AEROELASTIC TAILORING OF COMPOSITE WING BY USING MULTIDISCIPLINARY DESIGN ENVIRONMENT

K.A. Balunov*, V.V. Chedrik*, F.Z. Ishmuratov*
*** Central Aerohydrodynamic Institute (TsAGI)**

Keywords: *MDO, shape optimization, aeroelastic tailoring*

Abstract

The paper considers different aspects of aerostructural optimization of civil middle-range aircraft wing. The shape optimization aimed at determining the reasonable sweep angle of the wing tip part is performed. Observations from parametric studies of the influence of the orientation of an unbalanced layer and its percentage fraction in the composite laminate on the aeroelastic and strength characteristics of the wing are discussed. Several aspects and preliminary results of multidisciplinary optimization of the wing with tailored composite wing tip part are presented.

1 Introduction

Modern requirements to the efficiency of aviation structures [1] pose new challenges at the design of advanced aircraft structures. One of the main components of the aircraft influencing its efficiency is its wing, therefore great attention was paid to the development of methods and technologies directed on the design of the efficient wing structures during the whole time of aviation development. The important challenge at wing design of a modern passenger aircraft is account of wing flexibility. This requires simultaneous consideration of such disciplines as aerodynamics and structures at the early design stage. In recent decades, multidisciplinary optimization becomes a key technology to improve current designs and to explore new design spaces. It allows to take into account concurrent requirements issuing from these disciplines and influencing on the final design.

Another aspect that allows to obtain more efficient designs is a gradual increase in the application of composite materials in major and highly loaded structural components to take advantage of beneficial strength-to-weight characteristics. That is why the new generation civil airplanes like A350, B787 and Russian MC-21 contain a large percentage of composite material in their structures. Currently, the aeroelastic tailoring approach is actively developing to study the influence of anisotropic properties of composite laminates on aeroelastic and strength characteristics [2-4] of a structure. The benefit can be reached by change of the stiffness characteristics and the passive coupling between bending and torsion deformations of the wing. As an example, the so-called washout effect (when wing positive bending causes nose-down twist) leads to load alleviation at the wing tip part and therefore reduces the bending moment along the wing, which consequently allows to reduce the structural weight of the wing. Unfortunately, the application of composite materials is associated with the increasing complexity in the optimization process. It is necessary to include many additional parameters influencing on final design. Among these parameters are: laminate thickness, ply orientation, percentage fraction of layers in the laminate. It is worth noting that some of these parameters are discrete in their nature. For example, blending constraints (ply continuity in zones of laminates with different stacking sequences) which are necessary to provide manufacturability of a structure.

The paper is divided into three parts. The first part is devoted to the topic of shape optimization aimed at determining the reasonable sweep angle of the wing tip part (WTP), which makes it possible to obtain lighter wing structure while satisfying stress and flutter constraints. The second part of the paper is about parametric studies of the influence of the orientation of an unbalanced layer and its percentage fraction in the laminate on the aeroelastic and strength characteristics of the wing. Final part presents several aspects and preliminary results of multidisciplinary optimization of wing with tailored composite wing tip part.

2 Problem of Aerostructural Optimization of Civil Middle-Range Aircraft Wing

The aeroelastic optimization problem was formulated in details in [5]. The problem was to determine the sweep angle of the wing tip part together with structural parameters, such as skin and web thicknesses, cross section areas of spar and rib caps and etc., that minimize the structural weight and provide the best aerodynamic performance in cruise flight. The research subject was a middle range aircraft and its FE model is shown in Figure 1. Its main characteristics presented in Table 1. The internal load-bearing structure of the wing is shown in Figure 2.

