig. 1).

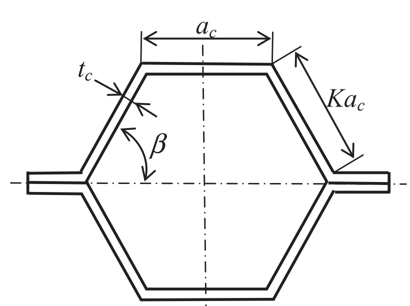

Fig. 1. Parameters for geometry of a honeycomb cell of the generalized form

Reinforcing fibers of PCM are laid symmetrically in the relation to the median surface of the package and lines of main curvatures, along which coordinate axes are selected. The initial stressed state until stability is lost is assumed to be momentless.

At the place of the junction of load-bearing skin with the filler, there in the influence of tangent shear stresses in the planes normal to the load-bearing layers. For load-bearing skin, the hypothesis of direct normals is accepted. Displacement of the filler is considered to be linearly changing along the height. Elastic symmetry of load-bearing skin takes place regarding a forming shell and a guiding circle.

Thus, the geometrical parameters of the shells δ_{cl} and h_{hc} and honeycombs FMC, at which a compartment does not lose stability ($\lambda_{cr} \geq 1$), can be obtained at the known external loads and non-deformable contours of face frames. In this case, the material of the orthotropic skin is considered to be known. Its properties are determined from expressions [28, 29]:

$$E_x = A_{11} - \frac{A_{12}^2}{A_{22}}; \quad E_y = A_{22} - \frac{A_{12}^2}{A_{11}}; \quad G_{xy} = A_{66};$$

$$\mu_{xy} = \frac{A_{12}}{A_{22}}; \quad \mu_{yx} = \frac{A_{12}}{A_{11}}; \quad A_{ij} = \frac{1}{\delta}\sum_{k=1}^{n} C_{ij}\delta_k, \tag{1}$$

$$C_{11}^k = \frac{1}{1-\mu_{12}\mu_{21}}\left(\begin{array}{l} E_1\cos^4\theta + E_2\sin^4\theta + \\ +\dfrac{1}{2}E_2\mu_{12}\sin^2 2\theta \end{array}\right) + G_{12}\sin^2 2\theta;$$

$$C_{22}^k = \frac{1}{1-\mu_{12}\mu_{21}}\left(\begin{array}{l} E_1\sin^4\theta + E_2\cos^4\theta + \\ +\dfrac{1}{2}E_2\mu_{12}\sin^2 2\theta \end{array}\right) + G_{12}\sin^2 2\theta;$$

$$C_{12}^k = \frac{1}{1-\mu_{12}\mu_{21}}\left[\begin{array}{l} \dfrac{1}{4}(E_1+E_2)\sin^2 2\theta + \\ + E_2\mu_{12}\left(\cos^4\theta + \sin^4\theta\right) \end{array}\right] - G_{12}\sin^2 2\theta;$$

$$C_{66}^k = \frac{\sin^2 2\theta}{4(1-\mu_{12}\mu_{21})}\left(E_1 + E_2 - 2E_2\mu_{12}\right) + G_{12}\cos^2 2\theta, \tag{2}$$

where E_x, E_y, G_{xy}, μ_{xy}, μ_{yx} are the modules of elasticity, shear, Poisson's coefficients of the composite load-bearing skin; E_1, E_2, G_{12}, μ_{12}, μ_{21} are the modules of elasticity, shear, Poisson's coefficients of mono-layers; Θ is the angle of laying mono-layers, δ_k is the thickness of the k-th monolayer, forming the composite load-bearing skin.

The specific use of the optimization procedure requires extremely high rigidity of compartment frames. In this case, the weight of the frames exceeds the weight of the shell itself and this approach does not lead to optimal by weight design of the system in general [20]. That is why the load-bearing skin of the shell and parameters of HF are selected so that the shell itself provides the parameter of critical load $\lambda_{cr} > 1$, that is it has a certain stability margin. This stability margin is compensated by flexible frames, allowing a decrease in the critical load at general deformation of the system. The stiffness of the frames and, therefore, their weight is selected on condition of ensuring the regulated deflection of the system. The total weight of the system of the shell and frames will be less than the total weight of the system during selection of the geometrical parameters of shell from the condition that $\lambda_{cr} = 1$.

