EXCELLENCIA
INTERNATIONAL MULTI-DISCIPLINARY JOURNAL OF EDUCATION
Volume 4, Issue 9, 2026 ISSN (E): 2994-9521

Analysis of Strength Indicators and Forecasting of Service Life of Polymer Composite Materials Used in Flights

Rustam Alijonovich Ruzmatov
Senior Lecturer of the "Course for Training and Advanced Training of Aviation Specialists" at the Institute of Military Aviation of the University of Military Security and Defense of the Republic of Uzbekistan

Abstract:

Polymer composite materials (PCMs) are increasingly used in aircraft structures because of their high specific strength, low weight, corrosion resistance, and fatigue performance; however, their anisotropic behavior and susceptibility to progressive damage under complex loading complicate strength assessment and service-life prediction. This study investigates the mechanical behavior, strength characteristics, and durability of polymer composite materials used in aircraft structures and develops an approach for evaluating their performance under variable loading conditions. The mechanical response of unidirectional, symmetrically reinforced, and quasi-isotropic composite specimens was examined under tensile, compressive, bending, and interlaminar shear loading at different fiber-orientation angles. Experimental testing was combined with analytical calculations and finite element modeling in Abaqus to determine elastic moduli, Poisson’s ratios, stress distributions, deformation behavior, and failure characteristics. The Hashin failure criterion was applied and modified to assess damage initiation and strength limits in individual layers and multilayer composite packages. The results demonstrate a strong dependence of the mechanical properties and failure mechanisms on fiber orientation and loading direction. The calculated elastic and strength characteristics showed generally good agreement with the experimental behavior, while discrepancies at particular orientation angles were associated primarily with matrix-dominated failure, shear deformation, and fiber degradation under compression. Finite element simulations reproduced the characteristic deformation response observed experimentally and provided a basis for evaluating stresses within multilayer composite structures. Based on the combined experimental and numerical analysis, an approach for estimating periodic strength and forecasting the service life of aircraft

polymer composite structures under variable loads is proposed. The findings can support more reliable strength assessment, damage prediction, and durability evaluation of load-bearing composite components used in aviation structures.

Keywords: Polymer composite material, anisotropy, orthotropic materials, strength, wear resistance, specific strength, corrosion resistance, fatigue resistance, numerical modeling, finite element method, tension, bending, compression.

Introduction

Polymer composite materials possess anisotropic properties, meaning the strength of the material changes depending on the direction of the fibers [1,2,3]. This requires calculation and a special approach to testing methods. In implementing these tasks, polymer composite materials (PCM) play an important role. PCM surpasses traditional metal materials in properties such as high specific strength, corrosion resistance, and fatigue resistance and the ability to provide aerodynamic shape.

In the design of military aircraft, composite materials are primarily used in wings, fuselage coatings, steering surfaces, and load-bearing elements. Composites made of carbon fiber are distinguished by their high strength and lightness. This contributes to an increase in flight range and speed by reducing the total weight of the aircraft.

At the same time, during flight, various aerodynamic, inertia, and thermomechanical loads act on the structural elements.

These loads cause complex stress-bending states in polymer composite materials, causing interlayer ruptures, fatigue cracks, and can lead to a decrease in strength [4].

These negative effects are particularly acute at high speeds, large flight angles, and maneuvering modes.

Therefore, determining the strength of polymer composite materials used in military aircraft [5], correctly assessing the forces acting on them, and researching ways to increase structural reliability while considering innovative production technologies is a pressing scientific task.

In this regard, it is necessary to determine the service life of such structures and create universal forecasting methods.

Research methods

High speeds, large flight angles and loads during maneuvering modes in polymer composite materials used in aircraft structures can cause complex stress-bending states, which can lead to interlayer separation of polymer composite materials, fatigue cracks, and strength degradation.

Therefore, let us consider a research analysis of the influence of stresses that can lead to the strength and wear of polymer composite materials.