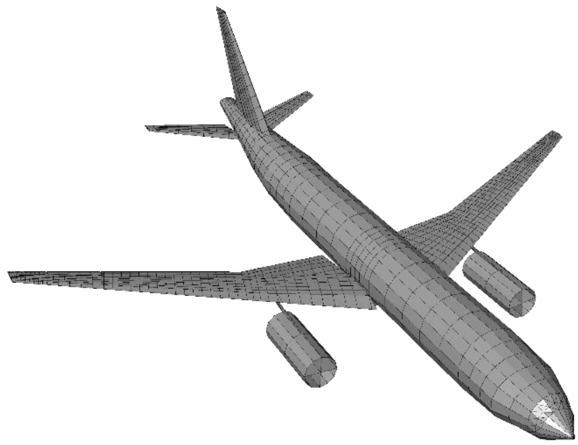

Fig. 1. Finite-Element Model of the Considered Aircraft

Table 1. The Main Parameters of the Aircraft

Maximum take-off weight	76.5 ton
Airplane length	42 m
Wing area	128 m^2
Wing span	40 m
Aspect ratio	12.5
Mean aerodynamic chord	3.58 m
Wing sweep angle of ¼ chord line	29°

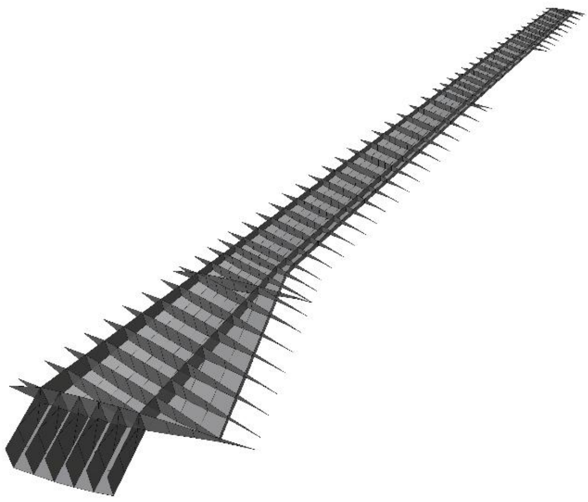

Fig. 2. The Internal Load-bearing Structure of the Wing

The doublet-lattice method is used for aerodynamic load calculations for three symmetric quasi-static load cases with limit factor of 2.5g. The twist angles are set in root, kink and tip sections of the aircraft wing.

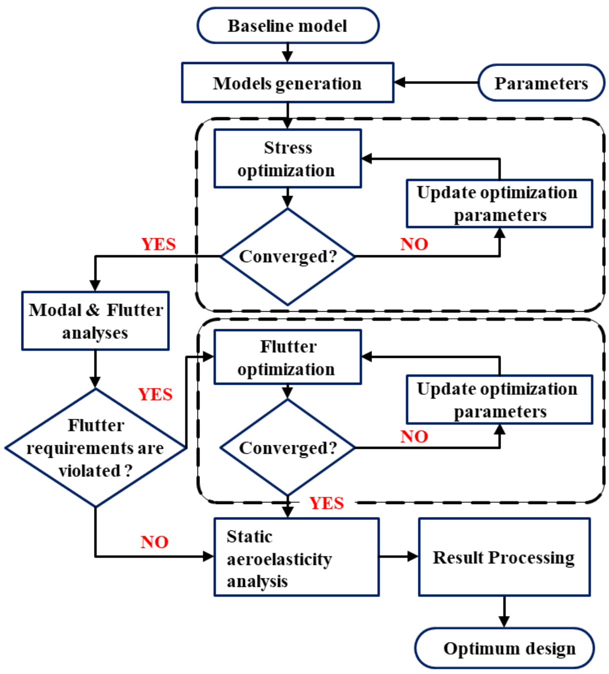

Fig. 3. The Flow Chart of Optimization Procedure

For optimization purposes the design model was prepared, it consists of 174 design variables that include domains of skins, spars, ribs and stringers of the wing. During the optimization problem the constraints on strength and flutter speed are imposed. The allowable stresses for aluminum alloy are chosen to be equal to 400 MPa for upper skin and 300 MPa for lower skin. For parts made of composite material the allowable stress for laminate is limited to 280 MPa with taking into account the shear stresses. The speed limit for the considered aircraft is V_D=186 m/s EAS at M=0.82, according to the National Aviation Rules it is necessary to provide the flutter speed more than $1.2V_D$ = 224 m/s.

The optimization procedure is performed in two stages: the structural optimization with stress constraints on the first stage and the optimization with flutter constraints on the second stage. The flow chart of the used aerostructural optimization procedure is shown in Figure 3. The additional static aeroelasticity analysis is carried out for the final design.

