Design of a structurally optimized bioinspired structural arrangement of a polymer composite wing

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Abstract. Developing trends in designing and manufacturing products made of polymer composite materials allow us to create previously unattainable structures. These include bioinspired structural layouts inspired by objects of nature, for example, the wings of insects, plants, and others. In turn, the structural layout of the wings of aircraft has reached its limit in terms of optimization in its classic form. The work is devoted to an urgent task – the choice of a bioinspired layout for an aircraft wing. A comparison of classic structural arrangement with a bioinspired structure is carried out. The total number of options considered is 14. The structure of the bioinspired wing was chosen based on the action of the load and stress distribution according to the results of preliminary calculations inspired by insect wings. The advantage of wings of a bioinspired design over classical ones by weight up to 32% is shown. The results of the initial stage of studies of bioinspired wings are presented.

1 Introduction

The arrangement of the wings of aircraft consists of longitudinal and transverse structural elements [1-2], the optimization of which, taking into account the multi-criteria of the task [3], the formation of complex algorithms for calculating strength by several parameters [4] is already close to exhaustion. The applied composite materials [5] make it possible to further optimize the design due to the anisotropy of properties and the selection of layout schemes [6]. However, fundamentally new design solutions, bioinspired structures based on natural structures [7], became possible only with the development of manufacturing technologies in the field of additive manufacturing and 3D printing [8-10]. Methods of mathematical modeling [11], interdisciplinary design [12], and topological optimization [13, 14]. For one of the main aggregates of the aircraft – the wing, approaches to the creation of periodic structures based on topological optimization are being formed [15]. Fundamentally new mesh schemes [16], as well as structurally optimized curved elements [17] are proposed to meet the stringent requirements for strength, resource, reliability, and minimum weight [18]. Methods and calculations are being developed that take into account numerical optimization [19], the effect of external forces and stress distribution in the structure [20], as well as other parameters. The

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limitations on aeroelasticity and the critical rate of flutter formation are taken into account [21]. Based on the above development of a structural arrangement wing from a PCM using a promising structural layout is an urgent task. The objective of the work is to reduce the weight of the wing by using curved structural elements while ensuring resistance characteristics and maximum load capacity.

2 Design and material

2.1 Object of the research

An aircraft wing with a span of 40 m, a sweep angle of 33.5°, and an area of 380 m^2 was considered as an object of research. Aerodynamic profile: root NASA SC(2)-0610, tip: NASA SC(2)-0606. Carbon fiber and fiberglass based on unidirectional tapes are used as the main structural materials (Table 1).

Table 1. Physical and mechanical characteristics of the materials

Parameter		**Fiberglass**	**Carbon fiber**
Density, kg/m^3		2000	1550
Modulus of elasticity, GPa	Along the fiber	37,2	50,6
	Across the fiber	26	35,4
Shear modulus of elasticity, GPa		21,7	29,7
Tensile strength, MPa	Along the fiber	352,6	483
	Across the fiber	49	67
Compressive strength, MPa	Along the fiber	202	297
	Across the fiber	78	107
Shear strength in the plane, MPa		191	262

2.2 Loads on the structures

The following loads were considered:
- airload;
- the unit's own weight and fuel weight of 10 tons;

The calculation of loads was carried out for the maneuver turn at a speed of 165 m / s, at 40 ° with a turning radius of 180 m at an altitude of 5000 m.

Aerodynamic loads were determined using the Ansys software package in the CFX module [22] taking into account flight parameters (speed, angle of attack) and atmosphere (Figure 1).

The calculations did not take into account the elements of wing mechanization, flaps, slats, ailerons, and air brakes.

