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MECHANICAL CHARACTERISTICS DETERMINATION OF AIRCRAFT WING CARBON PLASTIC PANEL

Ua У роботі представлено методику розрахунку механічних характеристик багатошарових композитних панелей. Була підібрана оптимальна послідовність викладки моношарів. Механічна поведінка композиції визначається співвідношенням властивостей армуючих елементів і матриці, а також міцністю зв’язку між ними. Серед найважливіших вимог, що висуваються до конструкцій сучасних літальних апаратів, можна назвати мінімальну масу, максимальну жорсткість і міцність вузлів, максимальний ресурс роботи конструкцій в умовах експлуатації, високу надійність. За допомогою розробленої методики, було визначено пружні властивості композитного матеріалу із різними кутами викладки шарів. Приведено розрахунки механічних характеристик вуглепластикових панелей із вуглестрічки та вуглетканини.

En The paper presents the method of calculating the mechanical characteristics of multilayer composite panels. The optimal sequence of laying out monolayers was selected. The mechanical behavior of the composition is determined by the ratio of the properties of the reinforcing elements and the matrix, as well as the strength of the connection between them. Among the most important requirements for the designs of modern aircraft, we can mention the minimum weight, the maximum stiffness and strength of the nodes, the maximum service life of the structures in operational conditions, and high reliability. With the help of the developed methodology, the elastic properties of the composite material with different angles of laying layers were determined. Calculations of the mechanical characteristics of carbon-plastic panels made of carbon tape and carbon fabric are given.

Introduction

In connection with the wide use of various composite materials, especially in aircraft construction, there are very relevant and important tasks of developing methods for assessing the strength of composite materials, creating mathematical models of deformation, developing methods for experimental research of deformation and strength properties of structural composite materials, as well as evaluating dangers of technological and operational defects arising in structural elements.

Composite materials bring a lot of useful things to aviation - they increase the strength of parts, reduce their weight and susceptibility to corrosion, and also

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allow to reduce the number of parts. It is known that a composite material consists of a high-strength filler oriented in a certain direction and a matrix.

A variety of fibers and matrix materials, as well as reinforcement schemes, used in the creation of composite structures, which allows us to purposefully adjust the strength, stiffness, level of operating temperatures and other properties by selecting the composition, changing the ratio of components and the microstructure of the composite [1 - 3, 7].

High-modulus carbon fibers are used for the manufacture of aircraft parts. Polymeric carbon plastics are characterized by low density, high modulus of elasticity, low thermal and electrical conductivity, low frictional wear and high damping capacity. By orienting the fibers at an angle to each other, it is possible to change the damping capacity of carbon fiber plastics to a large extent and to rebuild parts from the resonance mode without changing their geometric shapes [41 - 6].

Creation of monolayer packages

To identify any monolayer in a package of monolayers, the layer orientation code is used, which defines [3]:

– angle of inclination of the monolayer to the basic axis of the monolayer package X;
– the number of monolayers having a given angle of inclination;
– exact arrangement of monolayers.

Each monolayer is marked with a number showing the orientation of the monolayer in degrees between the direction of its fibers and the X axis. Fig. 1 shows the standard orientation of monolayers 0º, + 45 º, -45 º i 90 º.