3 Determination of Preferable Sweep Angle of WTP

In this paper, the range of the sweep angles of the WTP is limited from 21° to 42° degrees along the leading edge of the wing. Two models with the corresponding maximum possible deviation angles are shown in Figure 4.

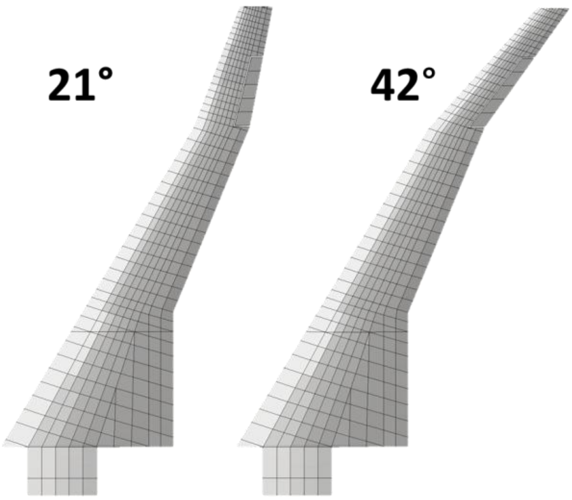

Fig. 4. Wings with 21° and 42° Sweep Angles of WTP

The account of elasticity for high-aspect ratio wings is a necessity at wing designing as it allows substantially decrease the bending moment practically in all sections of the wing. Initially loads were computed for the dominant load cases for "rigid" aircraft. For these loads the obtained optimum mass for baseline model (without kink at wing end) after stress optimization stage was 2660.7 kg. Whereas the obtained optimum structural mass at design for the "elastic" loads is 19% lighter and equals to 2155.2 kg. Therefore, further results are given only for elastic loads.

The obtained structural weights for first and second stage of optimization are shown in Figure 5. As can be seen the differences in the structural masses for two stages are almost the same for the range in question. It was also noted that the biggest difference in thicknesses for two stages was observed in area of front spar and skin between root section and section of engine attachment.

The obtained optimal sweep angle is about 40° with the corresponding mass of structure of 2173.4 kg. Note that the optimum design is lighter by 6.7% than for the baseline configuration.

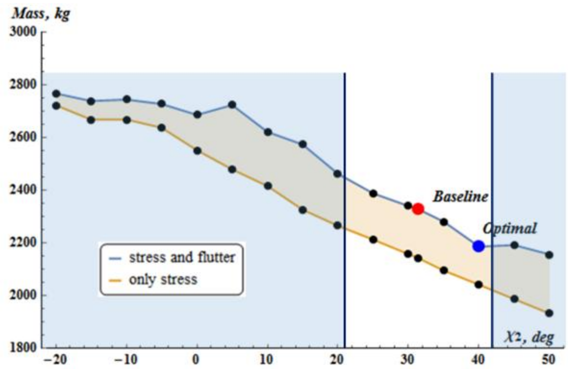

Fig. 5. Dependence of Structural Mass on Sweep Angle of WTP

4 Parametric Analysis of Wing with Composite Tip Part

The results described in the previous section were obtained by changing the geometry of the wing in WTP, but how much can be gained by additionally controlling the stiffness of the WTP by introducing a composite material?

To answer this question, the parametric analysis was performed. This study is interesting for both cases: with and without change of planform shape of the wing. The varied parameters are the orientation and the percentage fraction of an unbalanced layer of a composite laminate. The range for the parameter of orientation is chosen to be from -30° to +30° with respect to the stiffness axis and for the parameter of percentage fraction of an unbalanced layer is chosen to be from 44% to 76% of total laminate thickness. The characteristics of a ply used are the following: E_1=125.5 GPa, E_2=11.2 GPa, μ_{12}=0.31, G_{12}=5.15 GPa. The laminate stacking sequence during parametric analysis is 45°/45°/UL/UL/90°/UL/UL/45°/-45° where UL means unbalanced layer. The directions of orientation of unbalanced layer are shown in Figures 6-8.