A package of polymer composite materials consisting of:

of homogeneous layers, is equivalent to a single layer whose total thickness is equal to the sum of the thicknesses of all its constituent elements. The research characteristics of single-directional samples were analyzed.

from carbon plastic when calculating the hardness characteristics of single-directional composites under various loads, and during strength testing at various inclination angles to the longitudinal reinforcement axis.

To calculate the flexibility matrix of a polymer composite material, it is first necessary to convert the monolayer flexibility matrix into a coordinate system related to the sample under study:

$$[\Phi]=[T_{\varepsilon}][\Phi][T_{\varepsilon}]^{T}; \qquad [\Phi]=\begin{bmatrix}\Phi_{11} & \Phi_{12} & \Phi_{14}\\ \Phi_{21} & \Phi_{22} & \Phi_{24}\\ \Phi_{41} & \Phi_{42} & \Phi_{44}\end{bmatrix}$$

To determine the matrix [T], which establishes the relationship between the voltages in the monolayer and the voltages of the entire package, let us refer to unilateral compression or stretching of the sample [12]:

$$[\sigma]=\begin{bmatrix}\sigma_{xx}\\ 0\\ 0\end{bmatrix}; \qquad [\overline{\sigma}]=[T]\sigma_{xx},$$

The constituent parts of the [T] matrix are as follows:

$$[T]=\begin{bmatrix}T_{11}\\ T_{22}\\ T_{12}\end{bmatrix}=\begin{bmatrix}\cos^{2}(\varphi)\\ \sin^{2}(\varphi)\\ -2\cos(\varphi)\sin(\varphi)\end{bmatrix}$$

The elements of the matrix [T], the elastic properties of PCM made of carboplastic, depend on from the load application angle and manifest as follows:

$$E_{xx}=\frac{1}{\Phi_{11}}; \quad \mu_{xy}=-\Phi_{21}E_{xx}=-\frac{\Phi_{21}}{\Phi_{11}}; \quad \eta_{xy,x}=\Phi_{41}E_{xx}=\frac{\Phi_{41}}{\Phi_{11}}.$$

The experimental and calculated determination of the stiffness of a single-directional PCM package at various loading angles corresponding to these formulas is shown.

The relationship between ultimate compressive stresses and the direction of the applied load shows a high degree of consistency between the calculated and experimental data. At loads that do not coincide with the 0° axis, the destruction of samples occurs due to the destruction of the matrix.

This complicates the calculation of the coefficient α, which reflects the contribution of its shear stresses ($0 \leq \alpha \leq 1$). This coefficient can only be estimated for load slopes from 0° to 5°.

When evaluating the characteristics and properties of the tested material, a symmetrical reinforcement scheme is preferred, as when studying strength in a monolayer at laying angles greater than 5°, the binding component breaks down, causing stress concentration in the coverage area due to non-compliance with boundary conditions, as well as due to the deformation of the tested material under the action of shear stresses.

The coefficients of the compatibility matrix of a symmetric set can be expressed in the sample coordinate system using the following formula:

$$\Phi_{11} = \frac{K_{22}}{K_{11}K_{22} - K_{12}^2}; \qquad \Phi_{22} = \frac{K_{11}}{K_{11}K_{22} - K_{12}^2};$$

$$\Phi_{12} = \frac{-K_{12}}{K_{11}K_{22} - K_{12}^2}; \qquad \Phi_{44} = \frac{1}{K_{44}}.$$

Transitions into single-axis loading, stretching, or compression. The correlation coefficients $\sigma_{yy} = \sigma_{xy} = 0$ between the hidden layers of a multi-layer PCM are zero.