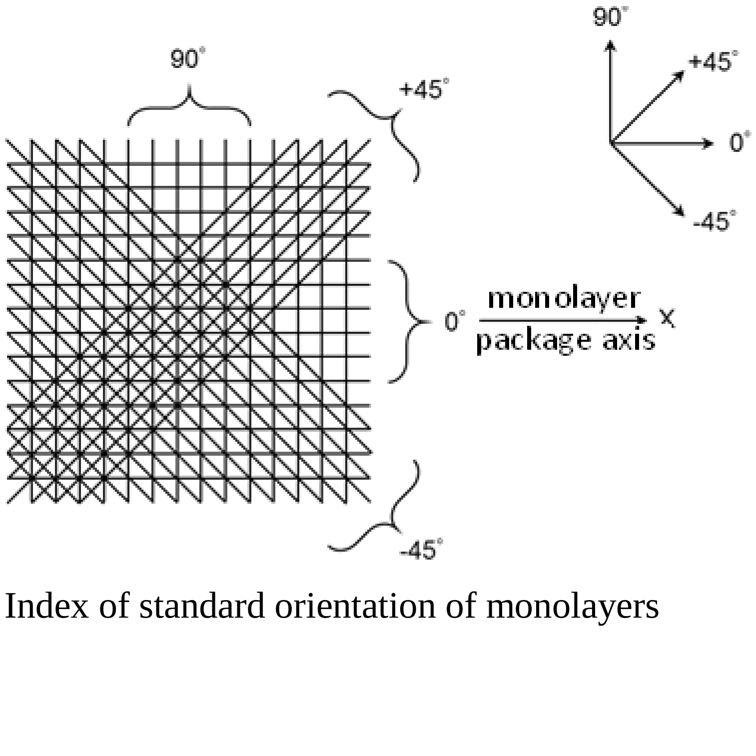

Fig. 1. Index of standard orientation of monolayers

Adjacent monolayers are divided by a diagonal line if their tilt angles are different. Monolayers are written sequentially from the front surface of one monolayer to another using parentheses.

Adjacent monolayers having the same angle are indicated by a numerical subscript. The subscript "T" in parentheses indicates that the complete set of monolayers is given. If adjacent monolayers have the same but opposite angle, the corresponding "+" or "-" signs are used. Counter-clockwise angles are considered positive.

Sometimes, instead of the negative angles of the first quadrant, the positive angles found in the second quadrant are used. For example, instead of the designation of the angle -45°, the notation is used 135°.

Dependence of stresses and strains for different coordinate systems

For a plane stress state when the axes are rotated by an angle φ° (fig. 2), the dependence of the acting stresses in the coordinate systems of the monolayer and the package of monolayers has the form

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} c^2 & s^2 & -2\cdot s\cdot c \\ s^2 & c^2 & 2\cdot s\cdot c \\ s\cdot c & -s\cdot c & c^2-s^2 \end{bmatrix} \cdot \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix},$$

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} c^2 & s^2 & 2\cdot s\cdot c \\ s^2 & c^2 & -2\cdot s\cdot c \\ -s\cdot c & s\cdot c & c^2-s^2 \end{bmatrix} \cdot \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix},$$

where $c = \cos\varphi^o$; $s = \sin\varphi^o$,

σ_1, σ_2, τ_{12} – are the stresses acting in the monolayer,

σ_x, σ_y, τ_{xy} – are the stresses acting in the monolayer packets.

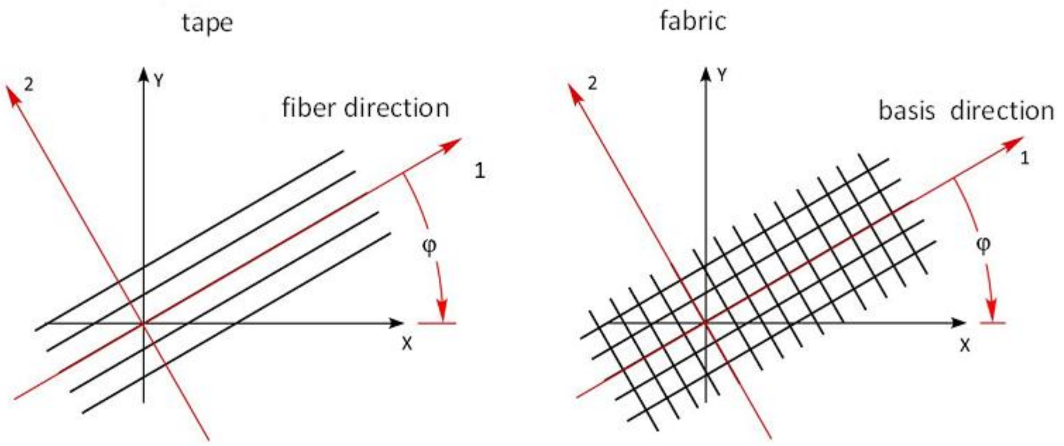

Fig. 2. A monolayer rotated by an angle φ° with respect to the coordinate system of the monolayer package

