Selection and justification of polymer composite wing load–bearing elements design parameters with material anisotropy and airload

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Abstract. The rapidly developing aviation industry is looking for new design solutions in the field of designing modern passenger airliners. To ensure reliability and increase the service life of developed products can help polymer composite materials, which are already successfully used in the construction of a number of aircraft. This work is devoted to the urgent task of determining and optimizing the structural parameters of the carbon fiber wing load–bearing elements, taking into account rational reinforcement schemes. The wall thicknesses, layup patterns of unidirectional layers, the safety margins of the wing structural elements, taking into account the current operational loads for several angles of attack corresponding to different flight modes. The work is part of the methodology for designing a wing of polymer composite materials.

1. Introduction

The wing development and design has always been a complex task requiring the consideration of many different factors, which only becomes more complicated with the use of new materials and technologies. In turn, promising developments actively introduced by world manufacturers, including in the field of polymer composite materials (PCM), do not find such widespread use in the Russian aircraft industry, in which metal alloys continue to remain the main structural materials and the design methods developed for them are applied. However, there is a need to improve and change approaches in the design of aircraft structures, including those from composite materials (CM), which can not only reduce the weight of the product being developed units, but also provide fundamentally new and effective layout schemes that could not be achieved with traditional design approach [1]. These include, for example, non–standard structural arrangement (SA), consisting of curved elements, the design of which implies general wing optimization (spars, skin ribs) followed by a particular one (for example, skin parameters in contact zones with other elements) [2]. In other words, the wing design parameters are selected at the level of the entire structure depending on the deformation, while the CSS is optimized as a subsystem from the conditions for satisfying these restrictions [3].

In order to simplify and speed up the calculations, work is carried out on comparing various variants for determining the strength characteristics, for example, the use of various finite element models [4]. Many complex multidisciplinary tasks are solved, such as optimization of a polymer composite and metal wing and a comparison of different types of stringers and their influence on the mass and deformation of the airliner wing [5]. The work performed using the commercial MSC Nastran
software aims to optimize for several design parameters, such as weight, deformation, strength, resistance to damage and aeroelasticity with preliminary grouping of layers in the package to reduce design variables [6] and variable stiffness and thickness matrix elements [7–9]. The buckling of a polymer composite wing are solved, for example, for a light sports airplane with vertical take–off and landing [10, 11]. The design work and the calculation of the parameters of thin–walled elements under the influence of airload [12], with the choice of SA and variants for the wing box junction with the center wing [13], panels [14], as well as determining the optimal layup in skins, do not go unnoticed. [15]. Today, designs use typical quasi–isotropic stackings with several different (usually no more than four) layer orientations. Moreover, the choice of the layers direction is one of the key features of the design of products from composite material. Therefore, for this purpose, work is underway to study the properties of PCM stacks other than quasi–isotropic [16, 17]. The effect of the layers orientation on aeroelasticity, for example, a triangular wing, is studied experimentally and numerically, but only angles with a step of 15 ° are considered [18]. When using hybrid PCMs in the wing structure of a suborbital reusable spacecraft, only typical quasi–isotropic stacking are also considered [19]. In this area, the developing technology of directional layup of fibers in layers, which can be carried out using automated fiber placement machines (AFP machines), is very interesting. It is assumed that the studied and developed composite materials with directional fibers in the layer (Tow–steered Composite) will improve the characteristics of wing aeroelasticity, but there is no obvious or intuitive structure of the fiber stacking that would give such a result. To this end, wings from the proposed composite material with directional fibers, conventional unidirectional PCM and metals in terms of fuel and weight efficiency of the structures obtained [20–23], as well as from a hypothetical composite material based on carbon nanotubes using optimization in strength and stability are compared [24, 25].

Based on the foregoing, the developed methodology for designing a polymer composite wing will simplify the design at the stage of design calculations. According to the general scheme of the technique, after determining the wing loads and designing the KSS, it is necessary to calculate the parameters of the structural elements from PCM.

The paper discusses the process of determining the structural parameters of the main elements from the PCM for the obtained wing geometric model under the action of operational loads.

2. Source data

We considered a swept wing with a span of 35 m, with a straightened section, an asymmetric airfoil of a mid–range passenger airliner consisting of upper and lower finned panels (which can be divided into skins and reinforcing each eleven stringers), two spars and fourteen ribs (Figure 1) [26].

