Mechanics of orthotropic plates with honeycomb filler

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Abstract. Materials with a honeycomb structure have a cellular geometry, which reduces the amount of material used to achieve mass perfection of the finished structure. Due to the widespread application of honeycomb composite materials (structures), the need for developing the design methods exists. It is especially important to have design methods to guarantee the longevity and reliability of the elements of aviation structures during the exploitation. The peculiarities of operation such complicated elements as honeycomb require consideration of existing of tough and soft layers, which work differently. The equations of motion of the three-layer plate with honeycomb filling are given. Some important issues of investigation based on this equation are described. In the paper, the questions of destructive and non-destructive diagnostics of composite constructions are discussed.

1. Introduction

The advantages of cellular structures made of composite materials (CM) today are well known and undeniable. These are high strength characteristics at low density, the combination of high rigidity with low specific gravity, resistance to crack development, the ability to orient the properties in the directions of the acting loads [1,2]. Materials with a honeycomb structure have a cellular geometry, which reduces the amount of material used to achieve mass perfection of the finished structure. In addition, the geometric dimensions of honeycomb structures can vary widely. This circumstance led to the widespread use of products made of CM with honeycomb filler in the rocket and space and aviation industry (Tu-204, Tu-334, Il-96, Il-114, RRJ-95, etc.) [3-5]. Despite the fact that the theory and practice of creation and application of cellular structures with cladding of CM today is quite seriously worked out and continues to develop, the problem of forecasting the durability of structures of such panels under the action of dynamic loads remains an urgent and important practical task [1, 2].

In [6] the model for estimation of elastic and strength characteristic was developed. The model is based on the use of asymptotic homogenization method of hierarchical periodic structures. In [7] three-layer (sandwich) structures consisting of external power sheathing and lightweight filler are described.

To guarantee the stable and reliable exploitation of complicated construction made of composite, the question of diagnostic is very important. In [8] the nowadays approaches to health monitoring including diagnostic of aviation construction are analyzed. As one of the practical solutions, to the problem of ensuring the weight efficiency of modern technical systems with increased reliability requirements can be the use of composite mesh (anisogrid) structures as power elements [9]. For sandwich structure composed of two laminated skins and a honeycomb core was proposed a numerical optimization procedure in order to obtain a true global optimal solution for the considered problem of strength [10].
To study the influence of structural and technological factors, engineering methods of identification for mechanical characteristics of unidirectional composites were developed in [11]. They consider the physical nonlinearity which is observed in complicated composite structures, which may be a consequence of shear stresses influence. Describing the mechanical properties of a laminate for a given structure was usually carried out based on the regularities of its constituent layers. The analysis of the viscoelastic properties of composite materials a physical nonlinearity was observed, which may be a consequence of shear stresses.

Under production conditions, the shell is modeled from hard (carbon fiber, fiberglass, etc.) and soft layers (honeycomb filler). Soft layers work only on "shear" and "stretch-compression", which are distributed evenly over the thickness of the layer. The arrangement of these layers is modeled in such a way as to fill the space between the panels with the maximum preservation of the mass perfection of the design. This method guarantees the condition of optimal operation of the structure.

2. **Considering the dynamic loads in the prediction of durability**

The prediction of the durability of cellular structures under dynamic loads should be understood as the definition of the forms and frequencies of natural oscillations. Knowledge of these parameters will allow developing methods for durability estimation.

The equations of motion of a three-layer plate with honeycomb filler have the form:

\[
\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = q + \rho \frac{\partial^2 \omega}{\partial t^2} + 2\xi_0 \frac{\partial \omega}{\partial t},
\]

\[
\left[ \frac{1}{S_x} \left( \frac{D_x}{\partial x^2} + \frac{D_y}{\partial y^2} \right) - 1 \right] Q_x + \left[ \frac{1}{S_y} \left( \frac{D_{xy}}{2} + v_x D_y \frac{\partial^2}{\partial x \partial y} \right) \right] Q_y
\]

\[
- \left[ D_x + (D_{xy} + v_x D_y) \frac{\partial^3}{\partial x \partial y^2} \right] \omega = 0,
\]

\[
\left[ \frac{1}{S_x} \left( \frac{D_{xy}}{2} + v_y D_x \right) \frac{\partial^2}{\partial x \partial y} \right] Q_x + \left[ \frac{1}{S_y} \left( D_y \frac{\partial^2}{\partial y^2} + \frac{D_{xy}}{2} \frac{\partial^2}{\partial x^2} \right) - 1 \right] Q_y
\]

\[
- \left[ D_y \frac{\partial^2}{\partial y^3} + (D_{xy} + v_y D_x) \frac{\partial^3}{\partial x^2 \partial y} \right] \omega = 0.
\]

Where \(D_x, D_y, D_{xy}\) – bending and rotating stiffness, \(S_x, S_y\) – shear stiffness, \(v_x, v_y\) – Poisson's coefficients for orthotropic three-layer plate, \(\rho\) - mass of the unit area of the plate, \(\xi_0\) - damping coefficient.

From the system of equations (1) it is possible to obtain differential equations for transverse displacement for an orthotropic three-layer plate, which were obtained in [12], where the solution of the problem of the orthotropic plate oscillation was also obtained by the asymptotic method of V. V. Bolotin [13]. As a result of these studies, the oscillation frequencies of the panel with all fixed edges were determined for the cases of a honeycomb panel made of carbon fiber with a reinforcement scheme \([0/\pm 45^\circ]\) with a thickness of 0.45 mm and a panel skin made of aluminum alloy AMG-2H with a thickness of 0.5 mm. The filler in both cases was taken by a honeycomb, the honeycombs of which are made of alloy AMG-2H with a cell size of 2.5 mm and a wall thickness of 0.03 mm. The obtained theoretical values of natural frequencies were compared with experimental data for panels with facings of aluminium alloy. The discrepancy between the calculations and the experiment was 8%, which may be due to the idealization of the sealing conditions adopted in the calculation of frequencies.