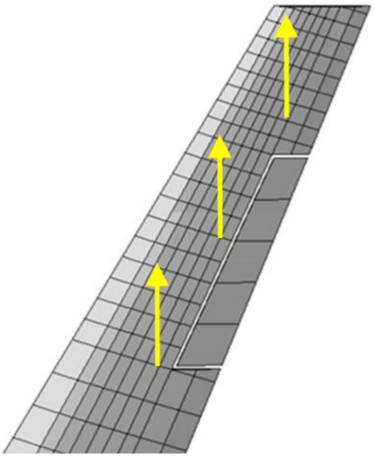

Fig. 6. The -30° Direction of Unbalanced Layer

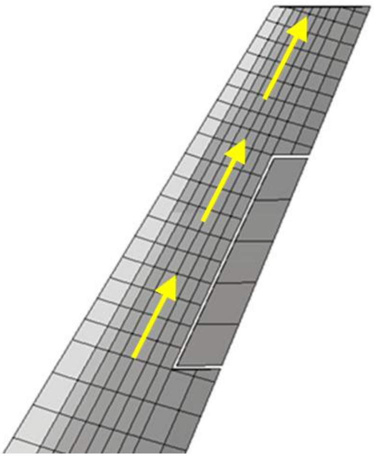

Fig. 7. The 0° Direction of Unbalanced Layer

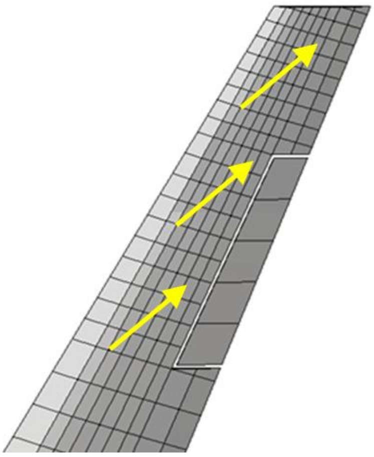

Fig. 8. The +30° Direction of Unbalanced Layer

Figures 9-11 shows the obtained displacements of wing tip parts with -30°UL and 30°UL variants as well as for aluminum material.

