Influence of orientation of layers of a multilayer composite material on the stressed state of a robotic structure under dynamic loading

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Abstract. The paper developed a method for calculating the stress-strain state of a robotic structure made of composite material under dynamic action. The bearing capacity of multilayer composite materials is affected by the location of the warp threads of the composite material. By changing the orientation of the layers, it is possible to change the bearing capacity of the composite material. In the present work, such a study was carried out for a robotic system made of a composite material under the action of a dynamic operational load. An eight-layer composite material with different layer orientations was considered. Carbon fiber was used as the basis. As a robotic system stand was considered, designed to simulate flight characteristics in laboratory conditions. The simulation of the stand was carried out. The bench was approximated by finite elements. The convergence of the results of the finite element model of the stand was checked by condensing the finite element mesh and comparison the results obtained. Robotic systems are equipped with elements that move the channels: bearings, gear rims, gearboxes, motors. In the present study they were replaced in the finite element model with a system of bar elements of identical stiffness. The design of the stand was a three-layer structure, consisting of external carrier layers of an eight-layer composite material and a filler layer between the carrier layers of lightweight material in the form of foam and used to absorb shear stresses and prevent the bearing layers from approaching. Calculation and analysis of the design of the stand for dynamic load is carried out, the stress-strain state of the stand is obtained for different arrangement of the layers of the composite material.

1 Introduction

Robotic structures are becoming more and more widespread in various fields [1-5]. This is due to the development of computer vision, which makes it possible to identify objects in the operations of assembling a structure, sorting mail, etc. To obtain optimal characteristics of robotic systems in terms of rigidity, strength, minimum inertial characteristics, and positioning accuracy, it is necessary to develop methods for calculating such structures under the action of operational loads: static and dynamic loading. For this apply materials with high specific strength characteristics - multilayer composite materials. Composite

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materials are currently replacing traditional homogeneous materials in aviation, mechanical engineering, rocket and space technology [6-8]. Due to the high specific strength characteristics and the ability to change the characteristics of the material depending on the orientation of the layers in a multilayer composite structure. Therefore, it is important to study the effect of layer orientation on the strength characteristics of materials in the structure under study. A significant number of works have been devoted to the study of structures made of composite materials. But all works mainly consider individual structural elements [9-14].

2 Materials and methods

2.1 The failure criteria

When studying the stress-strain state of a structure, especially when determining its bearing capacity, the safety margins are determined: the ratio of the allowable stress to the acting one or the ratio of the acting stress to its allowable value. The latter ratio is used in strength criteria in relation to multilayer materials with different bearing capacity of the layers. Currently, there are several proven strength criteria, named after the names of their presenters: Tsai-Wu, Tsai-Hill, Hoffman, Hashin, Paka, the theory used in NASA: LaRC and Kunse. The criteria have their advantages and disadvantages and are used for various types of compositions of multilayer materials. The multilayer composite material is calculated according to these criteria. Let us consider the criteria used in this study, the criteria for maximum stresses and deformations, Tsai-Wu, Tsai-Hill, Hoffman in more detail [15-18].

The criterion of maximum stresses and strains is based on exceeding one of the ratios of the effective stress to the allowable stress or the effective strain to the allowable strain of the unit.

$$\max\left\{\left|\frac{\sigma_x}{[\sigma_x]}\right|,\left|\frac{\sigma_y}{[\sigma_y]}\right|,\left|\frac{\sigma_z}{[\sigma_z]}\right|,\left|\frac{\tau_{xy}}{[\tau_{xy}]}\right|,\left|\frac{\tau_{xz}}{[\tau_{xz}]}\right|,\left|\frac{\tau_{yz}}{[\tau_{yz}]}\right|\right\}\leq 1$$

$$\max\left\{\left|\frac{\varepsilon_x}{[\varepsilon_x]}\right|,\left|\frac{\varepsilon_y}{[\varepsilon_y]}\right|,\left|\frac{\varepsilon_z}{[\varepsilon_z]}\right|,\left|\frac{\gamma_{xy}}{[\tau_{xy}]}\right|,\left|\frac{\gamma_{xz}}{[\tau_{xz}]}\right|,\left|\frac{\gamma_{yz}}{[\tau_{yz}]}\right|\right\}\leq 1$$

Here it is indicated: $\sigma_x, \sigma_y, \sigma_z$ - normal stresses, $\varepsilon_x, \varepsilon_y, \varepsilon_z$ - normal deformations, $\tau_{xy}, \tau_{xz}, \tau_{yz}$ - shear stresses in the corresponding plane, $\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$- shear deformations in the respective planes, the expressions in square brackets mean the allowable values of the respective strains and stresses.