The dependence of deformations in the coordinate systems of a monolayer and a package of monolayers has the form

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} c^2 & s^2 & -s\cdot c \\ s^2 & c^2 & s\cdot c \\ 2\cdot s\cdot c & -2\cdot s\cdot c & c^2-s^2 \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix},$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} c^2 & s^2 & s\cdot c \\ s^2 & c^2 & -s\cdot c \\ -2\cdot s\cdot c & 2\cdot s\cdot c & c^2-s^2 \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix},$$

where ε_1, ε_2, γ_{12} –are the monolayer deformations,

ε_x, ε_y, γ_{xy} – are the package of monolayers deformations.

Calculation of elastic characteristics of composite multilayer material

Each individual layer (monolayer) consists of unidirectional fibers that determine the direction of the layer, and a matrix that provides normal and transverse stiffness of the layer. Such a monolayer is orthotropic because it has two mutual axes of symmetry. Its characteristic feature is that normal stresses acting along the axes of orthotropy do not cause shear deformations, and tangential stresses - elongations. Hooke's law describing the stress-strain relationship for a unidirectional monolayer in a flat stress-strain state has the form:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} C_{11}^0 & C_{12}^0 & 0 \\ C_{21}^0 & C_{22}^0 & 0 \\ 0 & 0 & C_{66}^0 \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix},,$$

where σ_1, σ_2, τ_{12} – are the stresses acting in the monolayer;

ε_1, ε_2, γ_{12} – are the monolayer deformations;

C_{kl}^0 – are the coefficients of the stiffness matrix of the monolayer, which are determined as:

$$C_{11}^0 = \frac{E_1}{1-\mu_{12}\cdot\mu_{21}}; \qquad C_{12}^0 = \frac{E_1\cdot\mu_{21}}{1-\mu_{12}\cdot\mu_{21}} = \frac{E_2\cdot\mu_{12}}{1-\mu_{12}\cdot\mu_{21}};$$

$$C_{22}^0 = \frac{E_2}{1-\mu_{12}\cdot\mu_{21}}; \qquad C_{66}^0 = G_{12},$$

where E_1, E_2 are the longitudinal and transverse modulus of elasticity of the monolayer;

G_{12} is the monolayer shear modulus;

μ_{12} is the Poisson’s main ratio;

μ_{21} is the second-order Poisson's ratio, which is determined from Maxwell's relation:

$$\mu_{12} \cdot E_2 = \mu_{21} \cdot E_{12} .$$

Typical elastic characteristics of monolayers of carbon tape and carbon fabric are presented in Tab. 1.

***Table* 1**

Elastic characteristics of the monolayer

monolayer	Moduli of elasticity and shear, MPa			Poisson's ratios	
	E_1	E_2	G_{12}	μ_{12}	μ_{21}
carbon tape	143000	8400	5600	0,36	0,02
carbon fabric	65000	63000	6500	0,070	0,068

