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EXPERIMENTAL MECHANICS, DIAGNOSTICS, AND TESTING

Structural Design and Testing of Composite Wing High-Lift Device

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Abstract—A problem for designing aviation structures made of sandwich-like polymer composite materials has been examined based on the example of a typical device for mechanizing a wing-spoiler. The spoiler's loading pattern is chosen according to topological optimization. A way to determine the orientation, number, and proper order of layers laying has been examined as a problem of discrete optimization by using different algorithms. The peculiarities of layered structure simulation have been discussed. Tests results for spoiler have been presented and they verify the design and technological solutions.

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Nowadays, the bearing aviation structures are designed and manufactured of high-strength layered composite materials according to two main technologies, i.e., autoclave and different types of infusive, including impregnation by vacuumizing or under pressure (RTM) [1]. Each of the aforementioned technologies has its own peculiarities, which greatly influence the way to choose the loading pattern of the structure in addition to traditional requirements to properly transfer the loadings inside the structure.

The task for designing the airframe units can be formulated as follows, i.e., the structure of minimal mass placed inside the given space must be found. The known parameters are as follows: loads, and conditions of units joining with other parts of the airframe. Strength and rigidity conditions are taken as the limitations. Very often, the limitation on the maximal permissible mass of unit structure is set; this is the so-called "weight limit." During the design stage, it is necessary to chose the material and loading pattern of the unit, as well as to set the size of the structural elements close to optimal.

In terms of nonlinear mathematical programming, the problem can be defined as follows: the vector $\mathbf{x}^*$ at which the following is true must be found:

$$f(\mathbf{x}^*) \le f(\mathbf{x}) \quad \forall \mathbf{x} \in \Omega, \tag{1}$$

where $\Omega = |\mathbf{x} : g_j(\mathbf{x}) \le 0, j = 1, \ldots, m|$ is the set (area) of permissible projects, $\mathbf{x}$ is the vector of project variables, $f(\mathbf{x})$ is the target function, $g(\mathbf{x})$ is the limitation, and j is a number of limitation.

In this problem, the most complicated task is to choose the project variables, different numerical values of which correspond to different technical solutions, including optimal solutions. How to choose the loading pattern of thin-wall spatial structure is a problem of topological optimization, the solution of which is determined inside of a certain continuous elastic medium that fills the area selected for the structure. The problem is who should find it.

The problem of setting sizes of thin-wall elements of the structure made of the composite material should be examined as an integer-valued problem of structure-parametric optimization since, here, the number of layers of reinforcing fibers and fabrics and their orientation and laying order in different places of the structure are examined as project variables. The problem of designing units for transferring the concentrated forces to the thin-wall structure made of sandwich-like material is also a specific problem of topological optimization. It is hardly possible to solve problem (1) due to the curse of dimensionality and evident NP-completeness. That is why it is reasonable to separate it into a hierarchical sequence of simpler optimization problems.

In the work, we present our experience accumulated during the design and testing one of the most loaded elements for mechanizing the modern wing, i.e., the spoiler. The interceptor is intended to specially disturb the streamline flow-around wing profile, and it is actively used in different flight modes to

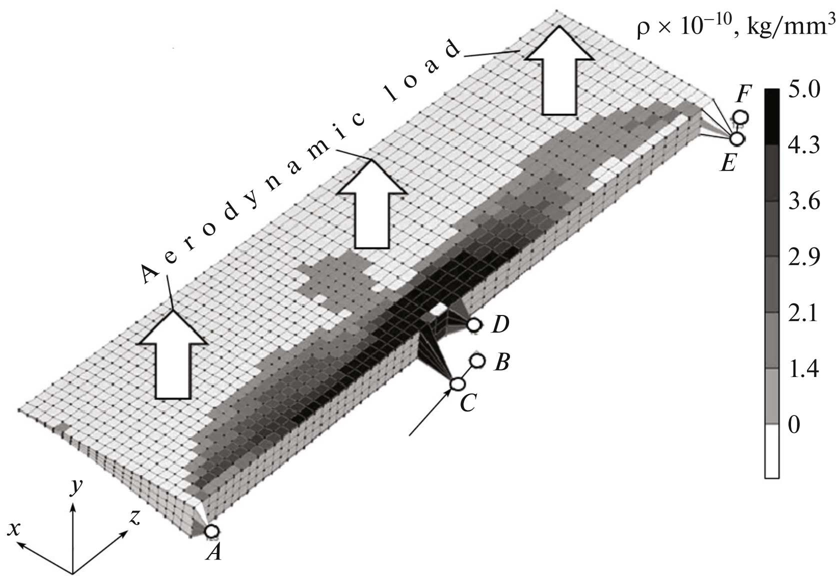

Fig. 1. Interceptor, loading pattern, material distribution in theoretically optimal structure.

decrease the lift of the wing during landing during emergency descent and roll controlling. Thus, this unit is very loaded by different-sign loads within the whole flight cycle [2] and is characterized by typical peculiarities intrinsic to aviation structures. The aim of the work is to show a fairly general approach to solving the defined problem.