Strength criteria Tsai-Wu, Tsai-Hill, Hoffman are quadratic criteria and are calculated from a second-order polynomial. When the value of this polynomial is less than or equal to one, it is assumed that the destruction of the multilayer material does not occur.

$$F = A_{11}\sigma_x^2 + A_{22}\sigma_y^2 + A_{33}\sigma_z^2 + A_{44}\tau_{xy}^2 + A_{55}\tau_{xz}^2 + A_{66}\tau_{yz}^2 + \\ 2A_{xy}\sigma_x\sigma_y + 2A_{xz}\sigma_x\sigma_z + 2A_{yz}\sigma_y\sigma_z + A_1\sigma_x + A_2\sigma_y + A_3\sigma_z \leq 1$$

depending on the type of coefficients A_{ij} and A_i.

For a plane stressed state in this polynomial, we must assume that $\sigma_z = 0$.

2.2 Tsai-Wu criterion

The coefficients in this criterion are calculated from the relations

$A_{11}=\frac{1}{[\sigma_{xt}][\sigma_{xc}]}$, $A_{22}=\frac{1}{[\sigma_{yt}][\sigma_{yc}]}$, $A_{66}=\frac{1}{[\tau_{yz}^2]}$, $A_1=\frac{1}{[\sigma_{xt}]}-\frac{1}{[\sigma_{xc}]}$, $A_2=\frac{1}{[\sigma_{yt}]}-\frac{1}{[\sigma_{yc}]}$,
where the index t means tension, c - compression.
Here $\sigma_x=\sigma_y=P$ is denoted and the remaining expressions are equal to zero.

$$A_{xy}=\frac{1}{2P^2}\left[1-P\left(\frac{1}{[\sigma_{xt}]}-\frac{1}{[\sigma_{xc}]}+\frac{1}{[\sigma_{yt}]}-\frac{1}{[\sigma_{yc}]}\right)-P^2\left(\frac{1}{[\sigma_{xt}][\sigma_{xc}]}+\frac{1}{[\sigma_{yt}][\sigma_{yc}]}\right)\right]$$

2.3 Hoffman criterion

For this criterion, the coefficient A_{ij} is determined from the relation

$$A_{12}=\frac{1}{[\sigma_{xt}][\sigma_{xc}]}$$

and the Hoffman failure criterion takes the form

$$\frac{\sigma_x^2}{[\sigma_{xt}][\sigma_{xc}]}+\frac{\sigma_y^2}{[\sigma_{yt}][\sigma_{yc}]}-\frac{\sigma_x\,\sigma_y}{[\sigma_{xt}][\sigma_{xc}]}+\frac{\sigma_x}{[\sigma_{yt}][\sigma_{yc}]}+\frac{\sigma_y}{[\sigma_{yt}][\sigma_{yc}]}\leq 1$$

2.4 Tsai-Hill criterion

The coefficients are calculated from the relations
$A_{11}=\frac{1}{[\sigma_x]^2}$, $A_{22}=\frac{1}{[\sigma_y]^2}$, $A_1=0$, $A_2=0$, $A_{12}=\frac{1}{[\sigma_x]^2}$,
and the failure criterion has the form

$$\frac{\sigma_x^2}{[\sigma_x]^2}+\frac{\sigma_y^2}{[\sigma_y]^2}+\frac{\tau_{xy}^2}{[\tau_{xy}]^2}-\frac{\sigma_x\,\sigma_y}{2[\sigma_x]^2}\leq 1$$

The criteria used in this study are the most general and are widely used in the study of the bearing capacity of multilayer composite structures. The disadvantages of the Tsai-Hill criterion include the fact that it does not take into account the different values of the tensile and compressive strength of the material. All the failure criteria presented assume that if the layer fails according to the corresponding criterion, then the entire multilayer material fails. The considered fracture criteria are used in various calculation programs.