In this situation, the hardness of the sample is calculated by analyzing the following ratio:

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & 0 \\ \Phi_{12} & \Phi_{22} & 0 \\ 0 & 0 & \Phi_{44} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{K_{22}}{K_{11}K_{22} - K_{12}^2}\sigma_{xx} \\ \frac{-K_{12}}{K_{11}K_{22} - K_{12}^2}\sigma_{xx} \\ 0 \end{bmatrix}$$

Based on the obtained dependencies, equations describing the dependence of the elastic modulus of the entire package and the Poisson coefficient on the hardness parameters of its constituent material can be determined:

$$E_{xx} = \frac{1}{\Phi_{11}} = K_{11} - \frac{K_{12}^2}{K_{22}}; \qquad \mu_{xy} = \frac{-\Phi_{12}\sigma_{xx}}{\Phi_{11}\sigma_{xx}} = \frac{K_{12}}{K_{22}};$$

The effectiveness of modeling the destruction of symmetric packages occurs at angles φ greater than 35°, where the strength of the matrix serves as the decisive factor. In the angle range of 5° ≤ φ ≤ 30°, it is difficult to obtain a reliable description of the test results. The curve of the matrix strength dependence has a characteristic limit T_{22}, equal to zero. Experiments show that at direction angles of 41.60°, the matrix is subjected to compressive loads, and at higher angles, to tensile loads.

However, at a direction angle of 30 degrees, a slight difference is observed from the calculated values, which may be related to the complete decomposition of fibers during compression. A similar situation with tension on the matrix strength curve has a specific direction angle where the value of T_{22} is zero. During compression, the dependence of the matrix position (stretched or compressed) on the positioning angle is manifested as follows: angles less than 4.6° correspond to the stretched position, and large angles correspond to the compressed position.

Results and Discussions

Let us turn to the results of experiments dedicated to studying the properties of PCM. The mechanical characteristics of samples cut at angles of 0°, 90°, and 45° relative to the reinforcement direction and possessing quasi-isotropic structures and strength properties were tested for compression, tension, shear, and bending. The tests were conducted on a test bench at room temperature and a constant capture speed of 2 mm/min.

For each sample, its geometric parameters were measured: thickness, working field width, and cross-sectional area.

When evaluating the strength properties of polymer composite materials, coated strip samples were used according to GOST 56785 -2015 [6], [7]. Each sample was placed on the test equipment's handles and subjected to strong impact until it broke. The applied loads and the displacement of the active grip were continuously monitored, and the longitudinal deformation of the sample's working zone was determined using a special measuring instrument.

To determine the Poisson coefficient in unidirectional samples directed along the reinforcement direction, relative deformation was measured in the longitudinal and transverse directions.

In these measurements, tenzoresistors were used, which are approximately

to the surface of the samples [8].

The following formulas were used during the study:

$$\sigma^{+} = \frac{P_{\max}}{bh}; \qquad E^{+} = \frac{\Delta P}{\Delta\varepsilon_{xx} bh}; \ \mu = \frac{\Delta\varepsilon_{yy}}{\Delta\varepsilon_{xx}},$$

where P_{max} - is the maximum load at which the sample is destroyed; the width of the sample b - and its thickness - h are expressed as $\Delta\varepsilon_{xx}$ changes in the longitudinal deformation of the sample as $\Delta\varepsilon_{yy}$ increases, and are defined as changes in the transverse deformation ΔP at the same width measured by the width of the sample.

Determination of the compressive strength of polymer composites was carried out on a device where coated tape samples manufactured according to GOST R 56812-2015 were tested with force before rupture. At the same time, a change in load and a shift in coverage were noted [9], [10]. Thermal resistors attached to the sample, we recorded its longitudinal deformation. Cross-sectional deformation was measured on test samples cut perpendicular to the reinforcement direction.

The properties of the material under the influence of compression were realized by the following expressions:

$$\sigma^{-} = \frac{P_{\min}}{bh}; \quad E^{-} = \frac{\Delta P}{\Delta\varepsilon_{xx} bh}; \qquad \mu = \frac{\Delta\varepsilon_{yy}}{\Delta\varepsilon_{xx}},$$

where $|P_{min}|$ - is the force applied to the sample before its destruction.