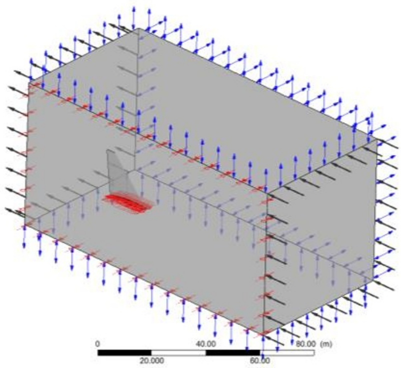


Fig. 1. Calculation model

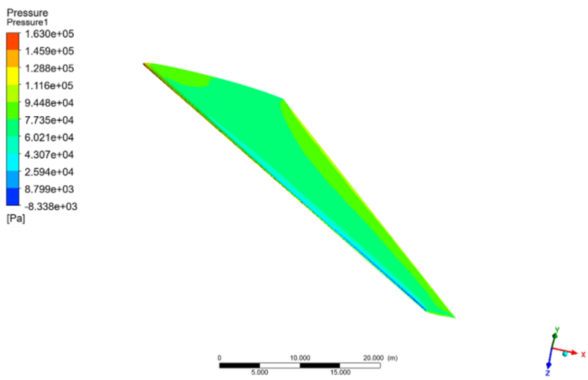
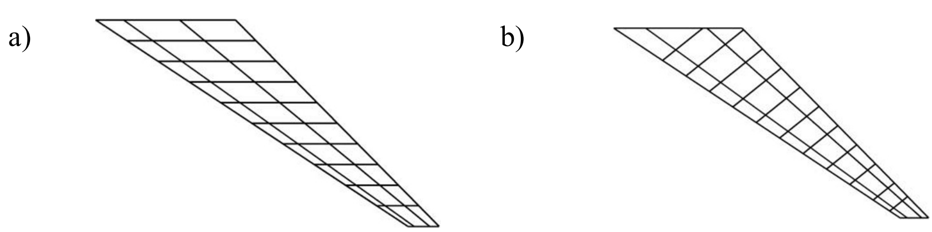


Fig. 2. Distribution of aerodynamic pressure on the surface of the wing, Pa

2.3 Structural layout of the wing

Classical structural layouts were considered, taking into account the possibility of curvature of elements, as well as bioinspired ones based on insect wings.

Classic structural layouts are shown in Figure 3 and have a two-spar design, with a different number of ribs and the direction of their installation. The ribs are directed in flight or perpendicular to the front spar. Reinforcing diagonal walls have been added to the two layouts. In this last option, the ribs are curved.



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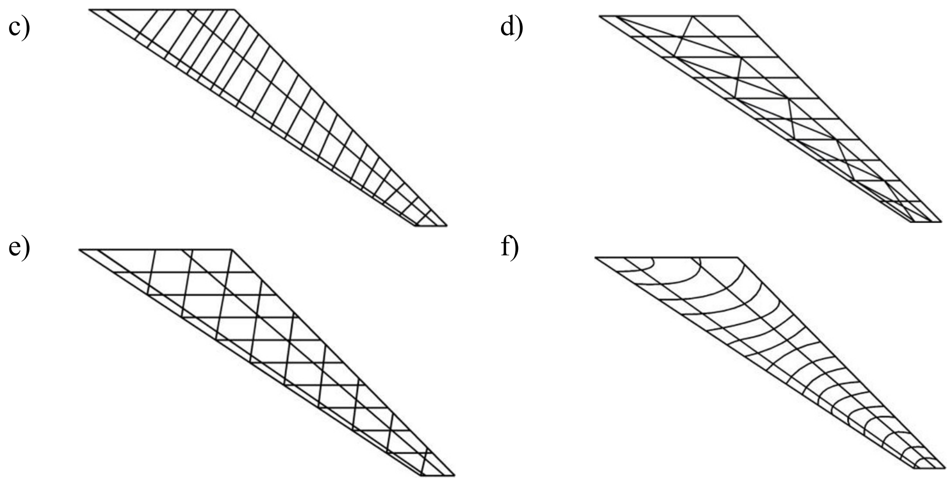

Fig. 3. Classic Structural Layouts: (a) — Option 1 with two spars, (b) Option 2 with lightweight ribs; (c) — Option 3 ribs perpendicular to the front spar; (d) — Option 5 wall structural arrangement; (e) – Option 6 truss ribs with two spars; (f) — Option 7 curved ribs

Bioinspired structural arrangements are designed based on the distribution of stresses obtained as a result of preliminary calculations from loads and insect wings [23]. The main species considered were Diptera, Reticulate-winged (Neuroptera), Hymenoptera, Freckles (Plecoptera), Dragonflies (Odonata), Hemiptera and Orthoptera (Figure 4) [24, 25]. The proposed Options of structural layouts are formed by analyzing more than three dozen photographs of the wings of each detachment with the identification of characteristic features of the structure, direction, shape, and structure and the analysis of scientific literature in this area (Figure 5).