DEFINITION OF MATERIAL LAYOUT IN THE SPOILER

Figure 1 depicts a traditional form of the spoiler and the way to fix it on the airplane wing. Displacements along the *X, Y,* and *Z* axes are fixed at points *A, B* in the local coordinate system along axes *X* and *Y* at point *D* and along axes *X, Y, Z* at point *E*. Points *B, C* and *F, E* are connected in pairs by rod elements that simulate special shackles. Points *A, B,* and *F* form the axis of rotation.

The structure of unit fixation should secure the independent deformations of spoiler and wing when they are loaded. This is done using the special structure of supports, including the so-called Cardan suspension and shackles, which secure almost statically determined spoiler fixation on the wing [2]. The feature of the examined spoiler is as follows: the main concentrated forces that act on the interceptor in the center of the unit are not in one plane.

In Fig. 1, the solid arrow corresponds to the force caused by the control system power drive, the direction of which is defined by the drive's orientation. Here, to choose the loading pattern of spoiler we suggest using the technology of structure (topological) optimization by applying the mathematical model for a solid with variable density [3–5]. According to this technology, the final-element model for solid elements is inscribed into the limits of spoiler's external sizes. At the initial stage, the density of all elements are similar and the strength and rigidity properties of the elements are set as linearly dependent on density as follows:

$$E = \overline{E}\rho, \quad \sigma_a = \overline{\sigma}_a\rho, \tag{2}$$

where ρ is the density of hypothetic material, E, σ_a are the modulus of elasticity and permissible stresses of a certain structure material, and $\overline{E}, \overline{\sigma}_a$ are the respective specific characteristics.

Below, we present the procedure for calculating the stressed-deformed state (SDS) of the structure. The density of separate elements and modulus of elasticity are determined as follows:

$$\rho_{i+1} = \frac{\sigma_i}{\overline{\sigma}_a}, \; E_{i+1} = \overline{E}\rho_{i+1}, \tag{3}$$

where σ is the equivalent stress and index *i* corresponds to the number of iteration. The solid body with variable density is characterized by internal static indeterminateness. That is why variations in density

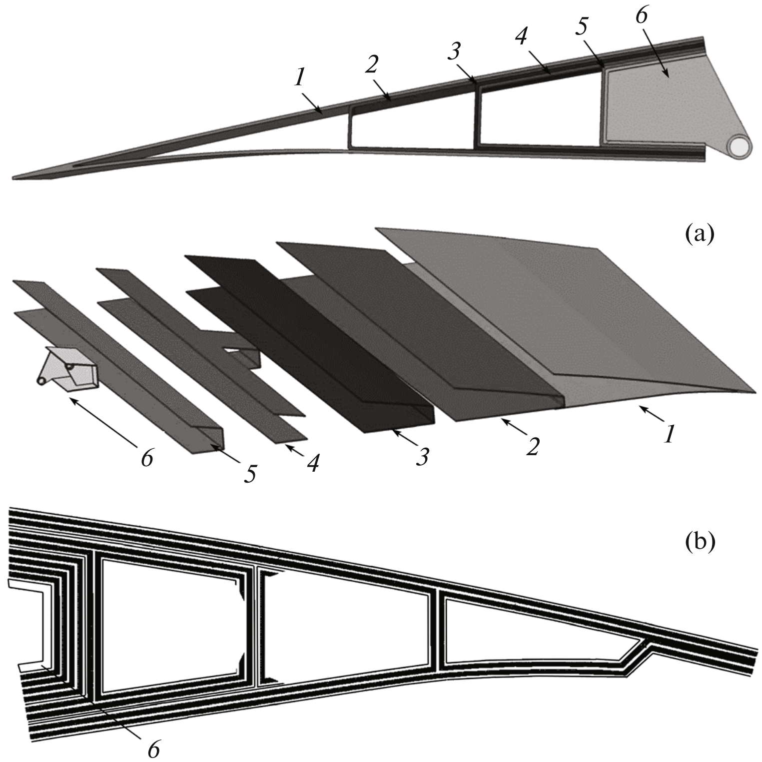

Fig. 2. (a)Structure and force pattern of the spoiler: *1*, skin (first curve); *2*, second curve; *3,* third curve; *4,* reinforcing plate; *5*, front longeron; *6,* central unit (shown schematically); lateral mounting brackets are not shown. (b) Layers distribution in the spoiler: *6* is the aluminum channel.