If the loading of the monolayer does not occur along the orientation axis, then it is in the state of layer-by-layer loading as part of the composite package. Then Hooke's law takes shape:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} C_{11}^{\varphi} & C_{12}^{\varphi} & C_{16}^{\varphi} \\ C_{13}^{\varphi} & C_{22}^{\varphi} & C_{26}^{\varphi} \\ C_{16}^{\varphi} & C_{26}^{\varphi} & C_{66}^{\varphi} \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix},$$

where the coefficients of the stiffness matrix of the monolayer rotated by an angle φ^{o}

$$C_{11}^{\varphi} = V_1 + V_2 \cdot \cos 2\varphi + V_3 \cdot \cos 4\varphi ;$$

$$C_{12}^{\varphi} = V_1 - 2 \cdot V_4 - V_3 \cdot \cos 4\varphi ;$$

$$C_{16}^{\varphi} = 0,5 \cdot V_2 \cdot \sin 2\varphi + V_3 \cdot \sin 4\varphi ;$$

$$C_{22}^{\varphi} = V_1 - V_2 \cdot \cos 2\varphi + V_3 \cdot \cos 4\varphi ;$$

$$C_{26}^{\varphi} = 0,5 \cdot V_2 \cdot \sin 2\varphi - V_3 \cdot \sin 4\varphi ;$$

$$C_{66}^{\varphi} = V_4 - V_3 \cdot \cos 4\varphi .$$

Here, the independent coefficientsV_1, V_2, V_3 and V_4 are determined:

$$V_1 = \left(3 \cdot C_{11}^{0} + 2 \cdot C_{12}^{0} + 3 \cdot C_{22}^{0} + 4 \cdot C_{66}^{0}\right)/8 ;$$

$$V_2 = \left(C_{11}^{0} - C_{22}^{0}\right)/2 ;$$

$$V_3 = \left(C_{11}^{0} - 2 \cdot C_{12}^{0} + C_{22}^{0} - 4 \cdot C_{66}^{0}\right)/8 ;$$

$$V_4 = \left(C_{11}^{0} - 2 \cdot C_{12}^{0} + C_{22}^{0} + 4 \cdot C_{66}^{0}\right)/8 .$$

Coefficients V_1 and V_4 characterize the average stiffness of the monolayer under tension and shear, and coefficients V_2 and V_3 characterize the degree of anisotropy of the material. Thus, the behavior of a monolayer in a flat stress-strain state is characterized by four independent elastic constants: E_1, $E2$, G_{12}, μ_{12} for reinforcement angles 0° i 90°; V_1, V_2, V_3, V_4 for reinforcement angles φ°.

Elastic characteristics of a monolayer rotated by an angle φ°:

$$E_x = \frac{\Delta C}{C_{22}^{\varphi}\cdot C_{66}^{\varphi} - \left(C_{26}^{\varphi}\right)^2}; \qquad G_{xy} = \frac{\Delta C}{C_{11}^{\varphi}\cdot C_{22}^{\varphi} - \left(C_{12}^{\varphi}\right)^2};$$

$$E_y = \frac{\Delta C}{C_{11}^{\varphi}\cdot C_{66}^{\varphi} - \left(C_{16}^{\varphi}\right)^2}; \qquad \mu_{xy} = \frac{C_{12}^{\varphi}\cdot C_{66}^{\varphi} - C_{16}^{\varphi}\cdot C_{66}^{\varphi}}{C_{22}^{\varphi}\cdot C_{66}^{\varphi} - \left(C_{26}^{\varphi}\right)^2},$$

where ΔC is the determinant of the stiffness matrix

$$\Delta C = \det\begin{bmatrix} C_{11}^{\varphi} & C_{12}^{\varphi} & C_{16}^{\varphi} \\ C_{12}^{\varphi} & C_{22}^{\varphi} & C_{26}^{\varphi} \\ C_{16}^{\varphi} & C_{26}^{\varphi} & C_{66}^{\varphi} \end{bmatrix}.$$

Changes in the modulus of elasticity and shear of the carbon tape (Tab. 1) depending on the angle φ° are presented in fig. 3, and Poisson's ratios are presented in fig. 4. Changes in modulus of elasticity and shear of carbon fabric (Tab. 1) depending on the angle φ° are presented in fig. 5, and Poisson's coefficients in fig. 6.

