Selection and justification of polymer composite wing structural arrangement using parametrical modeling

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Abstract. Currently, due to the increase in air traffic, the need for modern reliable airliners is increasing, the requirements for which are constantly growing. One of the options for meeting these requirements is the use of polymer composite materials (PCM) in the structure, in particular in the wing. This article is devoted to the urgent task of designing a polymer composite wing power circuit within the framework methods of designing developing. The modeling, calculation and analysis of ninety variants of the wing structural and power schemes. The rational geometric parameters of the primary structural member arrangement are established, including the step and installation direction of ribs, stringer, spars, providing the greatest margin of safety factor. The skin power element is considered in detail. The stringer shape and material based on the calculations made are justified. The work is part of the methodology for designing a polymer composite wing.

1. Introduction

The wing is one of the most critical airliner designs, which create aerodynamic lift and ensure dihedral stability of the airliner. The wings of modern airliners are mainly made of polymer composite materials (PCM), which can provide mass efficiency without compromising performance, as well as achieve geometric characteristics inaccessible to metal structures. However, their design has always been a difficult task, including: developing and analyzing a large number of circuit options, conducting expensive experiments to determine various parameters, which leads to significant time and financial costs. Therefore, the development of a universal methods of designing a polymer composite wing, which allows one to obtain the primary wing geometry in a relatively short time, is a relevant objective.

Worldwide aircraft manufacturing specialists carry out the aircraft structures designing. Attention is being increasingly focused on multidisciplinary and the transition from narrowly focused product design methods to an integrated approach to their creation [1]. Most of the works consider certain objects, wings types and are aimed at solving specific problems. A study is being carried out in the field of forward–swept wing aerodynamics with a surface consideration of the structural arrangement (SA) to assess the overall performance of the wing under load [2]. Optimization of wing stiffness under the airload of both the whole structure [3 – 9] and specific SA [10, 11], including composite materials [12, 13]. Particular attention is paid to the calculation and optimization of the wing structure weight [14], including the use of curved force elements [15]. In addition, PCM panels [16 – 20] with integrated stringers [21, 22] are considered as an optimization object, and the results of optimizing the
nose diaphragm are presented in [23]. Research is being conducted in the field of load–bearing element topology optimization taking into account only strength limitations [24, 25]. The design of the entire wing configuration is carried out at aviation enterprises using their own software products that are not available for commercial use [26, 27].

2. Selection of wing structural arrangement

2.1. Source data

The passenger airliner wing with a wingspan of 35 m, with a direct sweep, with a straightened section and an asymmetric airfoil was chosen as the object of study [28]. The calculation was carried out for three design cases — angle of attack are 0°, +11°, −7°. The corresponding load values were obtained when simulating the external aerodynamics. Figure 1 shows the aerodynamic pressure distribution over the wing surface in the mid section for a +11° angle of attack. In the root section, the wing is limited in movement and rotation relative to the axes [29, 30].

![Figure 1. Pressure distribution over the airfoil.](Image)

In the calculation, finite Shell type elements were used, the load–bearing element thicknesses were specified in groups: upper skin, lower skin, front spar, rear spar, ribs, stringers. It was simulated 90 variants SA. Table 1 shows the variable parameters.

| Spar pitch,% of chord (front / rear) | 20/70 | 30/60 | 25/65 | 20/60 | 30/70 |
|-----------------------------------|-------|-------|-------|-------|-------|
| Rib pitch,% MAC ^a | 20 | 30 | 40 |
| Ribs mounting orientation | I^b | II^c |
| Stringer pitch, m | 0,12 | 0,16 | 0,2 |

^a Mean Aerodynamic Chord
^b Perpendicular to the rear spar
^c Looking forward

Carbon fiber is the main structural material. Table 2 shows the carbon fabric properties.

| Property | Value |
|----------|-------|
| Density, kg/m³ | 1580 |
| Layer thickness, mm | 0,285 |
| Tensile modulus, along an axis 1^a / 2^b, GPa | 174,3 / 174,3 |
| In–Plane shear modulus, GPa | 2,9 |
| Poisson's ratio | 0,32 |
| Tensile (Compressive) strength, along an axis 1 / 2, GPa | 2,7 (2,9) / 2,7 (2,9) |
| In–Plane shear strength, GPa | 0,1 |

^a Warp
^b Weft

Taking into account the varied parameters, 210 design cases of SA are considered in the work.

2.2. Results

As a result of the calculation, stress–strain behavior were determined and the values of structure deformation under the airload were obtained.
Figures 2 and 3 show the values of mass and maximum deformation in the structure for all considered variants. Hereinafter, the values are presented for the design case with maximum load — flight at an +11° angle of attack.

Figure 2. Construction weight, kg.

Figure 3. Maximum structure deformation, m.

Figure 4 shows the values of normal stresses along the local Z axis for three groups of elements — sheathing, spars and stringers (longitudinal load–bearing elements), ribs (transverse load–bearing element). The tensile strength along the Z axis for fabric–based carbon fiber reinforced plastic is much smaller than along the other two axes due to the anisotropy of physical and mechanical properties and does not exceed critical values. In the direction of the X and Y axes, the value of the tensile strength is also not exceeded.