Equation of deformation of the flat composite shell takes the form of [21]:

$$\frac{\Phi_{xxxx}}{\delta E_y} + \frac{1}{\delta}\left(\frac{1}{G_{xy}} - \frac{\nu_{xy}}{E_x} - \frac{\nu_{yx}}{E_y}\right)\Phi_{xxyy} + \frac{\Phi_{yyyy}}{\delta E_x} =$$

$$= \frac{1}{R}\left(w - w_0\right)_{xx} + w_{xy}^2 - w_{0\,xy}^2 - w_{xx}w_{yy} + w_{0\,xx}w_{0\,yy}; \tag{3}$$

$$D_1\left(w_{xxxx} - w_{0\,xxxx}\right) + 2D\left(w_{xxyy} - w_{0\,xxyy}\right) +$$

$$+ D_2\left(w_{yyyy} - w_{0\,yyyy}\right) + \frac{1}{R}\Phi_{xx} + \Phi_{yy}w_{xx} +$$

$$+ \Phi_{xx}w_{yy} + 2\Phi_{xy}w_{xy} + q = 0. \tag{4}$$

Here

$$D = D_1\mu_{yx} + 2D_{12}; \quad D_1 = \frac{E_x\delta_{cl}^3}{12\left(1-\mu_{xy}\mu_{yx}\right)};$$

$$D_2 = \frac{E_y\delta_{cl}^3}{12\left(1-\mu_{xy}\mu_{yx}\right)}; \quad D_{12} = \frac{G_{xy}\delta_{cl}^3}{12};$$

w, w_o are the current and initial deflections; Φ is the function of stresses (indices x and y correspond to particular derivatives); R is the radius of the shell.

The initial deflection is assigned in the form [21]:

$$w_0 = f_{0asym}\sin\frac{\alpha x}{2}\sin\beta y + f_{0sym}\cos\alpha x, \tag{5}$$

where $\alpha = \pi/L$, $\beta = m/R$, f_{0asym}, f_{0sym} are the amplitudes of the initial non-symmetric and symmetric deflections; α, β are the parameters of wave formation.

The deflection is assigned in the similar form:

$$w = f_{asym}\sin\frac{\alpha x}{2}\sin\beta y + f_{sym}\cos\alpha x. \tag{6}$$

The solution to the original system using the Bubnov-Galerkin method leads to the system of nonlinear equations that describe bulging of orthotropic cylindrical shells:

$$-\left(\frac{16}{3}\frac{v^0}{K^0} + \frac{\lambda^0}{\eta^2\theta}\right)(\xi - \xi_0) + \frac{\lambda^0}{4\eta^0 v^{02}}\left(\xi_{asym}^2 - \xi_{0asym}^2\right) +$$

$$+ \frac{2v^{02}}{\eta^0\rho_1}\left(\xi_{asym} - \xi_{0asym}\right)\xi_{asym} -$$

$$- 8v^{02}\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right)\left(\xi\xi_k - \xi_0\xi_{0k}\right)\xi_k + \frac{8\bar{p}\sqrt{\lambda^0}}{\eta^0}\xi = 0; \tag{7}$$

$$-\left\{\frac{4}{3}\frac{\eta^{02}}{K^0}\left[v^{04} + v^{02}\left(\mu_{yx} + \mu_{xy}\lambda^0 + \frac{4K^0G_{xy}}{E_x}\right) + \lambda^0\right] + \frac{4v^{04}}{\rho_1}\right\}\times$$

$$\times\left(\xi_{asym} - \xi_{0asym}\right) - \lambda^0\eta^{02}\left(1 - \frac{v^{04}}{\lambda^0}\right)\left(\xi_k^2 - \xi_{0:}^2\right)\xi_k +$$

$$+ 2\sqrt{\lambda^0}\eta^0\left(4v^{02}\bar{p} - \bar{q}\right)\xi_k + \frac{16v^{04}}{\rho_1}\eta^0\left(\xi_{asym} - \xi_{0asym}\right)\xi -$$

$$- 64v^{04}\eta^{02}\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right)\left(\xi\xi_{asym} - \xi_0\xi_{0asym}\right)\xi +$$