The sample, placed on two stationary supports, was subjected to impact until complete destruction, and the dynamics of load changes and the displacement of the moving part of the structure were observed [11].

The deformation properties of PCM during bending were determined using the following formulas:

$$\sigma^{e} = \frac{3}{2}\frac{P_{\max} L}{bh^2}; \qquad E^{e} = \frac{1}{4}\frac{\Delta P}{\Delta\omega}\frac{L^3}{bh^3};$$

where L - is the distance and the plane separating the supports, which is 60 mm, Δw represents the difference in sample bending when the applied load changes by ΔP .

Determination of the PCM's strength characteristics against shear was carried out on sample tapes manufactured according to GOST 32659-2014. In the device's design, two fixed supports hold the sample, on which the punch acts with a load until the sample is completely destroyed [12]. During the testing process, the dynamics of force change and the displacement of the load application point were recorded.

To study the properties of the material under the influence of interlayer displacement, the following formulas were used:

$$\sigma^{qs} = \frac{3}{4}\frac{P_{\max}}{bh}; \qquad C^{qs} = \frac{\Delta P}{\Delta W},$$

When conducting tests using the short beam method, the bend value at the central point of the span is equal to:

$$w = \frac{PL^3}{48E^e \cdot I}\left(1 + \frac{24\gamma E^e \cdot I}{PL^2}\right)$$

where: L - is the distance between the support points (equal to 10 mm), E^e - is the elastic modulus measured for the material having a strength direction by angle 0° during bending [13].

The shear deformation was determined as follows:

$$\gamma = \frac{2w}{L} - \frac{PL^2}{2E^e \cdot bh^3}$$

The modulus of interlayer displacement was determined as follows:

$$G^{qs} = \frac{3C^{qs}}{4bh}\left(\frac{2}{L} - \frac{L^2 C^{qs}}{2E^e_{0^0} \cdot bh^3}\right)$$

As a result of the tests conducted to characterize the properties of PCM samples for stretching, the following main parameters were determined [8]:

E^+ - is the elasticity coefficient of the PCM along the reinforcement axis under the action of stretching loads;

- E^+ is the elasticity coefficient of the tested material, determined in the direction perpendicular to the reinforcement under the action of stretching loads;

- E^+ is the elasticity coefficient of the composite, measured at an angle

45 degrees to the reinforcement axis;

- E^+ is the strength component of the PCM, characterizing tension and possessing a quasi-isotropic distribution of characteristics;

$-\sigma^+$ maximum retained voltage KM when stretched along the reinforcement;

$-\sigma^+$ the maximum load-bearing capacity of the tested material when stretched in a direction perpendicular to the reinforcement;

$-\sigma^+$ the maximum stress that the composite can withstand when stretched at an angle of 45° to the reinforcement direction;

$-\sigma^+$ maximum load-bearing capacity of composite material with a quasi-isotropic structure under the influence of stretching loads;

$-\mu^{+}$ the Poisson index characterizes the deformation of the material during stretching along the reinforcement direction [14].

In the process of testing polymer composite materials the following main parameters were determined:

$E_{0^\circ}^{-}$ - elasticity coefficient of the material along the reinforcement axis (under compression loads);

$E_{90^\circ}^{-}$ - composite elasticity coefficient, perpendicular to reinforcement;

$E_{45^\circ}^{-}$ - the elasticity coefficient of the composite material (under compression loads), measured in the direction forming an angle of 45° with the reinforcement axis;

E_{κ}^{-} - the influence of compression on the elastic modulus of the composite material with quasi-isotropic structure;

$\sigma_{0^\circ}^{-}$ - defined as the maximum value of stresses that a composite material can withstand during compression along the reinforcement direction;

$\sigma_{90^\circ}^{-}$ - defined as the maximum load-bearing capacity of composite material in the transverse direction for reinforcement, equal to significant compression;

$\sigma_{45^\circ}^{-}$ - the maximum load-bearing capacity of a composite material loaded by compression at a 45-degree angle to the reinforcement axis is;

