Study of the effect of the elastic modulus of ribs on the stress-strain state of a composite mesh compartment

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Abstract. Modern fiber composites have extremely high specific strength and stiffness, significantly exceeding the corresponding characteristics of traditional metal structural materials. In the present work, the effect of the elastic modulus of circular and spiral ribs on the stress-strain state of a composite mesh compartment with cutouts reinforced with bezels investigated. For the calculations, the finite element method is used, which makes it possible to naturally consider the cutouts, stepwise varying thicknesses, various kinds of boundary conditions, and loads. The computational model of the composite lattice structure consisting of ribs is a finite element model constructed from beam elements. The parameters of the stress-strain state of a composite mesh compartment with notches reinforced by edgings are determined. The graphical dependences of the values of maximum stresses in the ribs and sheathing on the value of the modulus of elasticity are presented for the first time. The analysis of the obtained results carried out, which makes it possible to develop recommendations for an informed choice of carbon fabric types with different physical and mechanical characteristics for manufacturing the spiral and ring ribs, as well as the skin of the designed composite mesh compartments.

1. Introduction

Anisotropic gridshells made of composite materials based on carbon fibers and polymer matrix are widely used as primary structural elements of modern technology [1]. The advantages of modern composites and the advantages of composite-specific technological processes are most fully manifested in the mesh structures. It is known that modern fiber composites have extremely high specific to density) strength and stiffness, significantly exceeding the corresponding characteristics of traditional metallic structural materials. However, these characteristics appear only if the load has the direction along the reinforcement fibers. This directional nature of the properties of composites is fully consistent with the structure of the mesh structure, the main load-bearing elements of which are ribs reinforced in the longitudinal direction. During axial compression of the system of spiral and ring ribs, the spiral ribs are in a state of uniaxial compression, ring ribs are in a state close to uniaxial tension, and for all structural elements, the maximum effective...
stress coincides with the direction of reinforcing fibers. This, combined with the exceptionally high longitudinal specific strength and stiffness of modern unidirectional composites, determines the high weight efficiency of mesh structures.

The problems of optimal design [2], strength and stability [3] analysis of composite mesh anisogrid structures are considered in [2,3]. The features of the structural and technological concept of mesh aerospace structures [4], methods of their design, and main applications [5] are discussed. It should be noted a characteristic feature of composite mesh shells formed by a system of spiral and ring ribs. This peculiarity consists in the fact that in most cases the loss of bearing capacity of mesh structures is associated with the failure of spiral ribs in compression, while for thin-walled shell structures the typical type of failure in axial compression is the loss of stability. The point is that the mesh shells with the scheme considered in the article have a self-stabilizing shape effect, which consists of the following. During axial compression of a cylindrical or conical shell, the system of spiral ribs, shortening in the axial direction, expands in the radial direction. The spiral ribs, whose radial deformation is limited by the ring ribs, transmit forces equivalent to the internal pressure stretching the ring ribs. As a result, the circular shape of the shell cross-section is stabilized. In addition, the initial irregularities of the shape, which are known to lead to a significant decrease in the critical value of the axial compressive force for smooth, stringer, and three-layer shells, in the mesh shell tend not to develop, but to decrease in the process of loading. Thus, the critical load for the mesh shell turns out to be so high as to be by no means always achieved by loading.

2. Problem statement

In [6] it is noted that in the calculation of mesh shells it is necessary to consider a variety of types of bearing the capacity loss. The realization of one or another type of failure is determined, among other things, by the physical-mechanical characteristics (PMC) of the materials. In this regard, it is quite relevant to assess the effect of different types of carbon fiber-reinforced plastics, which differ in PMC, on the stress-strain state (SSS) of the mesh structure.

In the present work, a computational study of the effect of the elastic modulus of ring and spiral ribs on the SSS in the elements of a composite mesh compartment with notches reinforced by bezels was carried out. The problem statement is presented in [7].

Now consider a compartment made of carbon fiber-reinforced plastic according to the power diagram of a mesh anisogrid with cladding (figure 1) and representing a cylindrical shell with length \( L = 1.14 \, R \) (\( R \) is the radius of the shell on the outer surface of the cladding), loaded with an axial compressive force.

The main parameters of the composite mesh compartment structure have the following values (figure 2):

\[ \delta_c = 0.25h, \delta_r = 0.167, h_0 = 0.033h, a_c = 2.5h, \varphi = 20.3^{\circ} \]

where \( \delta_c \) – spiral rib width; \( \delta_r \) – ring rib width; \( a_c \) – the distance between spiral ribs; \( a_r \) – the distance between the ring ribs; \( h_0 \) – shell thickness; \( \varphi \) - the angle of spiral ribs to the formative; \( h \) – the height of spiral and ring ribs.