$$+ \frac{16v^{04}\eta^0}{\rho_1}\left(\xi\xi_{asym} - \xi_0\xi_{0asym}\right) = 0, \tag{8}$$

where

$$\rho_1 = \frac{v^{04}}{\lambda^0} + v^{02}\left(\frac{E_x}{G_{xy}} - \mu_{xy} - \frac{\mu_{yx}}{\lambda^0}\right) + 1;$$

$$\rho_2 = \frac{81v^{04}}{\lambda^0} + 9v^{02}\left(\frac{E_x}{G_{xy}} - \mu_{xy} - \frac{\mu_{yx}}{\lambda^0}\right) + 1;$$

$$\bar{p} = \frac{\sigma R}{\delta_{cl}\sqrt{E_x E_y}};\quad \bar{q} = \frac{qR^2}{\delta_{cl}^2\sqrt{E_x E_y}};\quad a_1^0 = \frac{E_x}{G_{xy}};$$

$$\lambda^0 = \frac{E_y}{E_x};\quad K^0 = 1 - \mu_{xy}\mu_{yx};\quad v^0 = \frac{\alpha}{2\beta};$$

$$\eta^0 = \frac{m^2\delta_{cl}}{2R};\quad \xi = \frac{f}{\delta_{cl}};\quad \xi_0 = \frac{f_{0sym}}{\delta_{cl}};$$

$$\xi_{asym} = \frac{f_{asym}}{\delta_{cl}};\quad \xi_{0asym} = \frac{f_{0asym}}{\delta_{cl}};\quad \theta = \frac{\alpha}{\beta}.$$

From equations (7) and (8), we determined dependences of symmetric and asymmetric deflections and convergence of the ends of one of the parameters of loading $(\bar{p}, \bar{q})$ at some value of the other for assigned amplitudes of initial deflections.

These equations make it possible to determine the optimal kind of reinforcement under axial compression and transversal pressure given the symmetrical and asymmetrical deflections at the assigned elastic properties of a unidirectional monolayer.

The critical load is determined by deflections or the extreme point on the curves of equilibrium states. For the value of initial deflections $\xi_0 = 0.06$; 0.1; $\xi_{0asym} = 0.06$; 0.1; and parameters $\lambda^0 = 0.6$; $a_1^0 = 1$; $\eta^0 = \nu^0 = 0.3$, such dependences are shown in Fig. 2 as an example.

In the case of a single axial compression, critical load (axial compression or external pressure) is minimized by the parameters of the wave formation at the constant value of the other parameter of the load.

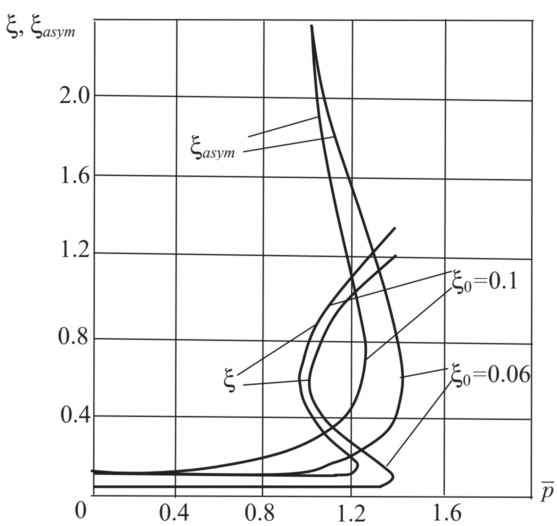

Fig. 2. Dependence of shell deflections under load

Fig. 3 presents some of the results of calculation of critical axial compressive load, depending on the symmetric component of initial deflection ξ_0 and asymmetric component ξ_{0asym} at the following values of the parameters: $a_1^0 = 3$; $\lambda^0 = 1$; $\mu_{yx} = 0.05$; $q = 0$.

