Application of optimization methods to reduce the mass of body parts of minibuses made of layered composite materials

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Annotation. This article proposes an approach to reducing the mass of parts from layered composite materials, including parametric and topological optimization of parts using the finite element method. The proposed approach made it possible to shape the body for a minibus with the least amount of time, which confirms its effectiveness.

Introduction

The finite element method (FEM) in general, and topological optimization, in particular, are well studied and are often used in the design of automobiles and other equipment [1]–[10]. However, this statement relates more to solid materials, but the calculations of layered composites, despite the increase in their popularity, are performed much less frequently. This is due to the insufficient study of optimization techniques for these types of materials [11]–[20]. At the same time, using the right approach, it is possible to significantly change the properties of these materials even without changing the geometry of the parts, reducing their thickness, and, hence, the mass [21]–[30]. This is especially true when designing load-bearing structures of automobiles made of fiberglass, such as the Shuttle minibus.

The purpose of this article is to evaluate the effectiveness of the combined approach, including parametric and topological optimization of load-bearing shell elements of body parts made of layered composites (in terms of thickness, quantity and nature of laying layers), from the standpoint of reducing their mass and reducing time costs.

Mathematical model

For the initial assessment, we will choose the object of the study, which is part of the Shuttle minibus floor structure. Its dimensions are 100x300 mm, its thickness is 3.2 mm, and its weight is 164 g. The floor experiences bending-torsional loads acting in different planes. For the plate, we select the design scheme shown in Figure 1: the support is carried out on two pivotally-fixed supports, and four concentrated forces act on the plate from above. The task is to reduce the weight of the plate by 70% with minimal compliance of the structure (since rigidity for the floor is crucial) and acceptable stresses.

Let's consider two options:
The plate is made of a homogeneous orthotropic material (table 1). For it, we perform the traditional topological optimization;

The plate is made of a layered material, 8 layers of which are laid in accordance with the scheme shown in table 2. For this plate we perform a three-stage optimization.

![Figure 1. Calculation scheme](image)

**Table 1.** Characteristics of the material used

| Material type | Designation | $E_1$, MPa | $E_2$, MPa | $\mu$ | $G$, MPa | $\rho$, t/mm$^3$ |
|---------------|-------------|------------|------------|-------|----------|---------------|
| orthotropic   | MAT8        | 110000     | 8500       | 0,3   | 4000     | $1.7 \cdot 10^{-9}$ |
| $\sigma_{ut}$ along the fibers, MPa | $\sigma_{uc}$ across the fibers, MPa | $\sigma_{uc}$ across the fibers, MPa | $\sigma_{ush}$, MPa |
| 1500          | 900         | 58         | 170        | 80    |

**Table 2.** Layout of composite material

| № layer | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------|---|---|---|---|---|---|---|---|
| Stacking | 0° | 45° | −45° | 90° | 0° | 45° | −45° | 90° |
| Layer thickness, mm | 0,4 | 0,4 | 0,4 | 0,4 | 0,4 | 0,4 | 0,4 | 0,4 |

**Comparison of source objects**

First, we perform the calculation of the original plate. For an object of homogeneous material, we obtain displacements of 1.22 mm, and stresses of 93.9 MPa. For a layered material, with equal mass, we have a displacement of 0.98 mm and a stress of 61.1 MPa. The calculation results are presented in Figure 2. Thus, already at this stage it is clear that the use of layered material can provide tangible advantages in the development of structures: the rotation of several layers without changing the shape of the product significantly reduces stress and displacement in the structure.
Continuous plate topological optimization
The final mass of the object is set at 30% of the original. The objective function is to minimize compliance. To converge, the solution took 22 iterations. As a result, it was possible to reduce the weight to 49 grams, while the displacements amounted to 3.01 mm, and the stresses increased to 181.7 MPa. The results are presented in Figure 3.
Layered plate optimization
We will perform optimization of the laminated plate in three successive procedures. Free-Size optimization allows algorithms to freely change the number of layers and their thickness, decreasing to values tending to 0 in the case when the layer does not carry a load. The final mass of the plate is set at 30% of the original. The objective function is to minimize compliance. The solution converged in 20 iterations. The total mass of 49 g, the maximum displacement of 2.53 mm, the maximum equivalent stress of 282.9 MPa. The solver broke the composite into 32 layers. The structure of the obtained composite is shown in Figure 4 and in table 3.