To determine the given characteristics of composite multilayer materials, the following equations are used:

2.5 The determining the reduced characteristics of a multilayer composite material

To determine the reduced characteristics of a multilayer composite material whose axes coincide with the orthotropic axes of the composite material, consider the relationship between stress and strain for a plane stressed state

$$\{\sigma\}=[E]\{\varepsilon\}, \tag{1}$$

$$[E]=\begin{Bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{Bmatrix},$$

$\{\varepsilon\}^T=\{\varepsilon_s,\varepsilon_\theta,\varepsilon_{s\theta}\}$, $\{\sigma\}^T=\{\sigma_s,\sigma_\theta,\sigma_{s\theta}\}$, $Q_{11}=E_s/(1-\nu_{s\theta}\nu_{\theta s})$, $Q_{12}=\nu_{s\theta}E_s/(1-\nu_{s\theta}\nu_{\theta s})$, $Q_{66}=G_{66}$ $Q_{11}=E_s/(1-$

$v_{s\theta}v_{\theta s}), Q_{12} = v_{s\theta}E_s/(1- v_{s\theta}v_{\theta s}), Q_{21} = v_{\theta s}E_s/(1- v_{s\theta}v_{\theta s}), Q_{22} = E_\theta/(1- v_{s\theta}v_{\theta s}),$

here $\{\varepsilon\}^T = \{\varepsilon_s, \varepsilon_\theta, \varepsilon_{s\theta}\}$ is vector of deformation , $\varepsilon_s, \varepsilon_\theta, \varepsilon_{s\theta}$ is deformations in the direction of the axis s, θ, and in the plane sθ, $\{\sigma\}^T = \{\sigma_s, \sigma_\theta, \sigma_{s\theta}\}$ is the vector of stress in the corresponding directions and plane, E_s, E_θ, $v_{s\theta,}v_{\theta s}$ are elasticity modulus, coefficients of Poisson , G_{66} is modulus of shear .

When the coordinate axes are rotated by an angle θ, the stress-strain dependence matrix is converted to the form

$$[\bar{E}] = \begin{Bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{21} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{61} & \bar{Q}_{62} & \bar{Q}_{66} \end{Bmatrix}, \qquad (2)$$

where $\bar{Q}_{11} = c^4 Q_{11} - s^4 Q_{22} + 2(Q_{12} + 2Q_{66})s^2c^2$, $\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})s^2c^2 + (s^2+c^2)Q_{22}$,

$$\bar{Q}_{16} = (c^2Q_{11} - s^2Q_{12} + (Q_{12} + 2Q_{66})(s^2-c^2))sc,\ \bar{Q}_{22} = s^4Q_{11} - c^4Q_{22} + 2(Q_{12} + 2Q_{66})s^2c^2, \qquad (3)$$

$$\overline{Q}_{26} = (s^2Q_{11} - c^2Q_{12} - (Q_{12} + 2Q_{66})(s^2-c^2))sc,\ \bar{Q}_{66} = (Q_{11} - 2Q_{12} + Q_{22})s^2c^2 + (s^2-c^2)Q_{66},$$

$$s = \sin\theta, c = \cos\theta.$$

For a layer located at a distance z from the middle surface

$$\{\varepsilon\} = \{\varepsilon^o\} + z\{\chi^o\},$$

here denoted by $\{\varepsilon^o\}$ - deformations of the middle surface, , $\{\chi^o\}$ - deformations of the curvature of the middle surface.