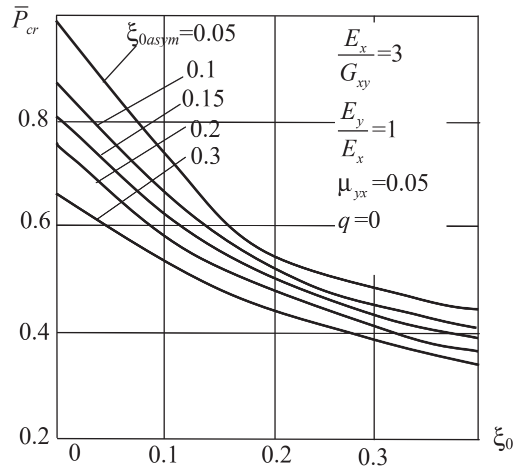

Fig. 3. Dependence of critical load on initial deflection

At other value of parameters a_1^0 and l^0, characterizing elastic properties of the orthotropic shell, the results of calculation of axial critical load on initial deflections are shown in Fig. 4. Continuous curves correspond to $a_1^0 = 3$; $\lambda^0 = 2$ and dotted curves correspond to $a_1^0 = 3$; $\lambda^0 = 0.5$. It should be noted that critical load at axial compression of the orthotropic shell greatly depends on dimensions of symmetric and asymmetric initial deflections.

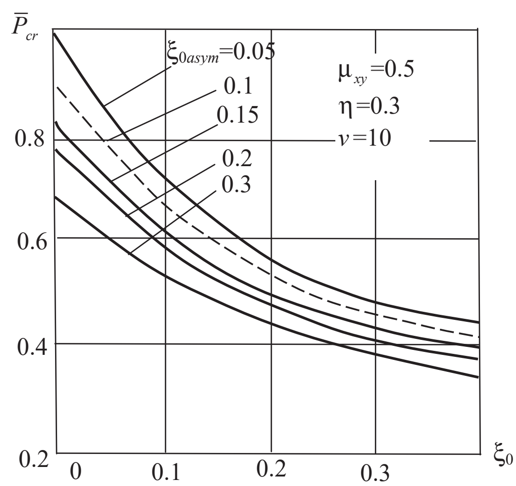

Fig. 4. Dependence of the critical load of initial deflection of the shell with different parameters

These deflections should be taken into consideration when calculating the stability of thin cylindrical shells from composite materials, especially provided $E_x \gg E_y$ [21, 22].

Fig. 5, 6 show the dependences of the critical load for the orthotropic shell in axial compression $(\bar{q} = 0)$ on the symmetric initial deflection ξ_0 at two values $\xi_{0asym} = 0.05$ and $\xi_{0asym} = 0.1$. Curves 1, 2 and 3 correspond to $\lambda^0 = 0.5$; 1.0; 2,0.

As it can be seen from the presented calculation results (Fig. 5, 6), critical load increases substantially at a decrease in magnitudes E_y/E_x and E_x/G_{xy}.

Transversal pressure greatly affects critical load (Fig. 7) $\xi_0=0.1$; $\xi_{0asym}=0.1$; $\lambda^0=1.0$.

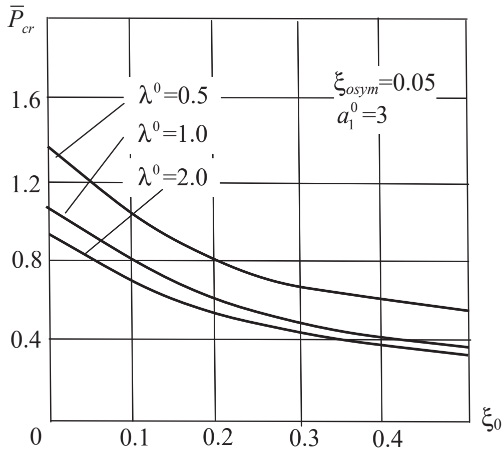

Fig. 5. Dependence of the critical load on symmetric deflection ξ_0 at non-symmetrical deflection $\xi_{0asym}=0.05$

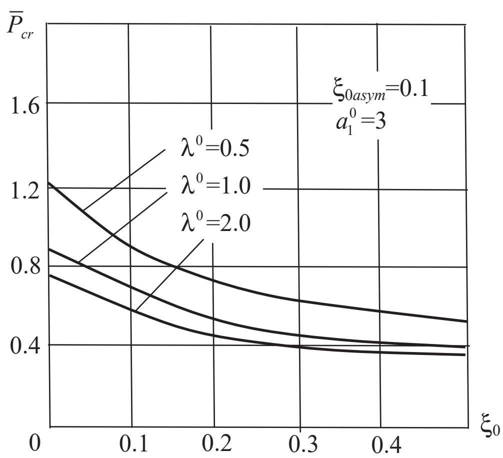

Fig. 6. Dependence of the critical load on symmetric deflection ξ_0 at non-symmetrical deflection $\xi_{0asym}=0.1$

