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COMPOSITE MATERIALS IN AIRCRAFT ENGINE BLADES

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ABSTRACT

The article investigates the strength of the propeller blades made of a multilayer composite material, subjected to centrifugal and gas loads with various combinations of fiberglass and carbon fiber and orientation of the material base. The finite element method is used as a research method. A propeller blade used in turbines of jet engines and compressors, made of composite materials, is considered as a naturally twisted rod, provided that the hypothesis of flat sections across the thickness of a multilayer composite package is valid under conditions of rigid contact at the boundary of layers. The propfan blade model is modeled by four-node finite elements of natural curvature with forty-eight degrees of freedom, taking into account the compression of the normal. The applied method for calculating the strength makes it possible to assess the strength of an arbitrarily reinforced blade in sections and layer by layer. The blades of hydrodynamic engines of the first and second stages were considered under the action of centrifugal and gas loads. The stress was determined at 17 points of 21 cross-sections in layers. As a result of the study, the strength parameters of the blades with different ratios of the dissimilar materials of the layers of the multilayer composite material were obtained. Conclusions are drawn, based on the fact that the blades made of composite material have significant advantages in terms of strength and weight characteristics compared to blades made of materials traditionally used in technology in the manufacture of propfans.

Introduction

Composite materials are becoming more widespread in various fields of technology, especially in those where it is necessary to achieve a low weight with sufficient strength and dynamic parameters: in aviation, rocket and space technology. Currently, composite materials are widely used in the construction of aviation technology, including in helicopter construction, where the use of composite blades has been thoroughly studied and widely used [1–13]. At the same time, composite materials are not used in aircraft engine blades; therefore, research in this area is an important and relevant topic.

The strength of composite materials mainly depends on the location of the composite base in the layer of composite multilayer structure, fiber material and binder. In the composite, the carrier fibers are about 0.005–0.010 mm in diameter. An epoxy-based composition is used as a binder in the composite structure. The use of carbon fiber reinforced polymer (CFRP) in the composite blade is explained by the fatigue strength that is more than 2 times higher than the composite with fiberglass fibers. The use of fiberglass, especially in the surface layers of the blade, is due to higher impact toughness, crack resistance, residual strength of the fiberglass composite and 20 % decrease in the strength of carbon fiber under the action of temperatures in combina-

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tion with moisture in the propeller blades during operation. Therefore, a reasonable combination of fiberglass and carbon fiber fibers is needed in structures such as propeller blades of turbojet engines. In addition, fibers located at different angles to the centerline of the propfan blade should not be neglected to perceive stresses in different planes of the blade.

1. Theoretical Basis

Composite materials are becoming more widespread in industry, especially in areas where the weight characteristics of the material are of great importance, as well as the specific strength of the material: aircraft and helicopter construction. The use of composite materials in the PD-14 engine blades allows reducing the engine weight by 40–45 % compared to traditionally used titanium alloys. The blades of the engine make up 30–40 % of the weight of the engine. In addition, since the engine blades are rotating masses, the load on the engine spindle, the moment of inertia, which saves fuel, etc., is reduced. Foreign companies such as General Electric use carbon fiber blades in their aircraft engines. Thus, it can be said that \ research, design and manufacture of engine blades from composite materials is an important and relevant topic. Currently, work on the use of composite materials in engines, in particular, engine blades, is being carried out at Baranov Central Institute of Aviation Motor Development (CIAM). When calculating an engine blade, it is necessary to consider the natural vibration frequencies and stress-strain state, resistance to shock loads and self-oscillations. It is impossible not to take into account the cost of a blade made of composite materials. According to CIAM data, the cost of a blade made of composite materials is from 50 to 70 % of the currently used engine blades made of titanium alloys. Composite materials allow varying strength characteristics depending on the base material and its location. The base of the composite material should be located along the lines of maximum tensile stresses and then the product receives the greatest rigidity and strength. To determine the trajectories of maximum stresses, it is necessary to quantify their location. The procedure for determining the trajectories of maximum stresses, in the direction of which it is necessary to position the base of the composite material in a multilayer composite structure for geometrically complex structures, can be reduced to the following:

- calculation of a product made of a homogeneous material is carried out under the action of operational loads;
- stress-strain state of the structure and the trajectory of maximum stresses are determined;
- product is made from a composite material with the arrangement of the base of layers of composite material along the lines of maximum stresses obtained by solving the problem from a homogeneous material;
- calculation of a composite material product for operational loads is carried out;
- stress-strain state and the trajectory of the maximum stresses of the composite structure are determined;
- correction of the arrangement of the base of the composite material is carried out in accordance with the results obtained for the product made of the composite material, etc.;
- final calculation of the composite structure is carried out, where the trajectories of maximum stresses will coincide with the trajectories of the base of the composite material in the layers of multilayer composite material, which will allow obtaining the structure with maximum strength and rigidity;
- it is also necessary to place a part of the base of the composite material in the layers of the multilayer composite at an angle to the trajectory of maximum stresses, which will restrain the shear stresses arising in the structure under the action of operational loads.