The relationship between stresses and strains takes the form

$$\{\sigma\} = [\bar{Q}]\{\varepsilon^o\} + z[\bar{Q}]\{\chi^o\}. \qquad (4)$$

For normal forces N and bending moments M, the dependences on stresses have the form

$$\{N\} = \int_{-h/2}^{h/2}\{\sigma\}dz,\ \{N\}^T = (N_s, N_\theta, N_{s\theta}),\ \{M\} = \int_{-h/2}^{h/2}\{\sigma\}zdz,\ \{M\}^T = (M_s, M_\theta, M_{s\theta}) \qquad (5)$$

Thus, we get

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = [E]\begin{Bmatrix} \varepsilon^o \\ \chi^o \end{Bmatrix}, [E] = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \qquad (6)$$

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ A_{61} & A_{62} & A_{66} \end{bmatrix}, [B] = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{21} & B_{22} & B_{26} \\ B_{61} & B_{62} & B_{66} \end{bmatrix}, [D] = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{61} & D_{62} & D_{66} \end{bmatrix}. \qquad (7)$$

$$\{A_{ij}, B_{ij}, D_{ij}\} = \int_{-h/2}^{h/2} Q_{ij}(1, z, z^2)\, dz, (i, j = 1,2,3) \qquad (8)$$

For the reduced of characteristics of the multilayer composite material, we have

$$A_{ij} = \sum_{k=1}^{n} \bar{Q}_{ij}(h_k - h_{k-1}), i, j = 1,2,6,\ B_{ij} = \sum_{k=1}^{n} \bar{Q}_{ij}({h^2}_k - {h^2}_{k-1}), i, j = 1,2,6, \qquad (9)$$

$$D_{ij} = \sum_{k=1}^{n} \bar{Q}_{ij}({h^3}_k - {h^3}_{k-1}), i, j = 1,2,6,$$

here A_{ij}, B_{ij}, D_{ij} are membrane, flexural-membrane and flexural stiffnesses.

Figure 1 shows the notation of formula (9)

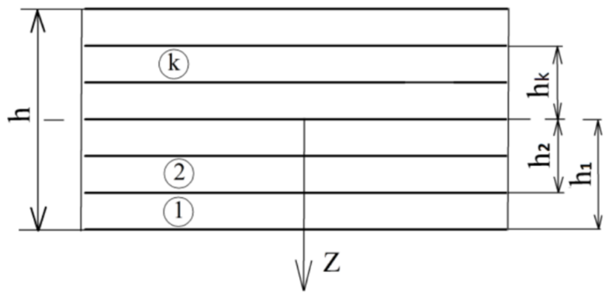

Fig. 1 Multilayer composite structure

2.6 Three-layer composite structure

In general, adjacent layers of a multilayer composite material can be considered as a structure consisting of carrier layers and filler between them. In the calculations, the main load is carried by the carrier layers, and the filler mainly perceives shear stresses and prevents the convergence of neighboring carrier layers. To take into account transverse shear deformations in the filler, the transverse shear matrix is supplemented with a shear stiffness matrix.

$$\begin{Bmatrix} \sigma_4 \\ \sigma_5 \end{Bmatrix}^{(k)} = \begin{Bmatrix} \bar{Q}_{44} & 0 \\ 0 & \bar{Q}_{55} \end{Bmatrix} \begin{Bmatrix} \bar{\varepsilon}_4 \\ \bar{\varepsilon}_5 \end{Bmatrix}^{(k)}, \tag{15}$$

Here $\bar{Q}_{44} = G_{13}, \bar{Q}_{55} = G_{23}, G_{13}, G_{23}$ -are shear module.

Denoting a total thickness t, the thicknesses of the outer bearing layers as t_1 and t_3, and the thickness of the filler t_2, we obtain the displacements and the angle of rotation of the normal of the filler for the neutral axis as a function of the displacements and rotation angles of the bearing layers.