The assumption that the sheathing works as a membrane is true when considering thin enough compared to the thickness of the honeycomb filler sheathing. It is possible to obtain equations for determining stresses in plate sheathing away from the edges. Using this assumption, it is possible to estimate shear stresses in the honeycomb filler provided that transverse shear forces are perceived only by the honeycomb.
The Puppo-eversen destruction criterion composite materials was adopted as a criterion for damage accumulation [14]. Knowing the voltages, it is simple enough to construct estimates for the mean squares of the voltages, the equivalent voltage, and the durability [15,16].

In the process of cyclic loading of composite materials, their stiffness and damping properties change. The change in the stiffness properties leads to the fact that the coefficients of the system of equations (1) become dependent on the acting stresses and time, or on the number of loading cycles. Changes in the stiffness characteristics and leads to a change in the mode of normal vibrations and self-resonant frequencies of the structure. However, in the case of loads with a wide and continuous spectrum, the most significant contribution to the values of dynamic stresses is made by changing the damping properties of the composite honeycomb structure.

In addition, studies have been conducted on the change in the logarithmic decrement of oscillations depending on the change in the stiffness of the sample in the process of bending fatigue tests with torsion. Torsional bending was realized by means of the asymmetrical load arrangement at the end of the excited cantilever-mounted specimen. Fig.1 shows the experimental dependence of the change in the logarithmic decrement of oscillations when changing the stiffness of the sample in the process of torsional bending tests. If such tests damage occurs due to honeycomb filler, so in this case, the change of the logarithmic decrement of the oscillations is associated only with the destruction of the honeycomb. The curve I in fig. 1 corresponds to a change in the logarithmic decrement of attenuation with a decrease in bending stiffness in the first form of bending oscillations. Curve II corresponds to a change in the decrement of attenuation with a decrease in torsional stiffness in the first form of torsional oscillations. From the presented graphs it can be seen that the decrements of attenuation, depending on the change in the stiffness of the sample, increase when the honeycomb filler is damaged.

Fig. 1. Dependence of change of logarithmic decrement of attenuation at the change of rigidity of a sample

It can be assumed that the stiffness and damping characteristics do not change much during cyclic loading and take into account only the change in the logarithmic decrement of attenuation over time. This assumption follows from the experimental curves shown in figure 1. Since the change in stiffness is small compared to the change in the decrement of attenuation, it can be concluded that in the pre-collapse state the dynamic stresses at the same load intensity are about three times less than in the undamaged panel.

3. Technological imperfections and their influence on deformation and strength characteristics of structures from CM. Defects diagnostic.

Characteristic defects of composite panels with honeycomb filler and structures made of these materials are delaminations, non-adhesives, voids, cracking of the inner layers, holes and so on. The use of nondestructive testing methods for the diagnosis of defects is limited by the characteristics of the material. For the control of composite panels, specially developed methods and conventional acoustic methods [17-19] are used to diagnose damage. The thermographic methods [18] and acoustic
emission method [17,18] have been applied. For the most part, these methods give a qualitative character of the geometry and the number of defects. It should be noted that the influence of the considered defects on the thermophysical characteristics of composite materials is little studied. The effectiveness of thermal methods in the diagnosis of composite materials is reduced due to the significant thermal inertia inherent in most types of composite materials.

The amplitude-frequency characteristics of honeycomb panels with carbon fiber and fiberglass sheathing were studied and their logarithmic attenuation decrement was determined. The frequency dependence of the amplitude of the span of the end of the cantilever-mounted honeycomb panel with carbon fiber sheathing is shown in Fig. 2 at different levels of exciting load. Cellular panels made of carbon fiber have a symmetric dependence of the amplitude of oscillations on the frequency. The logarithmic decrement of attenuation of a honeycomb panel with carbon fiber sheathing was determined, which amounted to δ₁ = 0.037.

![Fig.2. Dependence of amplitude span of the honeycomb beam end on frequency near resonance](image)

It is mentioned though, that when using acoustic methods, surface defects such as delamination can be omitted if the force pressing the finder to the controlled product is greater than necessary and thus assess the product as defect-free. The method of acoustic emission allows the identification of only developing defects. Additionally, the source of acoustic emission cannot be recognized by analyzing the frequency parameters of individual pulses. The main drawback when using non-destructive methods of flaw detection is the complexity of decoding signals and adequate modeling of defects occurring in the material.

As one of the other means to investigate the situation with strength resistance, the electron microscopy of the broken elements might be employed [20]. In case of honeycomb structures in might be applied to the broken elements of stiff components made of carbon plastic. In Fig. 3 the fragments of the electron microscopy of the broken unidirectional sample of carbon fiber are given. Investigating such type of images could help to understand the main types of breaking modes. In Fig. 3 the main types of breaking modes of unidirectional carbon fiber are written next to the images.

![Fig.3. The example of the main types of breaking modes of unidirectional carbon fiber](image)

### 4. Conclusions

The importance of investigation of dynamic loading in honeycomb panels is characterized and motion equations are presented.
Some important topics concerning defect diagnostic (acoustic emission, studying vibrations and electron microscopy) are discussed. The use of honeycomb structures, like other uses of composite materials [21,22], is at the forefront of technological development and requires close attention from scientists involved in the formulation of computational and diagnostic methods.

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