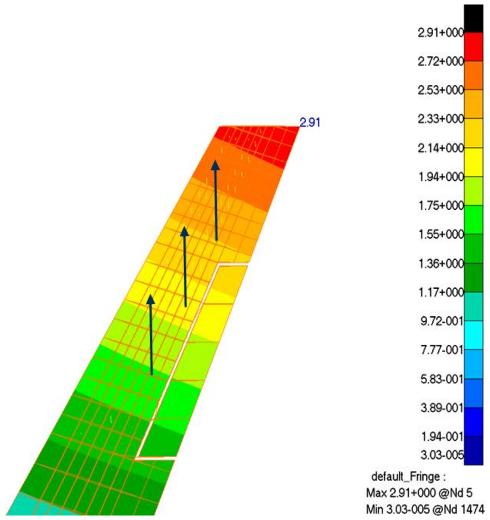

Fig. 9. Displacements for Composite WTP with -30° Direction of UL

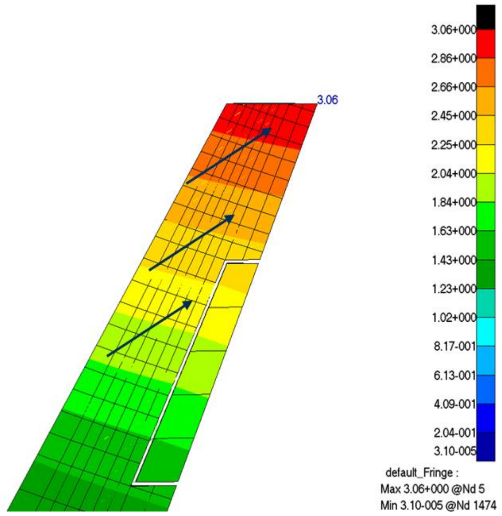

Fig. 10. Displacements for Composite WTP with +30° Direction of UL

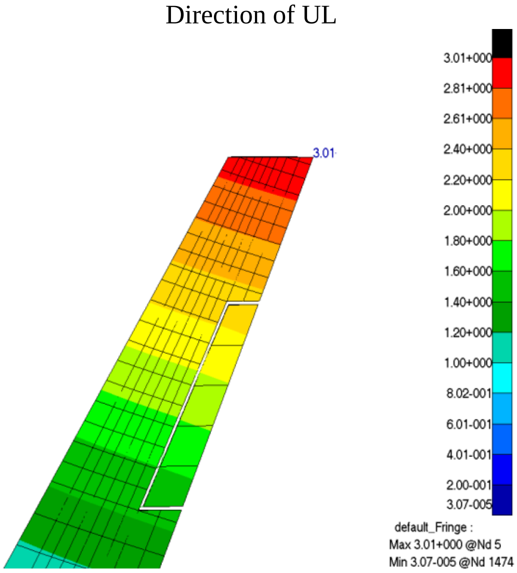

Fig. 11. Displacements for Aluminum WTP

The obtained minimum maximum displacement is observed for variant with -30° direction of UL with its fraction of 76% in composite laminate. It is 3.5% less than for aluminum alloy variant. From the displacement field it can be seen that elastic nose-down twist angles for the -30° variant are significantly higher than for the aluminum and the +30° variants. Although the 76% fraction of UL seems large at first look, the stress analysis shows that the strength in the WTP is satisfied because of low bending moments.

Figure 8 shows the effect of the application of a composite material in the wing tip part on the distribution of the bending moment along the stiffness axis of the wing. The use of a laminate with the 76% fraction of -30° unbalanced layer makes it possible to reduce the bending moment by 2-5% practically in all sections of the wing due to the load alleviation at the wing end sections. Note that a more significant reduction up to 30% in the bending moment can be achieved by additionally changing the sweep angle of the WTP according to the approach described in the section 3 of the current paper.

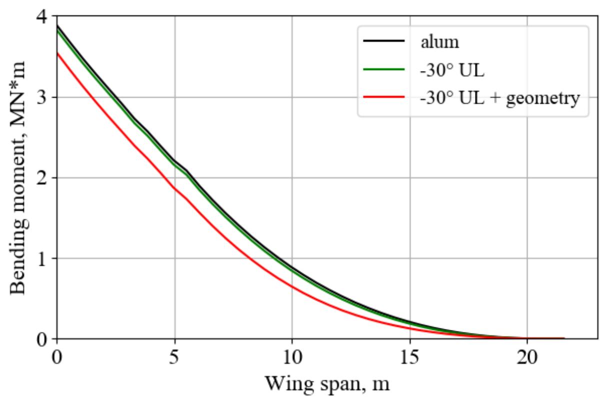

Fig 12. Bending Moment Along the Wing Span

Although even a slight increase in the sweep angle of WTP provides better flutter characteristics for the considered aircraft configuration [5], this change highly influences on the effectiveness of the outer aileron. The influence of the orientation of the unbalanced layer on the efficiency of the outer aileron is the same and shown in Figure 9. And for this type of requirement the -30° UL is not the preferable orientation for the laminate. The results of parametric studies showed that it is possible to find a compromise wing design using both aeroelastic tailoring and shape approaches.

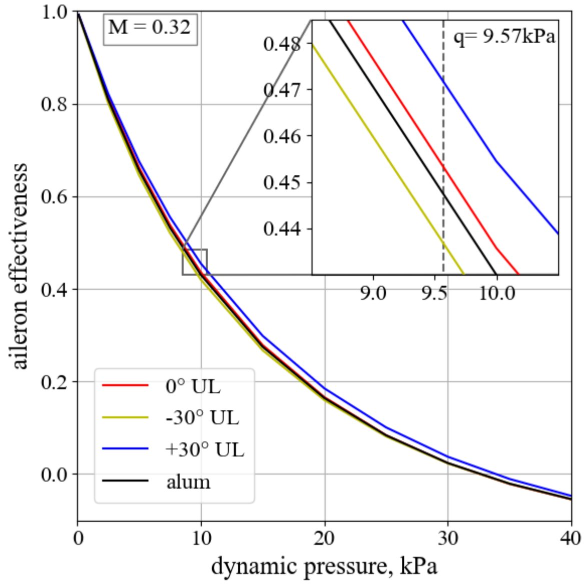

Fig. 13. Aileron Effectiveness for Different Orientations of Unbalanced Layer

5 Approach to Aeroelastic tailoring of WTP

In this section, we consider a hybrid variant of the wing, where the composite material is used only at the WTP, as shown in Figure 14.