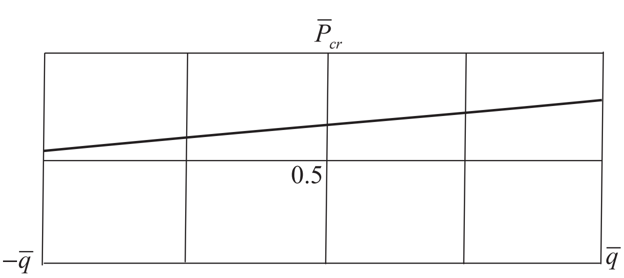

Fig. 7. Influence of transversal pressure on the axial critical load

Calculation of stability of composite shells was performed by the above outlined program for determining critical stresses of stability of shells in the light of initial deflections.

An enlarged algorithm for the optimization of sandwich shelled systems taking into consideration the stability of honeycomb elements is presented below.

The input parameters are assigned. They include mechanical characteristics of load-bearing skins; monolayer thickness; geometrical parameters of the compartment; external loads, taking into consideration technological impacts; mechanical characteristics of HF material, thickness, density; material of the frame, shape of spars, their relative height H. We also assigned:

– initial values of K_0; $(a_c/t_c)_0$; β_0;
– pitch for each coordinate: ΔK; $\Delta(a_c/t_c)$; $\Delta\beta$;
– accuracy for each coordinate: ε_K; $\varepsilon_{(ac/tc)}$; ε_β;
– limits of changing each of these parameters.

The stability of the HF cell at the technological limitation for initial data [27], which is adjusted taking into consideration this limitation, is verified.

We determined the weight of the compartment at the adjusted input parameters of HF with the implementation of the multi-cycle process of calculating G_{xz}^{hc} and G_{yz}^{hc} at the corresponding assignments $\lambda_{cr}>1$, taking into account the restrictions for deflections of the frames. The varied parameters t_c, h_{hc}, H are optimized in this procedure. As a result, a minimum of weight $M_{\min}$ of the compartment of first approximation is found.

The proper method of coordinate-by-coordinate descent for three coordinates is implemented: K, a_c/t_c and β at the replacement and adjustment of the initial data with the current data. In this case, the weight of the compartment of current approximation is compared to the minimum weight obtained at all previous approximations. The minimum weight of the compartment and optimum parameters corresponding to it are determined.

6. Results of the weight-based optimization of a multi-compartment sandwich shelled composite structure of the nose fairing type

The results of implementation of the proposed procedure for optimization are presented below. The multi-compartment sandwich shelled composite structure of the nose fairing type, included in the main unit of the space launch vehicle was explored as the object of research. Although the operation time of nose fairing in flight is only a few minutes, its design at a minimum weight is supposed to ensure integrity, efficiency and protection of useful loading during passing dense layers of the atmosphere by the launch vehicle [5, 20].

The system of six compartments with load-bearing skin from glass-reinforced and carbon filled plastic was explored during optimization (Fig. 8) [30].

The system was loaded with external pressure, equivalent compressive force and bending moment (Table 1).

FMC of the applied materials for load-bearing skin, frames and honeycombs are given in Table 2.

Results of the optimization of the system of six compartment with load-bearing skin of glass-reinforced plastic and carbon filled plastic are presented in Tables 3, 4.

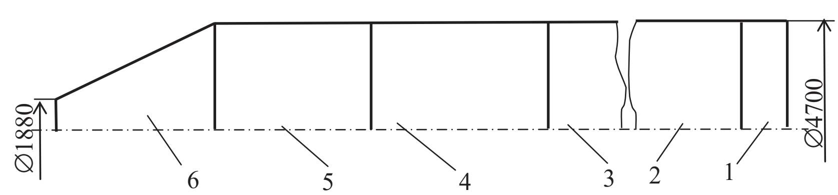

Fig. 8. Geometrical parameters of the system from six compartments

Table 1

Geometric dimensions and external impact of the system from six compartments

Length of the shell and external influences	Compartment number					
	1	2	3	4	5	6
Length of the shell, mm	960	4,810	4,810	4,810	3,510	4,800
External pressure, MPa	0.029	0.029	0.029	0.025	0.0187	0.08...0.12
Equivalent compressing force, kN	3,400	3,920	3,060	2,300	1,670	1,160
Bending moment, kNm		1,630	1150	642	293	6