Propeller blades made of various combinations of carbon-fiber-reinforced plastic and glass-fiber reinforced plastic in surface layers, of different thickness and direction, were studied. The minimum strength of the considered blades and their location were determined (Table 1). As a result of the study, the most optimal (from the point of view of strength) structure of the arrangement of the layers of the composite material in the blade made of the composite, material ratio and weight characteristics.

Table 1

Effect of the layers located at an angle of 0 degrees to the axis on the strength characteristics of the first stage blades of the following structure: h1 0^o / h2 0^o / 0.9 ± 15^oy / 0.9 ± 15^oc / 1.2 ± 30^oy / 1.2 ± 30^oc / 0.9 ± 15^oy / 0.9 ± 15^oc / 0.9 ± 15^oc / h3 0^oy // symmetrically

Parameter	Meaning								
*h*1, mm	0.1	1.0	2.0	3.0	4.0	4.5	5.0	6.0	8.0
*h*2, mm	0.1	1.0	2.0	3.0	4.0	4.5	5.0	6.0	8.0
*h*3, mm	16.8	15	13	11	9	8	7	5	1
Weight, kg	11.76	11.93	12.06	12.09	12.42	12.0	11.96	11.84	11.62
Stock of strength *K*	2.9	3.7	4.8	6.0	7.1	7.4	7.7	8.0	8.1
cross-section	14	14	14	14	14	14	14	14	7
Safety factor K^o	5.5	8.6	11	13	15	16	16	17	18
cross-section	9	9	9	9	9	9	9	9	9
Stock of strength *K* *	4.5	6.0	7.6	9.5	11	12	13	12	12
cross-section	14	14	14	15	15	14	14	14	14

Note: here and below: the slope is the boundary of the change in the structure of the layers, *h*1 (*h*2, 0.5 …) the layer thickness in mm, 0*y* (0*s*, ± 15^o*y* …) is the reinforcement angle. The blade counting from the vertical axis and the material type: *y* – UOL-300, *s* – T-25-VM-78, two inclined lines – the neutral axis of the blade.

The model of the considered blade made of composite material is a twisted rod [14, 15].

Twisted are the rods, the lateral surface of which is formed by the helical movement of the contour of a flat cross-section relative to its longitudinal axis. Such rods can be straight or curved of constant and variable section. In this paper, we consider slightly curved twisted rods. The twist shape of the rod in the undeformed state is called initial or natural, i.e. given from design, functional and operational requirements.

The condition of rigid contact between the layers of a blade made of a multilayer composite material is fulfilled, which obeys Hooke's law and the conditions of a plane section along the thickness of a multilayer package. Figure 1 shows the geometry of the considered composite blade model.

The resolving equations of the cut-off part of the composite blade can be represented as

$$\int_F \sigma dF = P;\ \ -M_{\text{кр}}^{\text{ц}} + \int_F \sigma s^2 \theta\, dF = M_{\text{кр}};$$

$$\int_F \sigma \xi dF = -M_\eta;\ \ \int_F \sigma \rightleftarrows \eta dF = -M_\xi, \qquad (1)$$

where σ is the stress along the normal to the cross-section; P is the cut-off part is subject to centrifugal force; $M_\xi, M\eta$ are the moments acting relative to the indexed axes; $M_{\text{кр}}^{\text{ц}}$ is the torsion from centrifugal forces; $M_{\text{кр}}$ is the applied torque; $\theta = \partial\alpha / \partial z$ is the twist angle of the cross-section from the centrifugal forces; $s = \left(\eta^2 + \xi^2\right)^{0.5}$ is the distance to the investigated point; F is the cross-sectional area.

We consider a one-dimensional problem. The voltage is determined from the ratio:

$$\sigma = E\varepsilon = E\left(\varepsilon_0 - \kappa_\eta \eta - \kappa_\xi \xi - s^2 \theta \frac{d\varphi}{dr}\right), \qquad (2)$$

where ε_0 is the tensile (compression) deformations of the blade axis, κ_ξ, κ_η are the curvature parameters and $d\varphi / dr$ is the blade twist angle are unknown parameters of equation 1.