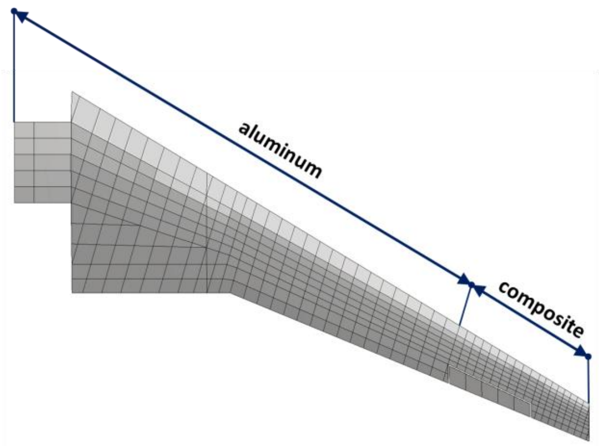

Fig. 14. Aluminum and Composite Sections of the Wing

Let's note that the use of direct methods of optimization allows to find only local minima which highly depends on the initial starting points and this circumstance is especially noticeable in the problems of aeroelastic tailoring. As was noted in the paper [6] with the wrong selection of the initial point the difference in the obtained optimum fiber directions leads to the up to 25% difference in value of objective function. Thus it is necessary to apply some physical intuition to obtain the initial reasonable fiber orientation.

One of apparent approaches is to place material in the direction of acting principle stresses, since this is the very direction in which the material will work most effectively, especially taking into account the anisotropic nature of the composite materials. So we propose to determine the initial fiber directions as the directions along the line of action of maximum principle stresses (by absolute value). These directions can be determined from the finite-element analysis of structure made of isotropic material and they are shown for models 24°, 31°, and 39° in their upper skins in Figures 15-17, correspondingly.

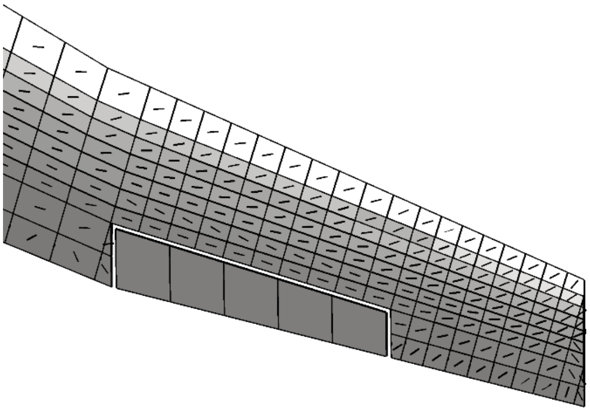

Fig. 15. Directions of Maximum Principle Stresses in Upper Skin for 24° Model

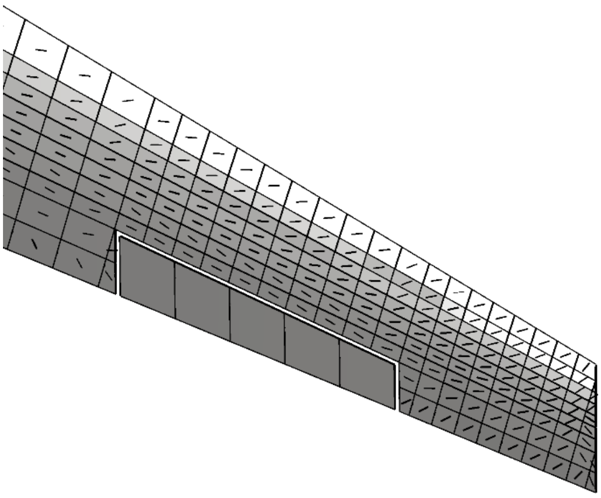

Fig. 16. Directions of Maximum Principle Stresses in Upper Skin for 31° Model (Baseline)