Physical and mechanical characteristics of the cladding material:

\[ E_1 = 70.8 \text{GPa}, E_2 = 65.6 \text{GPa}, G = 5.4 \text{GPa}, \mu_{12} = 0.19, \]

where \( E_1 \) – modulus of elasticity in the axial direction; \( E_2 \) – modulus of elasticity in the annular direction; \( G \) – shear modulus; \( \mu_{12} \) – Poisson's ratio.
At the upper and lower ends, the composite mesh compartment is supported by bends made of carbon fabric similar to the cladding material. The compartment structure has cutouts for hexagonal...
hatches, the areas around which are reinforced with trim made of carbon fabric wipes.

The boundary conditions at the upper (left in figure 1) end of the composite mesh compartment correspond to movable hinged support. Two variants of boundary conditions considered at the lower (right in figure 1) end: a rigid termination and a fixed hinge.

The composite mesh compartment structure is loaded with a compressive longitudinal load $P$ uniformly distributed across the top end.

3. Problem solution

Calculations were performed using the NASTRAN software package [8], which implements the finite element method [9-11], allowing for the natural consideration of notches, variable thicknesses, various kinds of boundary conditions and loads. The computational model of the composite compartment mesh structure consisting of ribs is a finite-element model formed from beam elements. The shell was modeled by the two-dimensional three-node finite elements based on Kirchhoff-Love plate theory.

The stress-strain state of the composite mesh compartment is characterized by edge effects approximately the notches. The maximum values of stresses in the spiral ribs and in the cladding in the axial direction are realized in the areas of the side corners of the cutouts and above the corner points of the bezels. In the annular ribs and in the cladding in the circumferential direction, where the tensile stress occurs in the case of a shell without concentrators, regions of compressive stress appear in the vicinity of the notches. The level of compressive stresses in the shell of the composite mesh compartment in the circumferential direction is 2-3 times lower than the level of tensile stresses, and in the annular ribs, the maximum values of tensile and compressive stresses are practically the same. The picture of stress distribution in the ribs and in the cladding for the option of supporting the compartment ends corresponding to rigid embedding is practically the same. Slight differences observed only in the areas of edge effects approximately the compartment ends.

In figure 3 shows graphs of changes in the characteristic parameters of the stress-strain state (SSS) of a composite mesh compartment with edge-reinforced notches, depending on changes in the elastic modulus of the spiral and ring ribs.

![Graph of stress-strain state](image_url)

**Figure 3.** Graphs of changes: 1 - maximum stresses in the spiral ribs of the composite mesh compartment, 2 - maximum stresses in the ring ribs, 3 - maximum axial stresses in the cladding.

Numbers 1,2 indicate graphs of maximum stresses in the spiral and ring ribs of the composite mesh
compartment with cutouts reinforced with bezels, \((\delta^* = \delta_{\text{max}} / \delta_0\)), where \(\delta_{\text{max}}\) – maximum value of stresses in structural elements, \(\delta_0\) – maximum value of stresses in the elements of the structure with no zones of concentrators). Number 3 - graphs of changes in the maximum axial stresses in the cladding. As can be seen from the presented graphs, the dependences of the values of maximum stresses in the ribs and cladding of the composite mesh compartment with the notches reinforced by the edgings on the value of the elastic modulus are close to the linear. A 65% increase in the modulus of elasticity of the ribs increases the level of maximum stresses in the ribs by 20–25 %, and in the cladding decreases by the same 20-25%.

The obtained results make it possible to carry out weight optimization of composite mesh compartments with cutouts reinforced with bezels and to develop recommendations for an informed choice of carbon fabric types with different physical and mechanical characteristics for manufacturing spiral and ring ribs, as well as the skin of the designed mesh compartments.

4. Conclusions
Thus, the following conclusion is based on the results of the research. For the first time, the obtained dependencies between the elastic modulus of spiral and ring ribs and the maximum values of the main parameters of the stress-strain state both in the ribs and in the skin of the composite mesh compartment with notches reinforced by the edgings have a character close to linear.

The results obtained have relevance in scientific terms and have an important practical value. These results will find application in the design and creation of composite mesh compartments in different areas of the national economy and especially in aviation and rocket-space engineering.

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