according to relationship (3) cause the distribution of internal forces and stresses in the structure. The procedure for calculating the stressed-deformed state and material redistribution according to (3) is repeated until the density value is stabilized in each element. In stable solution, the density of separate elements can degenerate to zero. According to Eq. (2), it is easy to show that, in the elements with not-zero density, the deformations intensities are the same as shown below:

$$\varepsilon_{i+1} = \frac{\sigma_{i+1}}{E_{i+1}} = \frac{\sigma_{i+1}\bar{\sigma}_a}{\bar{E}\sigma_i} = \frac{\sigma_{i+1}}{\sigma_i}\frac{\bar{\sigma}_a}{\bar{E}}. \quad \text{At } \sigma_{i+1} \approx \sigma_i, \quad \varepsilon_{i+1} \approx \frac{\bar{\sigma}_a}{\bar{E}} = \text{const},$$

and for a body of variable density, it can be interpreted as the strength balance. The distribution of the material obtained in this way is close to theoretically optimal, since in this process, value G [3] is minimized. We call value G the load-carrying factor, which expresses the value and extent of internal forces action in the structure

$$G = \sum_{k=1}^{N} \sigma_k V_k,$$

where σ_k is the equivalent stress in kth element, V_k is its volume, and the sum is spread to all elements chosen for optimization.

Figure 1 depicts the used finite-element mesh and shades of gray correspond to material's density in the theoretically optimal structure. Algorithm (3) is implemented in the form of script in MSC.Nastran for Windows. A detailed analysis of the material distribution in a theoretically optimal structure shows that, in this structure, the distribution of forces caused by the central unit of a suspend, which loads the spoiler mainly by torsion, is performed mainly by flows of tangential forces with different signs on the left and right with respect to the unit's suspension in the limit area along the front boundary of the spoiler. This fact makes it possible to decide whether it is reasonable to use a pipe construction for the spoiler, which is convenient for technologists to manufacture a structure as one unit made of the composite material by RTM method. The accepted loading pattern of the interceptor is presented in Fig. 2a by convenient groups for carbon material layout and laying.

Property	Value
Modulus of elasticity towards 0°, E_1, MPa	68600
Modulus of elasticity towards 90°, E_2, MPa	66900
Modulus of elasticity towards axis z (normal to the ear's plane), MPa	69000
The ultimate strength towards 0° (tension), σ_{1a}^{+}, MPa	720
The ultimate strength towards 90° (tension), σ_{2a}^{+}, MPa	780
The ultimate strength towards 0° (compression), σ_{1a}^{-}, MPa	−570
The ultimate strength towards 90° (compression), σ_{2a}^{-}, MPa	−670
Shear modulus, G_{12}, MPa	1100
The shear strength, τ_{12a}, MPa	114
Poisson ratio, ν_{12}	0.04

Let us point out that other variants of the mathematical model for a solid with variable density differed from (2) with original optimization methods are actively discussed in [6, 7] and in some other works. Technical solutions related to pipe structures for mechanizing the wing made of the composite material orientated for manufacturing by RTM method are also known [8, 9].

METHOD OF OPTIMIZING THE STRUCTURE OF MATERIAL LAYING

Designing processes of the internal structure of the unit is not trivial problem. In the examined example, a biaxial material is used with approximately equal strength and rigidity performances in two orthogonal directions (table). From the dynamics of composite materials [10, 11], we know that already, in three directions of fiber orientation, it is possible to generate a quasi-isotropic structure; that is why, in practical problems, it is possible to assemble a reinforcing structure using two directions of biaxial material 0°, 90°, and ±45°. The desired anisotropy of separate elements of the structure can be obtained using different numbers of layers in a given direction. Figure 2b depicts how the reinforcing material is laid in the structure for one technical solution, which set the technology for forming the internal structure of the unit.

In terms of mathematical methods for optimization this problem should be solved in a discrete definition, since the thickness of monolayer of the biaxial material is approximately 0.25 mm, and the rough calculations of the most stressed points in the structure near the central unit show that a stack of 10–15 layers of material may be required.

The problem of strength simulation of a layered structure made of composite materials is also not trivial. Nowadays, one of the most advanced software programs for calculating and designing structures made of composite materials is ANSYS, jointly with the Composite PrepPost module, where there are two variants of the finite-element simulation for calculating the sandwich-like structure of thin-wall structures. One variant is to use the shell elements of SHELL181 type; the second variant is to use solid elements of SOLID185 or SOLSH190 types. Each of these approaches has its own advantages and disadvantages. The shell meshes are simple to generate and save from a computation point of view.