For a multilayer composite material, the generalized parameters of the elastic modulus are determined from the dependencies given in article [16]. Longitudinal and transverse shear stresses are found from the following relations:

$$\tau_{\eta\xi} = 2G \frac{d\varphi}{dr} \xi,\ \ \tau_{\xi\eta} = G\theta s. \qquad (3)$$

When determining the safety factor, the maximum stresses in the *i*-th layer of the *j*-th section are calculated taking into account $\sigma_{\text{в}}^{+}(\sigma_{\text{в}}^{-})$, the permissible tensile (compressive) and $\tau_{\text{в},\eta\xi}$, the tangential stresses in the tangential and transverse directions of a blade made of a multilayer composite material.

$$\kappa_{ij} = \frac{\sigma_{\text{в}}}{\sigma_{ij}};\ \ \kappa^0 = \frac{\tau_{\text{в},\xi\eta}}{\tau_{\xi\eta}};\ \ \kappa^* = \frac{\tau_{\text{в},\eta\xi}}{\tau_{\eta\xi}}. \qquad (4)$$

When solving the problem of determining the strength of a composite blade, the blade model is approximated by four-node multilayer finite elements of natural curvature in the form of a quadrangle, proposed in the article [17, 18] and shown in the Figure 1.

2. Methods

The finite element used to approximate the blade has 4 nodes and 12 degrees of freedom at each node. The element provides transverse shear deformation, rotational inertia and normal compression: u_1^i, u_2^i, u_3^i are the linear displacements, $\frac{1}{A_1}u_1^{;\alpha_1}, \frac{1}{A_1}u_2^{;\alpha_1}, \frac{1}{A_1}u_3^{;\alpha_1}, \frac{1}{A_2}u_1^{;\alpha_2}, \frac{1}{A_2}u_2^{;\alpha_2}, \frac{1}{A_2}u_3^{;\alpha_2}$ are the derivatives of these displacements along curvilinear coordinates on the blade surface, γ_1, γ_2 are the rotation angles relative to the indexed coordinates and γ_3 is the compression of the blade normal.

The approximation of linear displacements is carried out by bicubic polynomials, the angles of rotation relative to the indexed coordinates, and the compression of the normal to the blade is carried out by bilinear polynomials. When solving the problem, 21 of the stress parameters – $\{N\}$ and $\{e\}$ – the deformation parameters corresponding to stresses are determined.

$$\{N\} = [N_1, N_2, M_{11}, M_{12}, M_{13}, M_{21}, M_{22}, S_{12},$$
$$H_{11}, H_{12}, S_{21}, H_{21}, H_{22}, Q_1, P_{13}, Q_{21}, P_{22}, P_{23}, N_3]^T. \qquad (5)$$

The designations and geometry of the finite element are shown in the Figure 1.

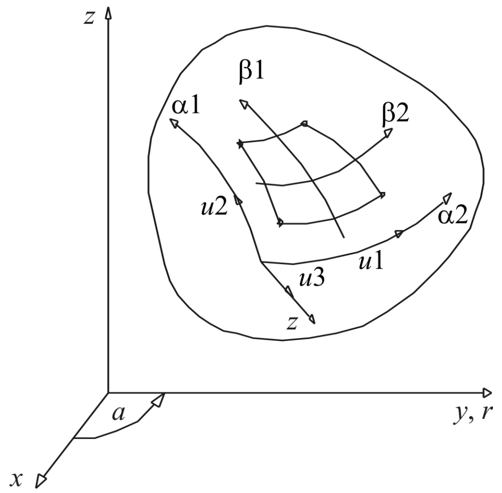

Fig. 1. Finite element

We derive the relations used in solving the problem determination of the stress-strain state of a multilayer composite blade depending on the location of the base layers of the multilayer composite material and their physical and mechanical characteristics.

We write the offset as a vector: $\{S\} = (u_1, u_2, u_3, \gamma_1, \gamma_2, \gamma_3)$.

$$\{S\}=[L]\{q\}^e;\ \{e\}=[d]\{S\}=[B]\{q\}^e;\ \{N\}=[D][d]\{q\}^e, \quad (6)$$

where $[B]=[d][L]$ is the matrix of communication of displacements and approximating functions; $[D]$ is the matrix of elastic moduli; $[d]$ is the transition matrix.

Applying the known transformations, we finally obtain the mass and stiffness matrices:

$$[K]^e=\iint_{S^e}[B]^T[D][B]A_1A_2d\alpha_1d\alpha_2;\quad [M]^e=\iint_{S^e}[L]^T[\rho][L]A_1A_2d\alpha_1d\alpha_2dz, \quad (7)$$

where $[S]^e$ is the surface area of the blade.