$$v_2 = (\bar{v}_1 + \bar{v}_3)/2, \varphi_2 = (\bar{v}_1 - \bar{v}_3)/t \tag{16}$$

$$\bar{v}_1 = v_1 - t_1 e_{13}/2, \bar{v}_3 = v_3 + t_3 e_{23}/2$$

The displacement of the filler at a distance from the neutral plane has the form

$$\begin{aligned} v_2(z) = v_1 + z\varphi_2 &= 0.5(v_1 - t_1 e_{13}/2 + v_3 + t_3 e_{23}/2) \\ &+ z(v_1 - t_1 e_{13}/2 - v_3 - t_3 e_{23}/2)/t_2, \end{aligned}$$

$$u_2(z) = u_1 + z\varphi_2 = 0.5(u_1 - t_1 e_{13}/2 + u_3 + t_3 e_{23}/2) + z(u - t_1 e_{13}/2 - u_3 - t_3 e_{23}/2)/t_2, \tag{17}$$

$$w_2(z) = w_2 + z(w_3 - w_1)/t_2$$

The stand considered in the article is a three-layer structure. The method for obtaining a three-layer stand is as follows. We create a stand model, assign filler characteristics to the model. We create surfaces on the model and assign the characteristics of the bearing layers to the surfaces: of the multilayer of the composite material.

2.7 Simulation of the stand of maximum rigidity and accounting for moving elements

Robotic systems have elements in their design that carry out movements. Such elements include bearings, gear rims, gearboxes, motors [19-23]. The identification of such elements is a complex task that requires extensive theoretical and experimental research in the process of development and manufacture. When calculating robotic systems, it is necessary to take into account the stiffness of these elements. In the present study, the stiffness of these elements was determined by the algorithm and the developed program. Accounting for these elements in the design was carried out by replacing them with rod systems of identical rigidity. The legitimacy of the replacement was confirmed by experimental and theoretical calculations.

To study structures made of composite materials in order to create a structure of maximum rigidity, it is necessary to place the base of layers of composite materials along the trajectories of maximum stresses obtained from solving the problem for a homogeneous material and to correct the trajectory from solving the problem for a composite material. Stand rigidity contributes to positioning accuracy, one of the main performance characteristics of stands.

3 Result

The purpose of the three-degree dynamic stand is to move the object under study in three degrees of freedom, simulating flight characteristics. The stand consists of a base, connected by means of a ring gear with a course fork. In the course fork on bearing supports there is a pitching ring inside which, with the help of bearings, a heeling ring rotates in which the test item is located (Figure 2). In the calculations, the pinching of the stand base along its base was used as the boundary conditions.

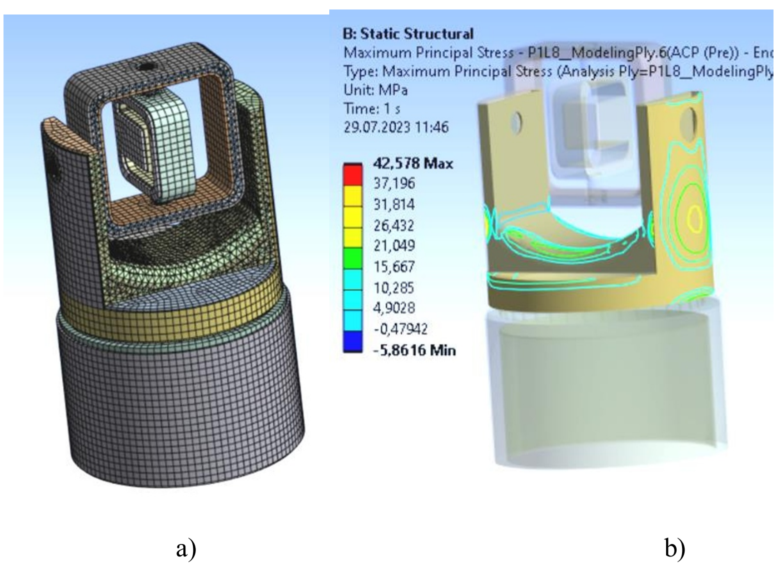

Fig. 2. a) Bench model approximated by finite elements, b) isolines of stress in 1 layers composite of material with orientation 0/15/30/-45/90/45/-30/0

Figure 2 shows approximation the bench by finite elements [24-29]. To approximate the elements that ensure the movement of the test bench channels: bearings, gear rims, gearboxes, motors, an algorithm has been developed and a program has been left for calculating the stiffness of such elements and made replacing them with rod systems of identical of stiffness. The convergence of the calculation results of the finite element approximation was determined by the refinement of the finite element mesh.