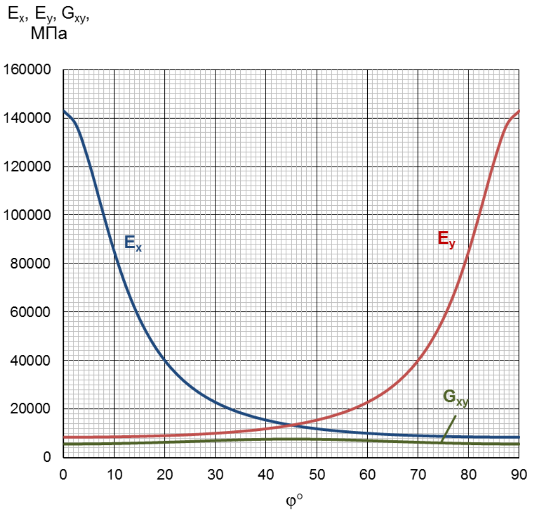

Fig. 3. The modulus of elasticity and shear of carbon tape depending on the angle φ°

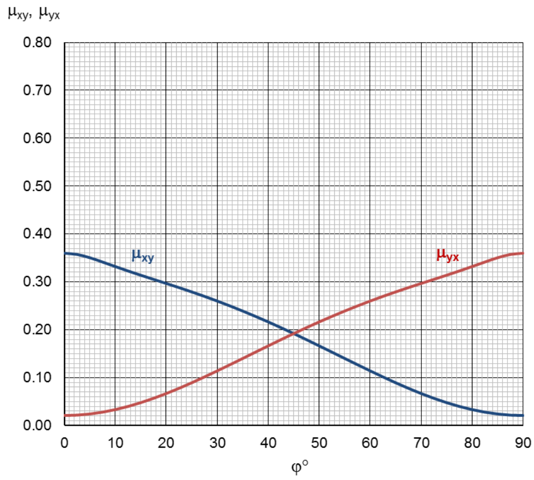

Fig. 4. Poisson's ratios of carbon tape depending on the angle φ°

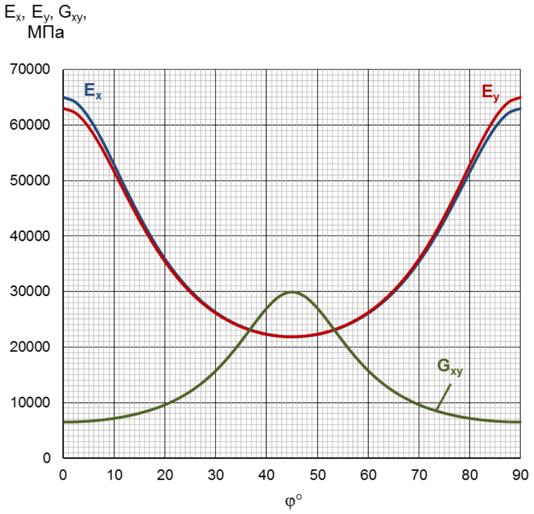

Fig. 5. The modulus of elasticityand shear of carbon fiber depending on the angle φ°

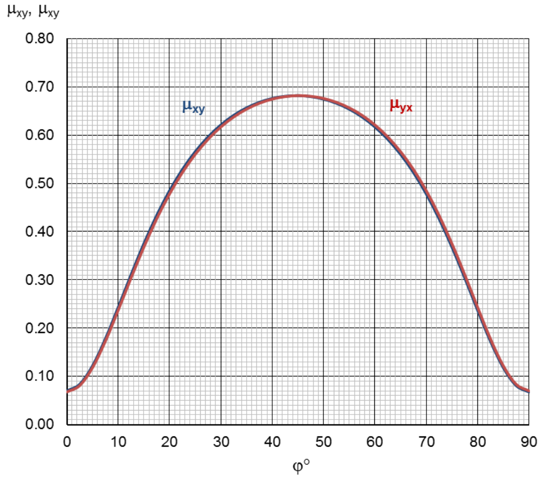

Fig. 6. Poisson's ratios of carbon fiber depending on the angle

Determination of elastic characteristics of carbon fiber for all angles φ

Monolayer stiffness matrix coefficients

$$C_{11}^{0}=\frac{E_1}{1-\mu_{12}\cdot\mu_{21}}=\frac{65000}{1-0,07\cdot 0,06785}=65310\,(\text{MPa});$$