Table 2

Characteristics of used materials of load-bearing skin, frames and honeycombs

Material	E_1, GPa	E_2, GPa	G_{12}, GPa	μ_{12}	μ_{21}	ρ, kg/m^3
Glass-reinforced plastic (+45/0/+45)	15.22	12.88	9.17	0,416	0,352	1,800
Carbon filled plastic (+45/0/+45)	55.7	22.21	7.22	0,758	0,302	1,400
Aluminum alloys	72		27	0.3		2,700

Table 3

Optimal parameters of the system with load-bearing skin from glass-reinforced plastic

Parameters of compartments	Compartment number					
	1	2	3	4	5	6
Optimal weight of the compartment, $M_{\min}$, kg	105.6	709.6	750.4	706	358.6	362
Ratio a_c/t_c	110	110	110	110	110	50
Angle of cell aperture, β, grad	52.5	55	55	55	55	51.3
Coefficient of cell shape K	1.8	1.8	1.8	1.8	1.8	2.6
Density of honeycombs ρ_{hc}, kg/m^3	22.8	22.8	22.8	22.8	22.8	36.15
Height of honeycombs h_{hc}, mm	38	40	40	36	30	40
Thickness of load-bearing skin δ_{cl}, mm	0.6	2.25	2.25	2.25	1.5	1.5
Weight of compartment using the nearest by size standardized honeycomb filler, M, kg	114.3	842	799	744	382	389
$(M-M_{\min})/M_{\min}$, %	8.24	6.5	6.48	5.38	6.52	7.46

Table 4

Optimal parameters of the system with load-bearing skin from carbon filled plastic

Parameters of compartments	Compartment number					
	1	2	3	4	5	6
Optimal weight of compartment, $M_{\min}$, kg	105.6	445.2	404.5	358.8	233.3	207.1
Ratio a_c/t_c	110	110	110	110	110	135
Angle of cell aperture, β, degrees	52.5	55	55	55	55	56.25
Coefficient of cell shape K	1.8	1.8	1.8	1.8	1.8	1.5
Density of honeycombs ρ_{hc}, kg/m^3	22.8	22.8	22.8	22.8	22.8	32.17
Height of honeycombs h_{hc}, mm	38	40	40	34	24	28
Thickness of load-bearing skin δ_{cl}, mm	0.6	1.2	1.2	1.2	1.2	1.2
Weight of compartment using the nearest by size standardized honeycomb filler, M, kg	114.3	495.9	454.4	395.6	251.7	211.5
$(M-M_{\min})/M_{\min}$, %	8.2	11.4	12.3	10.2	7.9	2.1

Thus, the obtained results made it possible to develop the procedure for optimization of sandwich composite structures supported by frames, variable parameters in addition to the thickness of load-bearing skin and filler, belts of frames, included geometrical parameters of HF. The algorithm and its software implement all the basic dependences of mechanical characteristics of honeycomb on their geometrical parameters and material. The developed procedure makes it possible to link the process of optimal designing honeycomb structures to the processes of formation of the product and capabilities of a specific production regarding structural materials and nomenclature of HF.

7. Discussion of results of weight-based optimization of the multi-compartment sandwich shelled composite structure

The conducted research allowed us to show the following.

The minimum of the weight of the considered composite shelled systems significantly depends on parameter a_c/t_c of the honeycomb filler, implemented in the range of its magnitudes from 50 to 135.

Application of the HF of the irregular hexagonal shape ($K\neq1$, $\beta\neq60°$) is a rather effective means of reducing the weight of the system. The gain in weight is given by all optimized compartments compared with similar compartments, in which the nearest by size standardized HF of the regular hexagonal shape are used. The average gain is from 2.1 to 12.3 %. The magnitude of the weight gain depends on the material of load-bearing skin and the filler.