Figure 1. The wing SA elements for choosing reinforcement schemes: 1 – upper skin, 2 – upper stringers, 3 – front spar, 4 – lower skin, 5 – lower stringers, 6 – rear spar, 7 – ribs.
The simultaneous action of the following concentrated and distributed loads was considered [27, 28]:

- dead load;
- engine weight (2400 kg);
- fuel weight of 20,000 kg (it is assumed that the tank is full);
- air-pressure corresponding to one of the considered angles of attack (cruising flight at a speed of 242 m/s, at an altitude of 11500 m, angles of attack: 0°, +11°, −7°).

When choosing the optimal thicknesses and layup angles, carbon fiber was adopted as the material (Table 1).

| Table 1. Carbon fiber stress–related characteristics. |
|------------------------------------------------------|
| Characteristic                                      | Value       |
| Tensile modulus, along an axis X / Y, GPa           | 48,57/48,57 |
| In–Plane shear modulus, GPa                         | 28,9        |
| Poison's ratio                                      | 0,44        |
| Tensile (Compressive) strength, along an axis 1 / 2, MPa | 483 (507)/483 (507) |
| In–Plane shear strength, MPa                        | 262         |

The thicknesses choice of the wing elements was carried out for two design models:

- Model 1 — upper and lower skins, front and rear spars, 14 ribs.
- Model 2 — upper and lower skins, front and rear spars, 8 ribs, 6 stringers (3 on each skin).

The step of the ribs and stringers was chosen to ensure uniform distribution over the wing box.

Table 2 presents the initial values of the thickness of the elements in a first approximation. The maximum and minimum ranges of thickness variation from 0,002 to 0,015 m, except for stringers for which the maximum value is 0,009 m.

| Table 2. Initial thicknesses of elements, m. |
|---------------------------------------------|
| Skins                                      |
| Front spar                                 |
| Rear spar                                  |
| Ribs                                       |
| Stringers                                  |
| 0,007                                      |
| 0,008                                      |
| 0,01                                       |
| 0,007                                      |
| 0,007                                      |

When choosing a layup, we considered both each element individually (casing, spars) and groups of elements (ribs, stringers).

The calculation was carried out iteratively for each element under consideration, starting from the upper casing until the installation from the previous step matches the values at the current one, and the error does not exceed 1.5%.

The layup angle ranged from −90° to 90°, and the initial value for all layers of each element was 0°.

The number of cases considered for each individual element or group without taking into account variation in the angle of attack exceeded 11 thousand.

3. Results

Because of the calculation by choosing the thicknesses of the elements, the deformation and mass of the structure are determined. Table 3 shows the parameters of the three selected variants (taking into account the angle of attack), from which the thickness values of the wing elements were selected.

| Table 3. Calculation results for choosing the thickness of the elements. |
|-------------------------------------------------------------|
| Thickness, m                                                 |
| Skin             | Spar      | Ribs   | String.   | Mass, kg  | Angle of attack |
| Upper            | Lower     | Front   | Rear      |           | 0°        | +11° | −7° | Deformation, m |
| I                | 0,002     | 0,0085  | 0,0065   | 0,0046    | 0,0025    | 0,0022 | 1041,1 | 0,517 | 0,827 | 2,030 |
| II               | 0,008    | 0,01    | 0,007   | 0,008    | 0,004     | 0,003  | 1717,2 | 0,277 | 0,397 | 1,035 |
| III              | 0,003   | 0,005  | 0,006   | 0,004    | 0,002     | 0,0025 | 823,89 | 0,510 | 0,835 | 2,027 |

It can be seen that the deflection and mass values of variants I and III are similar and are two times different from II. In this case, in none of the cases considered, the stresses in the structure reach the ultimate strength of the material, and the maximum values are due to stress concentrators and the error of the finite element mesh. Based on the foregoing, option III was chosen with the minimum calculated thicknesses, which can be increased with further calculation of elements taking into account various factors (for example, amplification for mechanization elements).
For the obtained thicknesses, the number of layers was determined based on the layer with rounding upwards Table 4.

| Skin | Lower | Spars | Rear | Ribs | Stringers |
|------|-------|-------|------|------|-----------|
| Upper| 11    | 18    | 20   | 14   | 7         | 9         |

The optimal stackings calculated for different angles of attack were compared, stacking from the initial approximation (orientation of all layers is 0°), two quasi–isotropic stackings, the ratio of the layers in which is presented in Table 5:

- A — optimal layup corresponding to an angle of attack of 0°;
- B — optimal layup corresponding to an angle of attack of +11°;
- C — optimal layup corresponding to an angle of attack of –7°;
- D — quasi–isotropic layup 1;
- E — quasi–isotropic layup 2;
- F — first approach layup.