$$C_{12}^{0}=\frac{E_1\cdot\mu_{21}}{1-\mu_{12}\cdot\mu_{21}}=\mu_{21}\cdot C_{11}^{o}=0,06785\cdot 65310=4431\,(\text{MPa});$$

$$C_{22}^{0}=\frac{E_2}{1-\mu_{12}\cdot\mu_{21}}=\frac{63000}{1-0,07\cdot 0,06785}=63301\,(\text{MPa});$$

$$C_{66}^{0}=G_{12}=6500\,(\text{MPa})$$

independent coefficients are

$$V_1=\left(3\cdot C_{11}^{0}+2\cdot C_{12}^{0}+3\cdot C_{22}^{0}+4\cdot C_{66}^{0}\right)/8=$$

$$=\left(3\cdot 65310+2\cdot 4431+3\cdot 63301+4\cdot 6500\right)/8=52587\,(\text{MPa});$$

$$V_2=\left(C_{11}^{0}-C_{22}^{0}\right)/2=(65310-63301)/2=1005\,(\text{MPa});$$

$$V_3=\left(C_{11}^{0}-2\cdot C_{12}^{0}+C_{22}^{0}-4\cdot C_{66}^{0}\right)/8=$$

$$=\left(65310-2\cdot 4431+63301-4\cdot 6500\right)/8=11719\,(\text{MPa});$$

$$V_4=\left(C_{11}^{0}-2\cdot C_{12}^{0}+C_{22}^{0}+4\cdot C_{66}^{0}\right)/8=$$

$$=\left(65310-2\cdot 4431+63301+4\cdot 6500\right)/8=18219\,(\text{MPa}).$$

Coefficients of the stiffness matrix of a monolayer rotated at an angle $\varphi^o = 45°$

$$C_{11}^{45} = V_1 + V_2 \cdot \cos(2\cdot 45°) + V_3 \cdot \cos(4\cdot 45°) =$$
$$= 52587 + 1005 \cdot \cos(2\cdot 45°) + 11719 \cdot \cos(4\cdot 45°) = 40868\ (\text{MPa});$$
$$C_{12}^{45} = V_1 - 2\cdot V_4 - V_3 \cdot \cos(4\cdot 45°) =$$
$$= 52587 - 2\cdot 18219 - 11719 \cdot \cos(4\cdot 45°) = 27868\ (\text{MPa});$$
$$C_{16}^{45} = 0,5\cdot V_2 \cdot \sin(2\cdot 45°) + V_3 \cdot \sin(4\cdot 45°) =$$
$$= 0,5\cdot 1005 \cdot \sin(2\cdot 45°) + 11719 \cdot \sin(4\cdot 45°) = 502\ (\text{MPa});$$
$$C_{22}^{45} = V_1 - V_2 \cdot \cos(2\cdot 45°) + V_3 \cdot \cos(4\cdot 45°) =$$
$$= 52587 - 1005 \cdot \cos(2\cdot 45°) + 11719 \cdot \cos(4\cdot 45°) = 40868\ (\text{MPa});$$
$$C_{26}^{45} = 0,5\cdot V_2 \cdot \sin(2\cdot 45°) - V_3 \cdot \sin(4\cdot 45°) =$$
$$= 0,5\cdot 1005 \cdot \sin(2\cdot 45°) - 11719 \cdot \sin(4\cdot 45°) = 502\ (\text{MPa});$$
$$C_{66}^{45} = V_4 - V_3 \cdot \cos(4\cdot 45°) = 18219 - 11719 \cdot \cos(4\cdot 45°) = 29937\ (\text{MPa}).$$