Certain difficulties, leading to a decrease in manufacturability, necessitate the use of different (non-standardized) honeycombs for compartments. This can lead to a solution to standardize in practice the honeycombs by compartments, aligning cell parameters K and β by any compartment. In the latter case, to align K and β, it is more effective to accept the optimal values of heavily loaded compartments as the base, which leads to a smaller weight loss. Unification of combs by K and β (alignment) is more effective than using the honeycombs of the regular hexagonal shape.

In an effort to reach a conditional minimum of the product weight, the program goes beyond limit a_c/t_c, followed by the loss of stability of honeycombs. Therefore, in all cases of deviations from $(a_c/t_c)_{opt}$, it is necessary to accept only $(a_c/t_c)<(a_c/t_c)_{opt}$. Then the weight loss of the compartment, if:

$$\Delta\bar{a}=\frac{\left[\left(\frac{a_c}{t_c}\right)_{opt}-\left(\frac{a_c}{t_c}\right)\right]}{\left(\frac{a_c}{t_c}\right)_{opt}}\le 10\,\%;\ \Delta K=\frac{\left[K_{opt}-K\right]}{K_{opt}}\le 10...15\,\%,$$

does not exceed 1 %. Angles of aperture of a honeycomb cell may vary in a wider range: $\Delta\beta=+(5...10)°$. This conclusion is rather important in assessing the quality of the technology of honeycomb production. Obviously, individual deviations from the regulated parameters a_c (through a_c/t_c at the assigned t_c), K and β must form the representative samples, the average values of which satisfy above constraints, that is:

$$\Delta\bar{a}_c\le 10\ \%;\ \Delta K\le 10...15\ \%;\ \Delta\beta=\beta_{opt}-\beta_{mid}=+10...15°,$$

where $\bar{a}_{copt}$, K_{opt}, β_{opt} are the parameters, regulated by optimization calculation; $\bar{a}_{cmid}$, K_{mid}, β_{mid} are the parameters, obtained through statistical treatment of the results of honeycomb measurements, taken according to the specific technology. Coefficient of variation of these parameters should not exceed 10 %.

The technology, ensuring the specified regulations, can be considered acceptable. In this case, the technological processes of honeycomb production, that ensures smaller deviations will be the best among the others.

If such criteria exist, $\Delta\bar{a}_c$, ΔK and $\Delta\beta$ should serve as major limitations. In view of the above, the proposed approach can appear very productive as a theoretical basis for certification of HF, depending on their purpose.

In contrast to papers quoted above technological (mounting) shell warpages in the form of relative deflections are taken into account when implementing the developed procedure. In this case, they are changed by the contour according to the sinusoidal law and by length according to the law of changing bending moments from operational impacts.

In addition, cross-sections of the frames that make up a significant part of the weight of HF were also optimized. Thus, in the case of the considered shelled system, optimized by the developed procedure, the share of frames, depending on external loads on the compartment by for compartments, made up (22...52) % of the total weight of the compartment or (27...97) % of the weight of load-bearing skin with HF. In this system as a whole, the proportion of the weight of frames was 43 %, and relative to the weight of load-bearing skin with HF, it was 70 %. The shown data testify to necessity to optimize the frames in the general complex of weight-based optimization of the considered class of structures. The advantage of the developed procedure is the possibility of taking into consideration the profile of technological imperfections of the product. However, this applied only to the technological imperfections of HF, moreover, implemented in first approximation. That is why load-bearing skin of the composite shell and parameters of HF are chosen so that the shell proper should ensure the parameter of critical load $\lambda_{cr}>1$, that is, should have some stability margin. This stability margin is compensated by flexible frames, allowing a decrease in critical load at the general deformation of the system. Stiffness of the frames and, therefore, their weight is selected from the condition for ensuring the regulated deflection of the system. The total weight of the system of the shell and frames will be less than the total weight of the system when selecting the geometrical parameters of the shell provided that $\lambda_{cr}=1$.

The obtained results in the end make it possible to determine the optimal thicknesses of load-bearing skin, the height of HF, parameters of the honeycomb cell of the generalized shape of the sandwich shell, supported by end frames and loaded by axial compressive force, external pressure and bending moment.