However, it is necessary to point out that the mathematical formulation of SHELL-elements contains significant simplifications under determining stresses of interlayer shear. The theory of Mindlin–Reissner is used as follow: normals after deformation are the straight lines, but it is not obligatory to be normal to the median surface. An approach developed by Roos [12] with some simplifications is used to calculate the interlayer stresses. That is why it is necessary to use solid models for places where the lateral bending and grate forces towards the normal to the elements' surface take place.

The process for generating solid meshes at spatial structures that are not regular is more labor-intensive, since it is performed in semi-automated mode. However, when it is necessary to increase the calculation reliability of critical places such as T-joints or surfaces of high curvature, it becomes absolutely necessary to use solid-finite-element simulation for the units made of the composite materials.

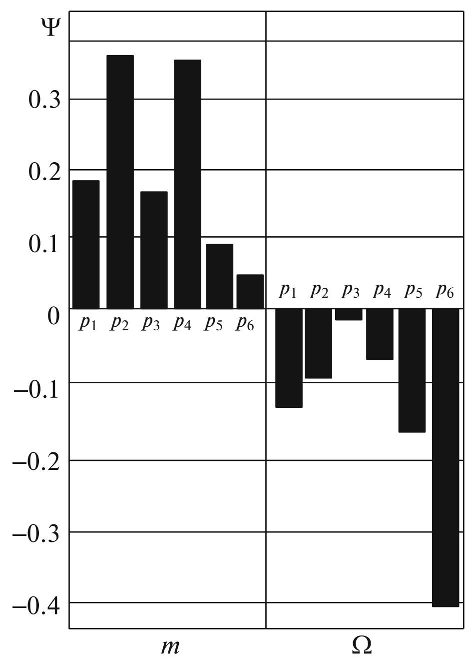

Fig. 3. Sensitivity coefficient representation over layers. Ψ is the sensitivity, m is the mass, Ω is the strength criterion.

The problem of optimizing the reinforcing structure is defined as follows: to determine the thickness of these layers and the order in which they are layered, for which the designed unit has minimal mass and meets the strength and rigidity requirements. Different approaches that include the genetic algorithms [13] are used at the initial stage for solving this problem.

During design, it is convenient to consider the correlation between the maximal strength criterion in the structure (Fig. 3) and design variables, i.e., the thickness and the number of layers of the reinforcing material in a given direction in the corresponding laying group.

The rigidity limitations are set in the form of limit displacements of angular points at the free edge. Maximal stresses criterion is used to estimate the strength. According to this criterion, the structure is operable in terms of its load-carrying capability until separate components of stress tensor are no higher than the permissible values as follows [10]:

$$\sigma_i \le \sigma_{ia}^{+}, \quad \text{if} \quad \sigma_i > 0, \quad |\sigma_i| \le \sigma_{ia}^{-}, \quad \text{if} \quad \sigma_i < 0 \quad (i = 1,2,3);$$
$$|\tau_{12}| \le \tau_{12a}, \quad |\tau_{13}| \le \tau_{13a}, \quad |\tau_{23}| \le \tau_{23a},$$

where $\sigma_{ia}^{+(-)}$ is the tensile strength (ultimate compressive strength) in ith direction and $\tau_{ik\,a}$ is the shear strength in the i–k plane.

This criterion properly describes the behavior of materials in which stresses σ_i and τ_{ik} are sustained by different elements (phases), of which the composite consists. The biaxial material used in the examined structure is related to this class of materials. In fact, the warp and weft fibers secure the strength of the material under tension-compression, while the polymeric matrix is responsible for the strength of the layers during shifting. A feature of the criterion is that it ignores the interaction between stress components and makes it possible to predict the failure mode. The initial data needed to calculate the stressed-deformed state of the structure and strength criteria are the mechanical characteristics (table), which are obtained while testing special plates made of single-directed composite according to the ASTM standard using the technology used to produce the unit.

The shear modulus G_{12} is determined by stretching the band reinforced under angles of ±45° and [10] $G_{12} = E_x/(2(1+\nu_{xy}))$.

However, it is impossible to determine strength τ_{12a} using this test, since the sample is in a complicated stressed state, i.e., normal stresses act over the shear areas and, as a result, we have understated the values in the diagram of $\tau_{12} \sim \gamma_{12}$ [11].

Fig. 4. Spoiler.