Determinant of the stiffness matrix is

$$\Delta C = \det\begin{bmatrix} C_{11}^{45} & C_{12}^{45} & C_{16}^{45} \\ C_{12}^{45} & C_{22}^{45} & C_{26}^{45} \\ C_{16}^{45} & C_{26}^{45} & C_{66}^{45} \end{bmatrix} = \det\begin{bmatrix} 40868 & 27868 & 502 \\ 27868 & 40868 & 502 \\ 502 & 502 & 29937 \end{bmatrix} =$$
$$= 2,67445\cdot 10^{13}\ (\text{MPa})^3 .$$

Elastic characteristics of a monolayer turned at an angle φ° = 45°

$$E_x = \frac{\Delta C}{C_{22}^{45}\cdot C_{66}^{45} - (C_{26}^{45})^2} = \frac{2,67445\cdot 10^{13}}{40868\cdot 29937\text{-}502^2} = 21864\ (\text{MPa});$$
$$E_y = \frac{\Delta C}{C_{11}^{45}\cdot C_{66}^{45} - \left(C_{16}^{45}\right)^2} = \frac{2,67445\cdot 10^{13}}{40868\cdot 29937\text{-}502^2} = 21864\ (\text{MPa});$$
$$G_{xy} = \frac{\Delta C}{C_{11}^{45}\cdot C_{22}^{45} - (C_{12}^{45})^2} = \frac{2,67445\cdot 10^{13}}{40868\cdot 40868\text{-}27868^2} = 29930\ (\text{MPa});$$
$$\mu_{xy} = \frac{C_{12}^{45}\cdot C_{66}^{45} - C_{16}^{45}\cdot C_{66}^{45}}{C_{22}^{45}\cdot C_{66}^{45} - \left(C_{26}^{45}\right)^2} = \frac{27868\cdot 29937 - 502\cdot 502}{40868\cdot 29937 - 502^2} = 0,68 .$$

Similarly, the elastic characteristics of a monolayer rotated at other angles φº are determined. The values of the modulus of elasticity and shear depending on the angle φº in the polar coordinate system are presented in fig. 7, and Poisson's ratio in fig. 8.

For typical reinforcement angles, the values of elastic characteristics of a monolayer of carbon fiber in the coordinate system of a package of monolayers are presented in Tab. 2.