Figure 4. Maximum normal tension (+) and compression (−)stresses along the local axis Z,
MPa: (a) — skins, (b) — longitudinal load–bearing elements, (c) — transverse load–bearing element.

Figure 5 shows the results of choosing the SA of the polymer composite wing, where the mass and the deformation corresponding to the maximum structure load–bearing ability are selected as criteria.

Figure 5. The distribution of values in relative units.

The results of SA calculations show that none of the variants exceeds the values of tensile strengths, the safety factor is not less than 1.8, therefore, the initial approximation of the load–bearing element wall thickness should be reduced by subsequent optimization (provided that operability is maintained as a result of adding additional loads to the structure — weight of fuel, engines, etc.). A lot of non–dominant alternatives were identified according to two criteria (Pareto set) — deflection and weight of the structure (14 variants). The optimal SA, from the obtained ones, can be determined both by introducing an additional parameter, for example, cost, and by choosing the shortest distance to the theoretical center (TC) according to the equation (1):

$$ K = \left[ \frac{(m_{TC} - m_i)^2}{m_{AM}^2} + \frac{(d_{TC} - d_i)^2}{d_{AM}^2} \right]^{1/2} $$

where $m_{TC}, d_{TC}$ — TC mass and deformation values, $m_i, d_i$ — variant mass and deformation values, $m_{AM}, d_{AM}$ — arithmetic mean mass and deformation values.

It was found that the smallest distance to the IC for variant 33 (Table 3). Figure 6 shows a front view of the deformed and undeformed wings at different angles of attack.

Table 3. The values of the selected wing SA geometric parameters.

| Parameter                        | Value |
|----------------------------------|-------|
| Front spar pitch, % of chord     | 20    |
| Rear spar pitch, % of chord      | 70    |
| Rib pitch, % MAC                 | 40    |
| Ribs mounting orientation        | $1^\circ$ |
| Stringer pitch, m                | 0.2   |

$^a$ Mean Aerodynamic Chord

$^b$ Perpendicular to the rear spar

It is determined that the maximum deformation from airload occur at the tapering end of the wing. In turn, at root section (where the wing is as wide as possible), deformations are insignificant or absent. It

Figure 6. Wing deformations: 1 — angle of attack $+ 11^\circ$, 2 — undeformed wing, 3 — angle of attack $7^\circ$, 1 — angle of attack $7^\circ$. 
follows that the engines (if placed on the wing) are rationally installed in the area of the straightened section or in the transition zone to the swept part. It has been established that longitudinal and transverse load–bearing elements (ribs, spars and stringers) unload the power schemes, and the stresses along the X axis in the global coordinate system (CS) are informative about the operation of the PCM structure. To assess the overall structure reliability qualification, it is necessary to consider each load–bearing elements (group of elements) in the local CS associated with the layers angles in the part, which is associated with a pronounced PCM properties anisotropy.

3. Selection of stringer

3.1. Source data

As an example of optimization of the load–bearing element, a calculation was made for the choice of the stringers shape and material. The following types of materials were used for the calculations: carbon fiber, fiberglass, aluminum alloy, and lightweight foam filler. Aluminum alloy is given as a comparison of PCM and metal. Figure 7 shows the considered variants of the stringers cross–sectional shapes.

Figure 7. Section shapes: (a) — angle–shape; (b) — T–shape; (c) — I–shape; (d) — square–shape with light foam aggregate; (e) — trapezoid–shape with light foam aggregate.

The calculation was carried out using finite element methods. To construct the finite element mesh, the geometry of stringers was simplified, in particular, fillets were not taken into account. In parametric modeling, 15 design cases were considered.

3.2. Results

As a result of the calculation, the stringers deformation and mass values were obtained. Figure 8 shows the results of stringer shape parametric optimization, where the mass and deformation corresponding to the maximum load–bearing ability are selected as criteria.

Figure 8. The distribution of values in relative units.
A certain Pareto set consists of four variants. Variant IX is excluded because corresponds to a metal stringer. The manufacture of stringers (panels) of metal implies a mechanical way of attaching the
casing to the stringers, for example, rivets, which requires equipment that is more complex. Variants VII (I–shape) and X (square–shape) are complex from a technological point of view, since for the manufacture of a stringer in the I–shape form, complex equipment is necessary, as in the case of a square–shape profile.  

Variant IV is easy to manufacture by laying out using a simple equipment. With equal thicknesses of the shelf and wall, the T–shape is less material-intensive than the I–shape. Based on the foregoing, a carbon–fiber stringer of T–shape was selected (variant IV).

4. Conclusion
In this work, based on the performed parametric modeling of 90 geometric models of the SA of the polymer composite wing at different angles of attack (0°, +11°, −7°) established:

- rational geometric parameters of the SA wing — the pitches of ribs, stringers, spars;
- shape and material of the panel element — stringer.

From the analysis of the simulation results, a SA variant was chosen in which pitch are: front spar is 20% of the chord, the rear spar is 70% of the chord, the rib is 40% of the MAC, the stringer is 0.2 m and the mounting orientation of the ribs is perpendicular to the rear spar.

Based on the solution of the parametric optimization problem, a T–shape stringer made of carbon fiber is selected.

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