One of the most ordinary tests for determining the shear strength in the reinforcing plane is the Iosipescu method (shear of the stripe with V cuts) [14]. In this case, it is necessary to point out that it is not problematic to interpret the results of a tension-compression test with respect to the ultimate strength, since the tension-compression diagrams are almost linear during testing towards the direction of the fiber, and the destruction is of a fragile type. There are problems for interpreting the results of shear tests, since the respective diagram that shows the binder's properties is not linear and strength estimations can be spread greatly [15].

At the same time, the results of structure optimization by considering strength limitations depend on this characteristic. The interactive design mode is used for draw a conclusion on laying the reinforcing material. In this mode, the designer analyzes the correlation between critical strength and rigidity characteristics of the structure and material quantity in different layers. This option is in the ANSYS system. Figure 3 depicts an example of this correlation for strength and mass, where p_i is the number of the layer. Then, the designer makes a decision on changing the structure by considering this information, as well as by considering several specific practical requirements, i.e., layers that alternate in the package; the symmetrical placement of the material with respect to the middle surface of thin-wall elements, the start of the material from the skin element to the wall element with a fillet formation and by considering additional technological requirements. The mass of the designed and manufactured spoiler with metallic units, which are also designed using the variable density model [16] is not beyond the given weight limits.

STATIC AND LOW-CYCLE TESTS OF THE SPOILER

The universal servohydraulic machine produced by MTS Company presented in Fig. 4 is used to obtain the mechanical characteristics of the sample made of the composite material and to test the spoiler. A feature of the machine is as follows: it has a channel for testing samples with load of 100 kN and a second channel in the form of hydraulic cylinder with maximal load of 25 kN with cardan suspension unit, which makes it possible to test the units.

The spoiler is tested using specially designed and manufactured equipment that simulates the real method of suspending the unit on the wing. Static test shows that the unit endures the design load without any signs of structural failure.

Up to 54 000 cycles of low-cycle fatigue tests have been performed. In this case, we see no signs of destruction, but the area of the hysteresis loop increases by approximately 25% (Fig. 5) and it can by explained by the mounting bracket wear.

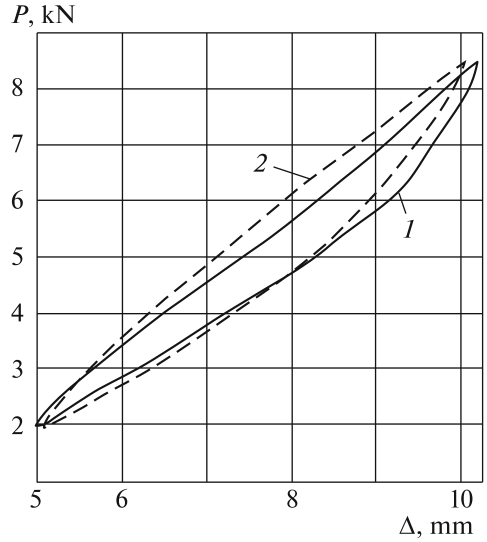

Fig. 5. Forces (P) and displacements Δ of hydrocylinder's rod. *1*—first test cycles, *2*—54 000 test cycles.

The static tests of the interceptor are stopped at a load higher by 30% than the design load, when it can be seen that the linearity of the diagram of force and displacement is spoiled according to measurements at the hydrocylinder's rod. These excess values can be explained as follows: we choose a sufficiently strong strength criterion and some safety factor for the thickness of structure elements made of composite material near the central unit, which are set according to sufficiently low (approximately 150 MPa) bearing stress at the bolted joint between the spoiler and the central unit. For the other part of the interceptor, the excess strength of the structure is conditioned by rigidity requirements in the form of limitations for maximal displacements of angular points of back edge in flight retracted position.

We think that it is possible to weaken these requirements if we use the interceptor's structure with the given deformations of the opposite sign and the interceptor is pressed to the wing's structure in angular areas of the interceptor in flight configuration as is done in several known aircrafts.

CONCLUSIONS

The problem of designing the aviation structures made of layered composite materials is defined in general form in terms of nonlinear mathematical programming. The efficient decomposition in three sequential problems of topological optimization is as follows: to choose the loading pattern of the thin-wall part of the structure, to choose the reinforcing procedure and to choose the structure of the joint units for transferring the concentrated forces is presented for solving this problem.

The developed structure for mechanizing the wing is promising in terms of weight and technological simplicity.

The presented design procedure, the essence of which is to use the new optimization model for a body of variable density and a properly grounded technical solution, i.e., a multiwall structure of the pipe type can be recommended for designing other units for mechanization (rudders, ailerons, and wing flaps).

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