The global stiffness matrix for the entire model of the approximated blade is constructed according to the known laws.

3. Results

As a result of the study, a propeller blade was modeled from a multilayer composite material. Two types of composite material were considered: based on carbon fiber and glass fiber.

In addition, for comparison, the stress-strain state of a titanium alloy propeller blade was calculated. The physical and mechanical characteristics of the materials used are shown in Table 2. To determine the stresses, the propeller fan blade was evenly divided along its length into 21 sections with 17 points of thickness. The stress-strain state of the blade under the action of operational loads has been determined.

The study of the influence of the grade of the material, its thickness in the layer of multilayer composite material and the location of the base of the composite material on the strength characteristics of the blade has been carried out. Received and indicated (Table 1) the maximum stresses and safety margins along the length and thickness of the blade. Blades made entirely of CFRP and fiberglass in the surface layers and mixed designs were investigated. As well as blades made of currently used titanium alloys.

Comparison of strength and weight characteristics of blades made of composite material of various designs with currently used blades made of titanium alloy (Table 1) has been carried out.

On the basis of the presented equations, performed according to the theory of twisted rods, it is possible to estimate the stress-strain state of a blade made of a multilayer composite material and to determine the safety margins in the sections and layers of the blade.

Stresses and strains at 17 points of 21 sections in layers are determined. Composite blades of hydrodynamic engines of the first and second stages under the action of working loads: centrifugal and gas are considered.

The strength of CFRP largely depends on the characteristics of the carbon fibers and their binder. CFRP has high fatigue strength, which is 2.5 times higher than that of fiberglass plastics, a higher elastic modulus and less damage to the polymer matrix. In addition, small defects, for example, holes less than 4 mm in the design of the fan screw under tension, have little effect on the long-term and fatigue strength of CFRP located at an angle of 45° to the axis of the direction of travel load. At the same time, composite materials based on plastic reinforced with carbon fiber have low impact toughness, fracture toughness and residual stress concentration. The combination of glass and carbon fibers improves fracture toughness, crack propagation, toughness and stress retention. Also, when designing fan screw from composite materials made of carbon fibers, it is necessary to take into account the decrease in strength characteristics under the influence of elevated temperatures and humidity by 15–20 % [19, 20].

We investigate the influence of layers of angles located at an angle of zero degrees with the axial curvature lines in the outer layers of the blade on the strength characteristics. In this case, for the perception of shear stresses of 25 layers from the thickness, we take cross ± 15°, ± 30°, ± 15°.

The change in the structure of the outer layers made it possible to draw the following conclusions:

- at low content in the outer layers of material located at an angle of zero degrees to the center line of the curvature of the blade, the strength characteristics are small;
- increasing the content of outer layers with the orientation of the base of zero degrees to the center line of curvature leads to a monotonous increase in strength characteristics. Moreover, these conclusions apply to fiberglass and carbon materials.

Table 2

Material characteristics

Comparative characteristics of fiberglass, carbon fiber and titanium			
Parameter	GRP	CFRP	Titanium
Density, kg / m^3	1800–1900	1700	4500
Elastic modulus, GPa	55	140	110
Specific modulus of elasticity, km	2895–3056	8235	2444
Ultimate strength, MPa	1700	680	300–450
Specific ultimate strength, km	89–94	40,0	7–10
Fatigue to static strength ratio (10^7 cycles)	0.29	0.29	0.27
Resistance to aggressive chemical media, salt solutions	Racks	Racks	Susceptible to electrochemical corrosion. Special protective measures are required
Hygroscopicity, %	0.5	0.5	–
Possibility of implementation of architectural and design solutions	Requires manufacturing of inexpensive technological equipment	Requires manufacturing of inexpensive technological equipment	Requires expensive reconstruction of equipment

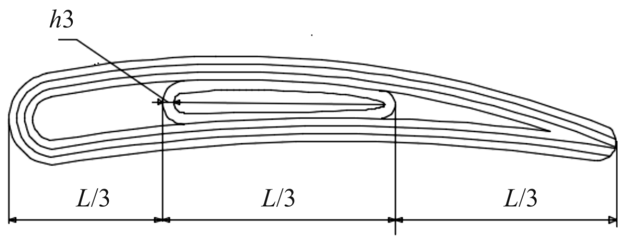

Fig. 2. Sectional of blade

Proceeding from this, in the first approximation we can suggest the following structure of the blade feather: in the outer layers, the layers with the orientation of zero degrees to the axial lines of curvature of the blade and the cross layers ± 15°, ± 30°, ± 15° in the ratio 2: 1 should be uniformly distributed, respectively. Such a scheme, in our opinion, is the most compromise, given that the inner layers disappear when approaching the edges of the blade.