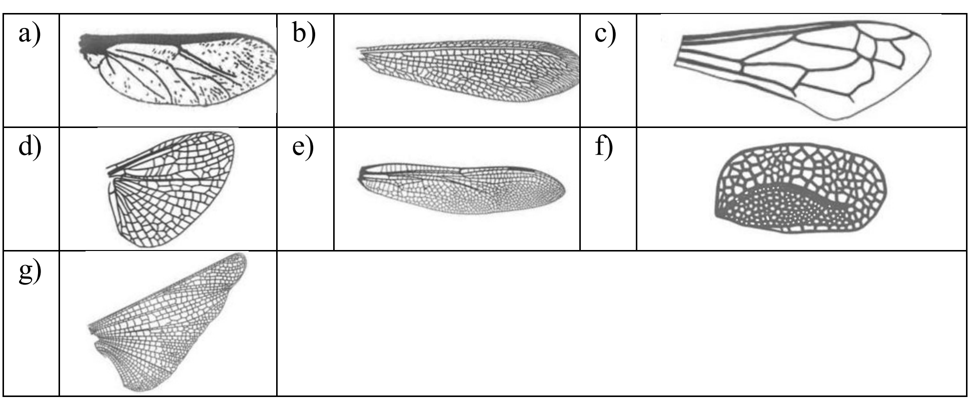

Fig. 4. Insect wing: a — Diptera; b — Neuroptera; c — Hymenoptera; d — Plecoptera; e – Odonata; f — Hemiptera; g — Orthoptera [23-25]

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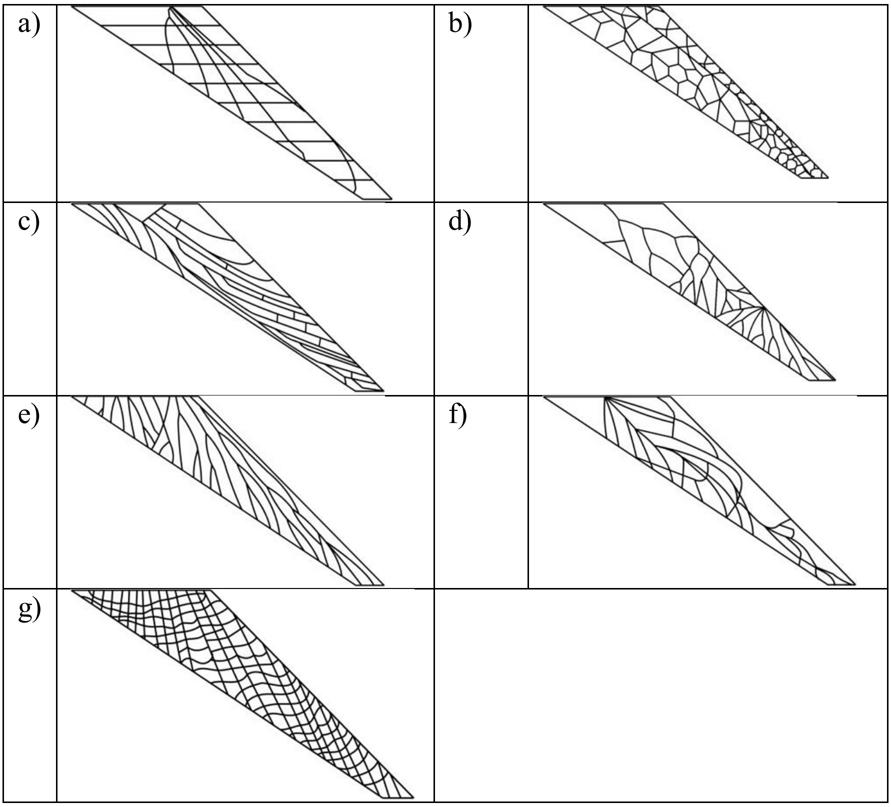

Fig. 5. Bioinspired structural arrangement: (a) — Option A Diptera; (b) — Option B Neuroptera; (c) — Option C Hymenoptera; (d) — Option D Plecoptera; (e) – Option E Odonata; (f) — Option F Hemiptera; (g) — Option G Orthoptera

3 Calculation results

For the two major types of layouts described (seven layouts for each), the stress-stress state under the action of a load has been determined. The mass, deflection, and stresses in the structure were analyzed. All of the considered structural arrangements have a safety margin factor of more than 1.5. This indicates the possibility of additional optimization of each option.