σ_{κ}^{-} - quasi-isotropic structure, determined by the action of compressive loads, the maximum load-bearing capacity of the composite material;

μ_{12}^{-} - Poisson's index, characterizing deformation in a direction perpendicular to the reinforcement direction under the action of compressive forces;

The bending tests of the samples revealed the following main parameters:

$E_{0^\circ}^{-}$ - elasticity effect during bending of the tested material in the form of an armature module;

$E_{90^\circ}^{-}$ - the elasticity coefficient of the composite, which determines its impact on

bending in the direction perpendicular to the reinforcement is indicated;

$E_{45^\circ}^{-}$ - the elasticity of the composite material in the direction perpendicular to the reinforcement axis, determined by the modulus at bending under a 45-degree angle;

E_{k}^{e} - bending properties of a composite with a quasi-isotropic elastic modulus;

$\sigma_{0^\circ}^{e}$ - defined as the maximum value of stresses that a composite material can withstand during bending along the reinforcement direction;

$\sigma_{90^\circ}^{e}$ - the maximum load-bearing capacity of the composite material during bending, measured by force in a direction perpendicular to to reinforcement;

$\sigma^{e}_{45^{\circ}}$ - the maximum load-bearing capacity of the composite material during bending, measured according to a normal drawn at a 45-degree angle to the reinforcement axis;

σ^{e}_{k} - maximum load-bearing capacity of the composite material with a quasi-isotropic structure during bending, expressed as a parameter.

Testing composite material samples for stability to the interlayer shift, the following was established:

$\sigma^{qs}_{0^{\circ}}$ - strength limitation during displacement between layers in the direction of fastening;

$G^{qs}_{0^{\circ}}$ - an element that ensures interlayer displacement, executed according to the scheme and directed along the reinforcement direction;

the maximum value of voltage that a sample can withstand with a quasi-isotropic structure when shifting between layers;

G^{qs}_{k} - the displacement between layers carried out by a quasi-isotropic structure is established as a model.

During the numerical modeling of bending tests, a pattern of impact on the sample was developed similar to the experimental model in the final - element model. The supports and Punson were represented using three-dimensional rigid elements, and corresponding connections were established between the sample, supports, and Punson surfaces. The modeling of the sample load was carried out using a specified Poisson motion trajectory [15].

Due to the specificity of the structure and properties of the polymer matrix, it is impossible to test single-directional composite material samples cut at angles of 45° and 90°, as this inevitably led to the rupture of the matrix under the influence of stretching forces.

The considered model characteristics, strength criteria, and methods for determining composite material parameters were obtained by simulating the effects of stretching, compression, bending, and interlayer displacement using samples with a single-directional quasi-isotropic structure to strengthen performance.

Composite material samples were modeled based on finite element models using Abaqus software. At the same time, it is advisable to utilize our own developments on composite material characteristics and strength criteria, determine monolayer properties based on experimental data, and test single-directional samples for stretching and compression.

For modeling, shell elements were used, consisting of 16 layers with a thickness of 0.125 mm each and oriented in different directions, as a result of calculations, the obtained data with patterns characteristic of the sample deformation process were compared with the data obtained during experiments.

Based on the analysis of the obtained calculation data, the dependence of sample bending on the force acting on the punch was determined. To evaluate the accuracy of the calculations, these dependencies were compared with the experimental results.

Conclusion

Based on the above analysis, the following scientific problem has been formulated: polymer composite materials used in aircraft operate in a complex stress state under the influence of high aerodynamic and inertia loads, but existing design methods do not fully account for these circumstances. As a result, a sufficient strength reserve in the structural elements is not ensured.