The dynamic impact on the stand was an angular operational acceleration of 500 rad/s of the fork around the vertical axis. As a result of the calculation, the stressed state of the eight-layer composite material was obtained layer by layer (Figure 3) with different

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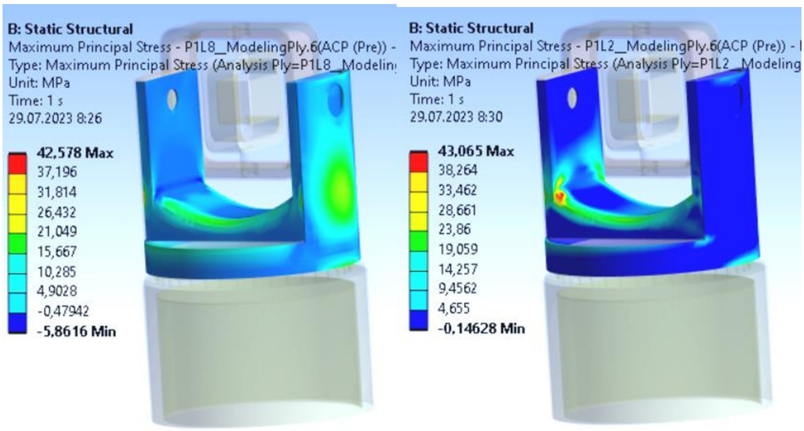
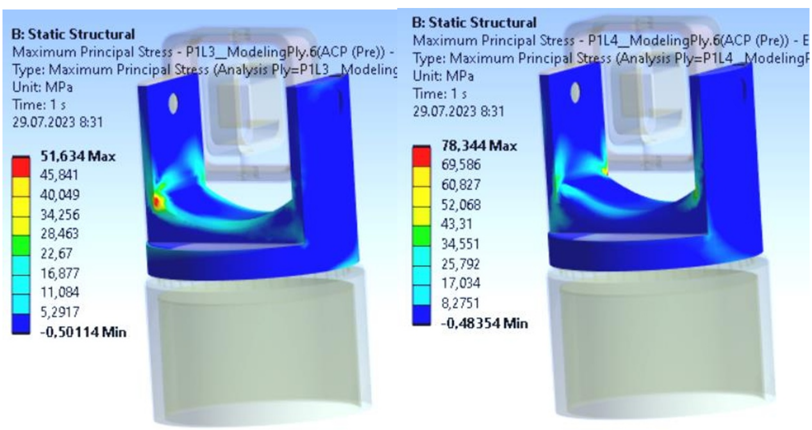
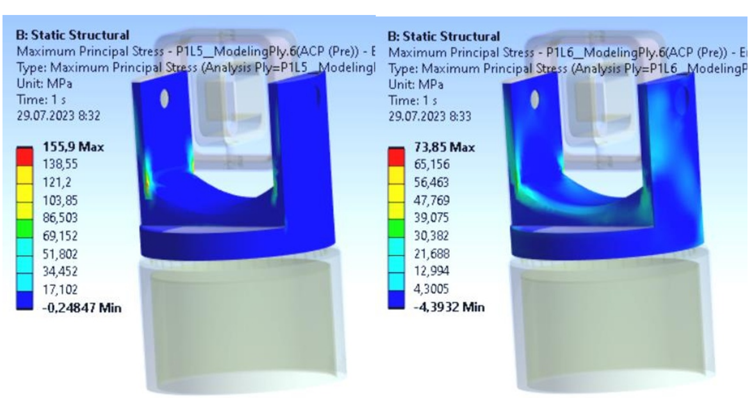
orientation of the layers (Table 1). The most strength combination of layer orientation was revealed 0/15/30/-45/90/45/-30/0.