The selection was based on two criteria: mass and deflection. Figures 6 and 7 show the distributions of options of classical arrangements and bioinspired ones, respectively.

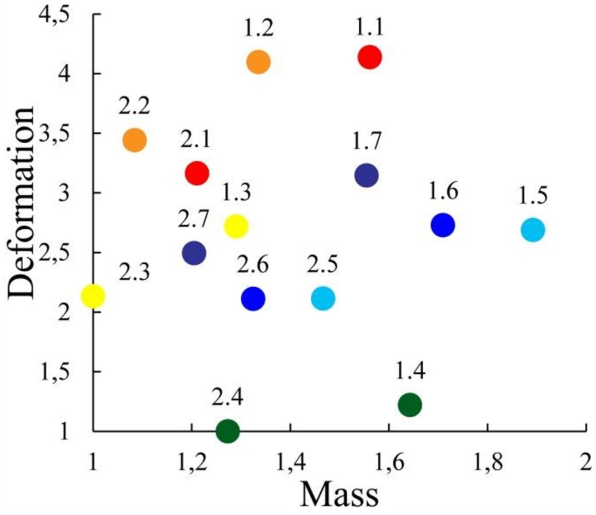

Fig. 6. Distribution of classical layouts by mass and deflection in relative units

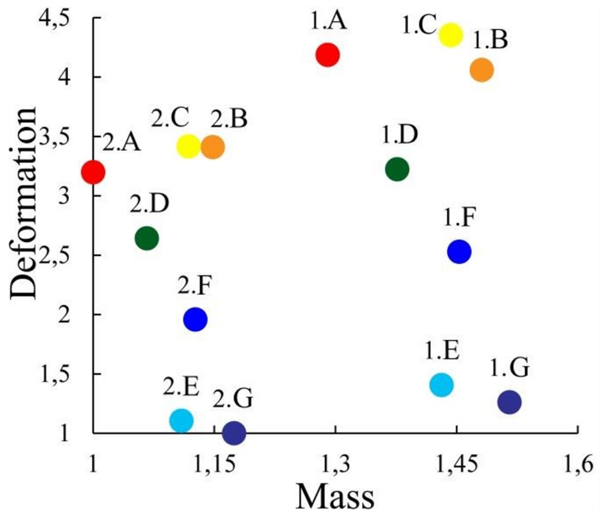

Fig. 7. Distribution of bioinspired layouts by mass and deflection in relative units

Options made of Fiberglass (index 1) are located further from the ideal center (IC). This is due to the higher density of the material. They are closest to the Options IC made of carbon fiber (index 2).

The optimal structural arrangement, 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):

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

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.

The most approximate classical arrangement was found to be option 4 with twenty-two thin-walled ribs. Its weight is 709.49 kg, with a maximum displacement of the end part of 72.10 mm, due to the rigidity of the structure. The optimal variant for a Bio-inspired layout is the E - layout based on Dragonfly wings, with a mass of 586.58 kg and a deflection of the end part of 64.67 mm.

As a result of the calculations, two classical and bioinspired structural arrangements were obtained, with a mass lower than the initial option (870 kg) by 19% (709.49 kg) and 32% (586.58), respectively.

4 Conclusion

Optimal layouts have been identified for the two main types of structural design described. A bioinspired structural layout of the wing based on the Odonata wing is proposed. The mass of the resulting optimized bioinspired is 20% less than the classical one, and compared to the initial one by 32% and is 586.58 kg.

It has been found that the wings of a bioinspired species based on insect wings have a high load capacity during flight and a lower mass. Bioinspired wings have no analogs in the world and are a new promising direction in aviation.

This study is the initial stage of work in the field of bioinspired structures.

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