Figure 4. Composite structure (Free-Size optimization)

Table 3. Layout after Free-Size optimization

| № layer | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Stacking | 0°  | 45° | −45°| 90° | 0°  | 45° | −45°| 90° |
| Layer thickness, mm | 0.00518 | 0.00646 | 0.0640 | 0.00610 | 0.00500 | 0.00656 | 0.00551 | 0.00531 |
| № layer | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Stacking | 0° | 45° | −45° | 90° | 0° | 45° | −45° | 90° |
| Layer thickness, mm | 0.13351 | 0.12730 | 0.13594 | 0.13652 | 0.14388 | 0.09563 | 0.08252 | 0.05818 |
| № layer | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Stacking | 0° | 45° | −45° | 90° | 0° | 45° | −45° | 90° |
| Layer thickness, mm | 0.25161 | 0.25271 | 0.24520 | 0.24271 | 0.24324 | 0.27939 | 0.28975 | 0.29090 |
| № layer | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
| Stacking | 0° | 45° | −45° | 90° | 0° | 45° | −45° | 90° |
| Layer thickness, mm | 0.00971 | 0.01352 | 0.01246 | 0.01467 | 0.00788 | 0.01842 | 0.02223 | 0.04561 |

The second stage is Size optimization. The initial data are the results obtained in the previous step. The point of this stage is to achieve the same technologically feasible layer thicknesses. The maximum mass of the plate is set at 100% of the original. The objective function is to minimize compliance. The target thickness of one layer is 0.2 mm. The solution converged in 5 iterations. The total mass of
49 g, the maximum displacement of 2.77 mm, the maximum equivalent stress of 160.2 MPa. The solver has reduced the number of layers to 15, and the total plate thickness is now 3 mm. The thicknesses and orientations of the layers are presented in Table 4, and the distribution of the material is shown in Figure 5.

The third stage is Shuffle optimization. Here, the solver varies only the mutual arrangement of the layers, achieving the optimal location. The objective function is to minimize compliance. The solution converged in 2 iterations. The total mass of 49 g, the maximum displacement of 2.69 mm, the maximum equivalent stress of 150.2 MPa. The calculation results are shown in Figure 6, and the final thickness and orientation of the layers are presented in Table 5.

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**Table 4. Layout after Size Optimization**

| № layer | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Stacking | 0°  | 45° | −45° | 90° | 0°  | 45° | −45° | 90° |
| Layer thickness, mm | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |

**Table 5. Layout after Shuffle Optimization**

| № layer | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Stacking | 45° | −45° | 0°  | 90° | 45° | −45° | 0°  | 90° |
| Layer thickness, mm | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
For clarity, we present Table 6 with the calculation results.

**Table 6. The results of the calculations**

| Model                             | Mass, g | Displacement, mm | Stress, MPa |
|-----------------------------------|---------|------------------|-------------|
| Original, orthotropic            | 163     | 1,22             | 93,9        |
| Original, layered                 | 163     | 0,98             | 61,1        |
| After topological optimization    | 49      | 3,01             | 181,7       |
| After Free-Size Optimization      | 49      | 2,53             | 282,9       |
| After Size Optimization           | 49      | 2,77             | 160,2       |
| After Shuffle optimization        | 49      | 2,69             | 150,2       |

**Applying Combined Optimization to a Van Body**

As you can see, the optimization of the layered material will achieve better outcomes than the calculations with orthotropic material. At the same time, optimization of composite materials is much more laborious both in terms of creating models and the time spent on calculations. For best results with minimal time, it is proposed to combine these two methods. Let us consider the proposed algorithm more clearly by the example of preliminary optimization of the Shuttle minibus body made of laminated fiberglass, shown in Figure 7.
First, a finite element model is created, including a frame, suspension, batteries, as well as the estimated mass distribution. The body is modeled on the basis of a design project, door openings are determined. Then, orthotropic material is set, and the traditional topological optimization of the body is performed on the basis of a dedicated package of design cases, for example, parking, breakdown of the front wheel, torsion, skidding, as well as static simulations of tipping, side and frontal impacts. Based on the results obtained, the future power framework is built and included in the calculation model (Figure 8).

Figure 8. Creating a power frame

The homogeneous model of the body material is replaced by a layered one, which is attached to the designed frame. Using the previous load conditions, the optimization of a layered body is performed: Free-Size, Size and Shuffle. As a result, an optimized design is obtained, on the basis of which the body is built, intended for further deeper research.

Conclusions
The use of a combined approach based on a combination of parametric and topological optimizations as applied to structures made of composite materials made it possible to obtain better parameters for a layered material compared to a homogeneous one. In the considered example, it was possible to reduce the plate mass to 49 g, and at the same time achieve maximal displacements of 3.01 mm and stresses of 181.7 MPa for a homogeneous material, and 2.69 mm and 150.2 MPa for a layered material, respectively.

The proposed combined approach, combining topological optimization with the optimization of layered composites, made it possible to form the appearance of a body with a supporting frame for a minibus with the least time costs, which confirms its effectiveness.

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