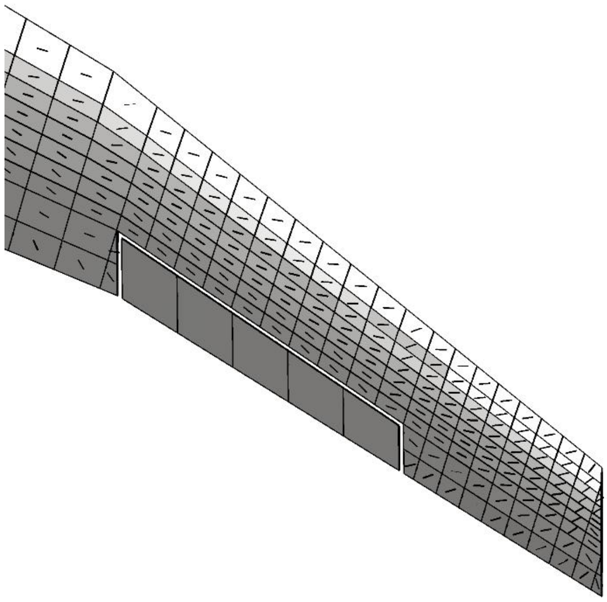

Fig. 17. Directions of Maximum Principle Stresses in Upper Skin for 39° Model

From the analysis of the stress directions, for all considered models, it can be seen that in wing-box these directions are from 10° to -40° with respect to the local stiffness axis and near the rear spar they are close to the spar direction. Additionally, taking into account the manufacturability requirements, it was determined that it would be prudent to break the projected area into 8 panels, 4 for the upper skin of the wing and 4 for the lower skin as shown in Figure 18.

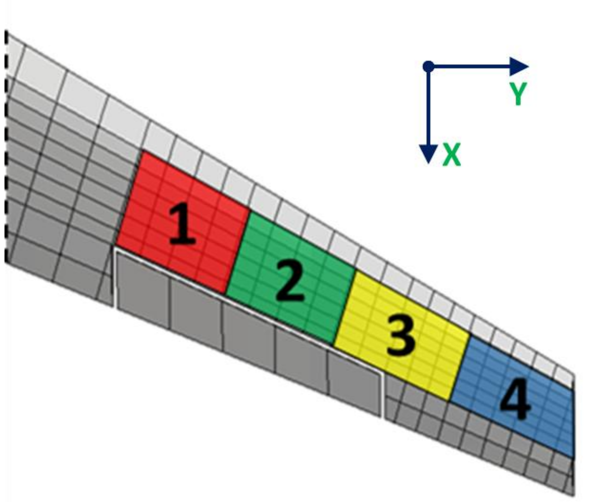

Fig. 18. Different Areas in the Upper Wing Skin

Note that in each of these areas the direction of the material for all elements is the same and is equal to the weighted average over the panel. As an example, the directions for the wing variants of 24° and 39° are listed in Table 2. The angles in the table correspond to the positive rotation from the x axis which is shown in Figure 18.

Table 2. UL Direction in Different Panels

#	WTP 24°	WTP 39°
Panel 1	78.26	59.97
Panel 2	82.05	62.83
Panel 3	89.00	72.94
Panel 4	85.13	63.37
Panel 5	76.57	57.93
Panel 6	82.52	62.28
Panel 7	90.79	72.77
Panel 8	80.46	61.44

Unfortunately, the results from aerostructural optimization of wing with WTP made from composite materials with the prescribed unbalanced layer directions showed that additionally only up to 2% of the wing mass can be saved. We find these results unconvincing, therefore, further research is needed.

6 Conclusion

Aerostructural optimization with taking into consideration stress and flutter constraints was accomplished. It allowed to determine the optimal shape of wing tip part and structural parameters such as skin/web thicknesses, spar/rib cross-section areas. The structural mass for the obtained optimal wing structure is about 6.7% less than one for optimized baseline configuration.

Numerical investigations were also directed to determine the reasonable placement of unbalanced layer of composite material at the wing tip part. The introduction of composite material into design process allowed additionally to decrease the structural mass of the wing by 2%. Therefore, further research is needed, and it will be directed to substantiation of the possibility and rationality of the introduction of composite material in such low loaded parts of the wing structure.

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8 Contact Author Email Address

mailto: kirill.balunov@gmail.com

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