| Layup 1 | Layup 2 |
|---------|---------|
| Upper skin | 2/8/1 | 18/73/9 | 3/6/2 | 27/55/18 |
| Lower skin | 4/12/2 | 22/67/11 | 6/8/4 | 33/44/22 |
| Front spar | 6/12/2 | 30/60/10 | 6/10/4 | 30/50/20 |
| Rear spar | 4/8/2 | 29/57/14 | 4/6/4 | 29/43/29 |
| Ribs | 2/4/1 | 29/57/14 | 2/4/1 | 29/57/14 |
| Stringers | 1/6/2 | 11/67/22 | 3/4/2 | 33/44/22 |

The evaluation criteria were the values of the entire structure deformation and the safety factor (for stresses, strains and the Tsai – Wu criterion). Each structural element was considered separately. Table 6 shows the results of the optimal layup for each element depending on the angle of attack.

| AA² | Skin | Spar | Ribs, No. | Stringers |
|-----|------|------|-----------|-----------|
| Upper | Lower | Front | Rear | 1, 14 | 2–5 | 6–13 | Upper | Lower |
| 0° | C | C | C | A | C | A | C | C | C |
| –7° | A | B | A | A | F | A | A | F | F |
| +11° | A | A | A | A | A | A | A | A | A |

² Angle of attack

It can be seen that at an angle of attack of 0° for the structural elements, the optimal variants are C (66.67%) and A (33.33%). For the angle of attack –7° — A (55.5%), F (33.3%) and B (11.2%), and for +11°, for all structural elements, layup A (100%). Because for all angles of attack, the largest number (63%) of optimal variants correspond to A; a comparison was made with B, C, F for the following elements: upper and lower skin, front spar, ribs No. 1, 6–14, upper and lower stringers. As a result, it was found that the deflection of the wing during layup A increases by 0.004 m (2%), the values of the safety factor are reduced by no more than 17% (where 100% is the destruction of the structural element) compared to option C. However, such a large decrease in the safety factor can be neglected, because the zone of the indicated voltages is incomparably small in comparison with the area of the element in which the supply is high, and is due to the stress concentrator and a coarse grid.

In turn, layup variant B and F show the best values of deflection and safety factor — the gain in deflection is 0.177 m (17%) and 5% in the safety factor for layup B, 0.004 m (2%) in deflection and 16% by coefficient — F, but only for several elements (skin, ribs, stringers) at one angle of attack. Therefore, they can also be neglected.
There is a gain in the mechanical properties of the structure, in the elements of which optimized styling is used compared to quasi–isotropic. For some elements, the difference reaches 40%.

As a result, variant A was selected (Table 7).

**Table 7. Layup of wing elements.**

| Upper skin         | 28°/–10°/–48°/56°/–2°/–1°/–23°/–3°/–7°/–10°/14° |
|--------------------|-----------------------------------------------|
| Lower skin         | –90°/0°/–30°/–54°/–64°/–74°/–76°/–79°/–80°/–82°/–84°/–85°/–86°/–86°/ |
| Front spar         | 0°/–12°/17°/–17°/44°/27°/34°/13°/–11°/66°/–30°/–52°/14°/–45°/33°/33°/–4°/ |
| Rear spar          | –40°/29°/13°/–16°/30°/–52°/–26°/–27°/21°/–78°/11°/80°/–1°/47° |
| Ribs No. 1, 1, 4   | –30°/4°/–48°/28°/48°/–85°/10° |
| Ribs No. 2–5       | 41°/13°/7°/49°/–1°/33°/5° |
| Ribs No. 6–13      | 63°/–37°/0°/–84°/–4°/–40°/–20° |
| Stringers          | 14°/2°/–22°/–12°/8°/4°/–15°/90°/–18° |

**4. Conclusion**

Because of polymer composite wing elements, calculations at different angles of attack (0°, + 11°, –7°) determine:

- rational minimum possible number of layers;
- rational orientation layers angles;
- thickness;
- structure deformation values for the selected optimal layup;
- safety factors of structural elements.

The advantage (up to 40%) of layup optimized for operational loads over quasi–isotropic is shown. The maximum structure deformation is achieved at an angle of attack of –7°, is 1.22 m and is due to the interference of existing loads. The safety factor does not exceed 0.35, with the exception of several zones in which it reaches 0.47, which is due to the stress concentrator and the error of the finite element mesh.

The obtained values of the characteristics correspond to the level of the outline design and will be optimized upon a detailed examination of each element.

The results of this work are part of the compiled polymer composite wing design methodology and will be taken into account and used in its compilation.

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