Proceeding from the adopted scheme, we will investigate the influence of the ratio of glass-reinforced plastic (GRP) and CFRP on the strength characteristics of the blade under the action of centrifugal and gas loads. As a result of the study, strength parameters of the blade having different ratio of dissimilar materials were obtained. It was found that the most rational from the point of view of strength characteristics is the ratio at which the percentage of fiberglass in the carbon fiber blade is more than 40 %. At the same time, despite the higher strength characteristics of carbon-fiber materials, it is not recommended to completely eliminate fiberglass plastic. This is due to the fact that the CFRP has a lower impact strength and erosion resistance and is difficult to machine.

Strength calculations for a blade made of titanium, the most used material of metal blades, were also carried out. The strength parameters in this case were $K_{ij} = 2.1$, $K^0 = 3.6$, $K^* = 3.8$ and the mass of the titanium blade exceeded the mass of the blade from the composite by 2.5 and more times. The physical and mechanical characteristics of the materials used are summarized in the Table 2 [21–27].

The calculation results are shown in the Table 1.

Geometric characteristics of the blade in meters: length – 1.04, width: at the bottom – 0.23, at the top – 0.154, $h1$ and $h2$ – thickness of the outer surface layers of the blade shell, $h3$ – shell thickness equal to 1/3 of the blade width, located along the blade axis, inside the blade shell (Figure 2, 3).

Conclusions

Comparison of strength and weight characteristics shows that blades made of composite materials compare favorably with blades made of titanium in strength and weight characteristics. Thus, on the basis of the calculations performed, the blades made of composite material have significant advantages in terms of strength and weight characteristics compared to blades made of materials traditionally used in technology for the manufacture of propellers.

Also, as it was noted above, in addition to the physical and mechanical characteristics in terms of cost, the use of a composite material is economically beneficial in comparison with titanium alloys.

At the same time, it is necessary to investigate the ratio of CFRP and fiberglass layers, as well as the location of the base of the composite layers to obtain the highest strength, rigidity and impact strength of the outer surface of the blades of aircraft engines.

To identify the optimal structure of propfan composite blade for all types of operating loads, it is necessary to study natural vibration frequencies, surface impact strength and blade fatigue strength.

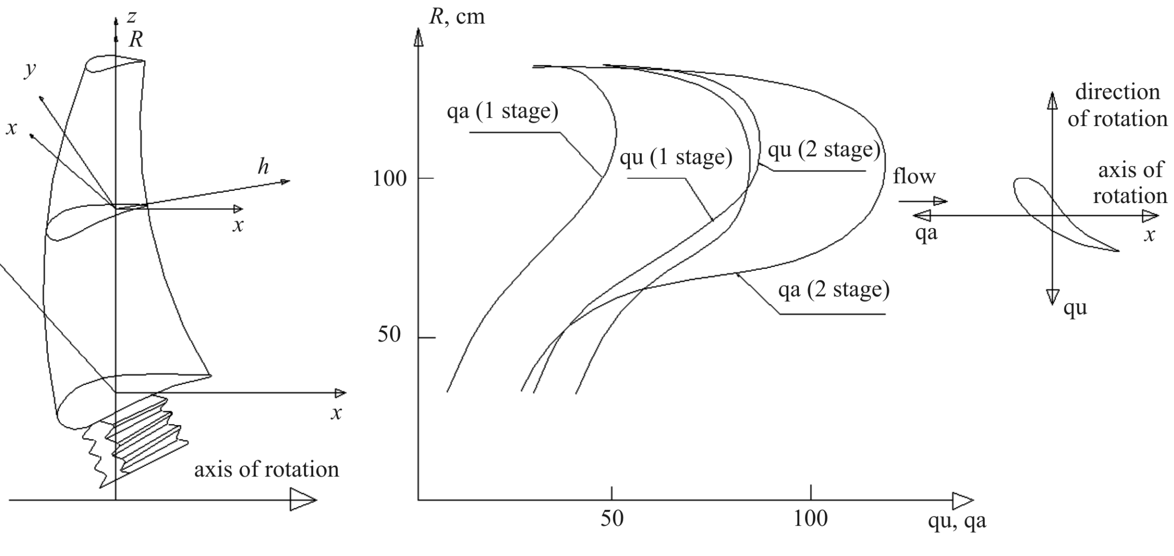

Fig. 3. Location of the axes of the rotor blade and the parameters of the loads acting on the blade

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