8. Conclusions

1. The procedure for the optimization of the sandwich shelled composite structures with the honeycomb filler was developed. Variable parameters in the methodology include thicknesses of load-bearing skin, honeycomb filler and bends of frames, honeycomb geometric parameters; technological mechanics of structures is also taken into consideration. The distinctive feature of the procedure is consideration of the technology (mounting) and operational warpages of the considered shelled systems during its implementation. The developed procedure and its software implemented all major dependences of mechanical properties of honeycomb on their geometrical parameters and material. This made it possible to link the process of optimal designing honeycomb structures to the technological processes of product shaping and possibilities for a specific production for structural materials and nomenclature of HF.

2. Implementation of the proposed procedure for optimization of parameters of multi-compartment sandwich shelled composite system of the type of nose fairing of a space launch vehicle revealed its theoretical effectiveness, expressed by the possible reduction of the weight of the optimum product. It was shown, that application of HF of the irregular hexagonal shape is a rather effective means of reducing the weight of the system. The weight gain can be given by all optimized compartments compared with similar compartments, in which the nearest in size standardized honeycombs of the regular hexagonal shape can be used. On average, the gain can make up from 2.1 to 12.3 %. The magnitude of the mass gain depends on the material of load-bearing skin and the filler.

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UDC 3326. 01
DOI: 10.15587/1729-4061.2019.154342

INFLUENCE OF ELASTIC CHARACTERISTICS OF RAW COTTON ON THE MECHANICS OF FEED ROLLERS IN THE CLEANERS FROM SMALL IMPURITIES

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Від зрілості залежить вплив пружних характеристик бавовни-сирцю на механіку живлячих валиків у очищувачах дрібного сміття. У очищувачах дрібного сміття застосовуються механізми, в яких використовуються колкові валики з асиметричним розташуванням лопатей. Асиметричність розташування живлячих валиків з прямолінійними лопатями можна характеризувати значенням кута θ відставання або випередження лопатями одного валика лопатей іншого. Відносною характеристикою величини асиметрії може служити відношення модуля θ до його граничного значення $k_{as}=\theta/\pi$, інтервал зміни якого $0\le k_{as}\le 1$. Аналіз показав, що зі збільшенням $к_{ac}$ у очищувачах дрібного сміття спостерігається погіршення якості очищення бавовни-сирцю. Запропоновано матричний метод аналізу механізмів бавовно-переробних машин, в тому числі живлячих валиків у очищувачах дрібного сміття і розроблено алгоритм його комп'ютерної реалізації. Зі збільшенням асиметрії колкових валиків (k_{as}) розпірні сили, що виникають між валиками, зменшуються на 20–25 %, що призводить до зниження очисного ефекту машини.

Розроблено схему живильника, де поряд з традиційними лопатевими валиками використовуються колкові або колково-планчаті розпушувальні валики. В живильнику даної конструкції можна виявити як рівномірне живлення машини бавовною, так і зміна технологічних характеристик бавовни-сирцю. Додаткові валики призводять до зміни технологічних характеристик бавовни-сирцю, тим самим створюють процес інтенсивного виділення смітних домішок. Очевидно, деформація, що отримується часткою в схемі, яка розглядається, буде максимально можливою, граничною, так як нова конструкція виключає прослизання продукту в зонах між лопатевими і розпушувальними валиками, що не виключається в реальній конструкції.

Отриманий досвід показує, що застосування розробленої схеми живильника у очищувачах дрібного сміття дає значне збільшення (18 %) очисного ефекту машини

Ключові слова: очищувач дрібного сміття, живлячі валики, колкові валики, лопать, деформація шару, розпірні зусилля, якість очищення бавовни-сирцю, структурні частки

1. Introduction

A highly important issue for the cotton-ginning industry is to intensify the process of removing impurities from raw cotton. A high quality of cotton fiber and seeds can be achieved as a result of developing improved designs of cleaners from small impurities, finding new ways of cleaning raw cotton from small and large contaminations, and choosing modes of cleaners.

A careful study is necessary to specify the mechanics of the interaction of the working elements of the feed devices with a layer of transported material, and it is essential to search for new designs of such charging systems with a directional change in the technological properties of raw cotton.

An 80–90 % increase in the cleaning effect of these technological processes allows obtaining fiber with the amount of impurities and defects within the norms. It is actually important to develop a system for assessing the uniformity of