Research on the strength and wear of composite materials:

an approach has been proposed, including a structural analysis of the deformed state of the tested sample, the law of elastic deformation of orthotropic materials, as well as the Hashin strength criterion for determining the strength of polymer composite materials;

the correspondence of the obtained values of elastic properties strengthens the reliability of the proposed approach to evaluating monolayer parameters;

the dependencies describing the stresses arising during the action of stretching and compression loads on the layers of a symmetrical set of polymer composite materials have been determined. The Hashin criterion is used to evaluate the reliability of packets. A method has been proposed that allows for the evaluation of parameters based on the testing of samples reinforced by symmetrical and single-directional circuits. A modification of the Hashin criterion has been proposed, allowing for good consistency between modeling and experimental research results;

a method for determining the periodic strength of polymer composite materials, allowing for the determination and forecasting of the service life of polymer composite materials used in the design of aircraft under variable loads, taking into account experimental data and asymmetry coefficients.

References

[1] S. A. Ambartsumyan, *General Theory of Anisotropic Shells*. Moscow, Russia: Nauka, 1974, 466 p.

[2] A. N. Andreev and Yu. V. Nemirovsky, *Multilayered Anisotropic Shells and Plates*. Novosibirsk, Russia: Nauka, 2001, pp. 287–288.

[3] E. K. Ashkenazi, “Issues of strength anisotropy,” *Polymer Mechanics*, no. 2, pp. 79–92, 1965.

[4] A. N. Anoshkin, V. E. Wildeman, D. S. Lobanov, and A. I. Chikhachev, “Assessment of repair efficiency in structures made of polymer fibrous composite materials,” *Mechanics of Composite Materials*, no. 3, pp. 441–450, 2014.

[5] D. R. Abashev, V. S. Bondar, I. A. Vorobyov, and V. I. Sharova, “Determination of elastic parameters of polymer composite materials and cylindrical shells made from them,” *Problems of Strength and Plasticity*, no. 1, pp. 45–59, 2024.

[6] V. S. Bondar, D. R. Abashev, and I. A. Vorobyov, “Application of the Hashin strength criterion for assessing the strength of composite materials with a symmetrical reinforcement scheme,” *Mechanical Engineering and Engineering Education*, no. 3, pp. 12–19, 2024.

[7] A. S. Vasilev, *Mathematical Modeling and Numerical Research of Composite Materials in the Field of Ultimate Strength*. Komsomolsk-on-Amur, Russia, 2016.

[8] S. A. Vladimirov, I. A. Vorobyov, and V. I. Sharova, “Method for determining the elastic parameters of polymer composite materials and assessing their strength,” *Cosmonautics and Rocketry*, no. 1, pp. 68–75, 2024.

[9] E. I. Grigolyuk, E. A. Kogan, and V. I. Mamay, “Problems of deformation of thin-walled layered structures with stratification,” *Solid State Mechanics*, pp. 6–32.

[10] *GOST R 56785-2015: Polymer Composites—Method for Testing Flat Samples for Tension*. Moscow, Russia: Standartinform, 2016, 20 p.

[11] E. Carrera, “Theories and finite elements for multilayered plates and shells: A unified compact

formulation with numerical assessment and benchmarking," *Archives of Computational Methods in Engineering*, vol. 10, no. 3, pp. 215–296, 2003, doi: 10.1007/BF02736224.

[12] A. I. Lurie, *Theory of Elasticity*. Moscow, Russia: Nauka, 1970, 940 p.

[13] A. I. Lurie, "Concentration of stresses in the area of an opening on the surface of a circular cylinder," *Applied Mathematics and Mechanics*, vol. 10, no. 3, pp. 397–405, 1946.

[14] A. N. Polylov and N. A. Tatus, "Substantiation of fiber composite strength criteria based on experimental data," *Bulletin of Scientific and Technical Development*, no. 7(59), pp. 35–50, 2012.

[15] V. E. Wildeman, T. V. Sannikova, and M. P. Tretyakov, "Experimental study of the patterns of material deformation and destruction in a plane stress state," *Problems of Mechanical Engineering and Reliability of Machines*, no. 5, pp. 106–111, 2010.