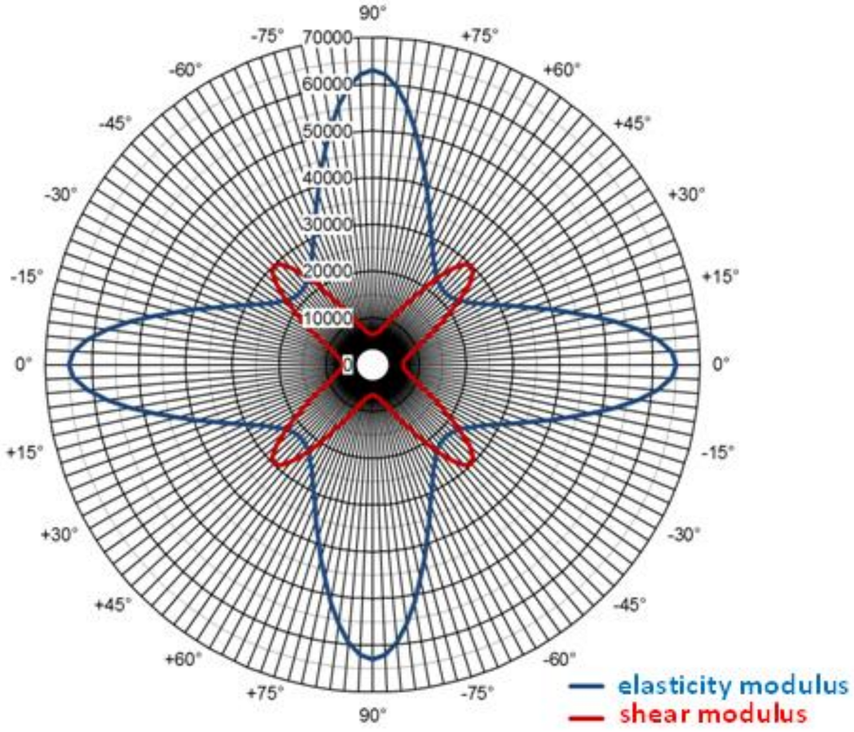

Fig. 7. The modulus of elasticity E and shear G for carbon fiber depending on the angle φº in the polar coordinate system

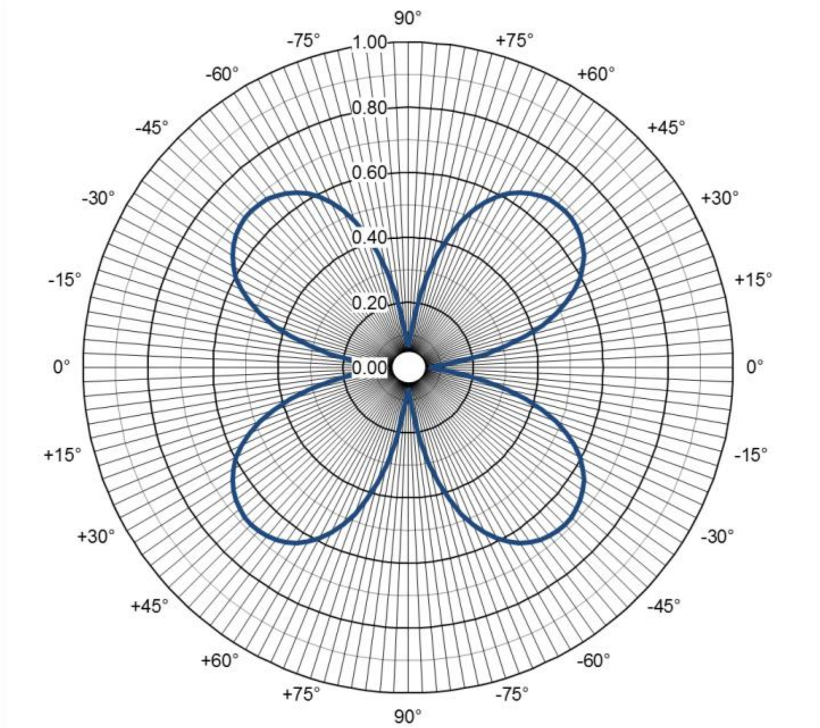

Fig. 8. Poisson's ratio for carbon fiber depending on the angle φº in the polar coordinate system

***Table* 2.**

Change in the elastic characteristics of a carbon fiber monolayer in the coordinate system of a package of monolayers

φ	E_x (МПа)	E_y (МПа)	G_{xy} (МПа)	μ_{xy}
0	65000	63000	6500	0,070
15	43583	42795	8082	0,375
30	26255	26088	15743	0,621
45	21864	21864	29930	0,682
60	26088	26255	15743	0,617
75	42795	43583	8082	0,368
90	63000	65000	6500	0,068

Conclusions

The paper presents the method of calculating the mechanical characteristics of multilayer composite panels. The optimal sequence of laying out monolayers was selected. With the help of the developed methodology, the elastic properties of the composite material with different angles of laying layers were determined. Calculations of the mechanical characteristics of carbon fiber panels made of carbon tape and carbon fabric are given, and a comparison of composites made of carbon tape and carbon fabric is made.

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