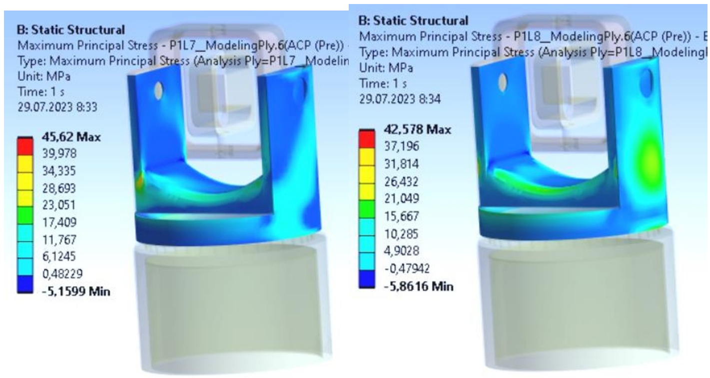
1st and 2nd layer



3rd and 4th layer



5th and 6th layer



7th and 8th layer

Fig. 3. Stress state of 8 layers of composite material

Table 1. Stresses in MPa in eight layers of composite material depending on the orientation of the layers.

Orientation of layers, deg	1 layer	2	3	4	5	6	7	8
0/0/0/90/90/90/0/0	60,04	50,09	40,33	117,8	106,78	96,91	20,24	20,50
0/0/90/90/90/0/0/0	68,54	57,77	116,63	106,51	97,54	22,22	20,84	19,45
45/0/-45/0/0/-45/0/45	108,19	57,21	96,89	45,40	41,07	59,90	32,91	79,40
45/-45/90/45/0/-45/-45/45	69,05	82,86	130,45	43,73	87,99	38,98	51,75	65,67
0/0/0/45/-45/0/0/0	57,91	47,37	37,15	100,48	99,54	31,64	34,43	77,41
45/-45/3/45/-45/-3/-45/45	86,97	98,38	82,98	58,91	50,78	69,40	55,96	68,62
45/-45/5/45/-45/-5/-45/45	86,89	98,54	82,24	58,64	50,79	68,96	55,56	68,79
45/-45/10/-45/45/10/-45/45	86,27	98,82	79,39	57,58	50,45	67,17	54,73	68,02
0/15/30/-45/90/45/-30/0	64,02	43,07	51,63	78,34	155,90	73,85	45,62	42,58

The analysis of the stress state of the eight-layer composite material shown in Table 1 shows that the most unfavorable ratio of the orientation of the layers in terms of stresses corresponds to the arrangement of layers with an orientation of 45/-45/90/45/0/-45/-45/45. And the orientation of the layers 45/-45/10/-45/45/10/-45/45 corresponds to the minimum stresses at the same load. Given that most of the failure criteria are based on the principle that the destruction of one layer leads to the destruction of the multilayer composite material as a whole. It can be said that the 45/-45/10/-45/45/10/-45/45 ply orientation is the strongest. More accurate results are provided by the failure criteria discussed in Section 2.1 of this article.

4 Calculation

As a result of the work carried out, a three-layer HIL simulation bench was modeled from an eight-layer composite material. The calculation of the layer-by-layer deformed state of the layers of an eight-layer composite material was carried out, which made it possible to apply the failure criteria to the eight-layer composite material as a whole. To obtain a composite material of high density and hardness, an analysis was made of the orientation of the layers in an eight-layer composite material, showing that the structure of the stand has a high rigidity with the arrangement of layers of the form 45/-45/10/-45/45/10/-45 /45, where the numbers show the location of the layer at an angle to the trajectory of maximum stresses in degrees, the slash means the separation of the layers. The location of the trajectories of maximum stresses were obtained as a result of the calculation of a stress-strain stand made of a homogeneous material. Next, the orientation of the layers was located along the trajectories of the maximum values obtained from the solution of the problem of a stand made of a homogeneous material. Subsequently, the trajectory of the maximum values was corrected according to the results of the calculation of the stand made of composite material. The reliability of the results obtained is ensured by the convergence of the finite element partition and the ANSYS program, which has confirmed its reliability by solving a large number of test cases. The stand belongs to the robotic system, since it has bearings, gear rims, gearboxes, motors in its design. Therefore, the developed methods and solutions are applicable to a large class of robotic systems.

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