STRUCTURAL OPTIMIZATION OF WING ELEMENTS OF AN UNMANNED AIR VEHICLE

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ABSTRACT –

The significance of lightweighting in aerospace industry is undeniable. Besides lowering the material costs, lightweight aerospace structures result in increased flight time and lower impact on the environment. Unmanned aerial vehicles (UAVs) display several advantages, largely because of the absence of crew on-board reduced design requirements, reduced operational cost, ability to operate under hazardous conditions and increased flight endurance. Modern aerospace structures are consisted of multilayered laminated surfaces which are fabricated easily due to the evolution of the manufacturing methods

In this study, the wing module of an UAV made of composite materials is investigated. The main goal is weight minimization while maintaining the highest stiffness possible. Air pressure distribution and acceleration loads, from CFD simulations, have been included in the procedure, describing loads acting to the structure during flight. During the optimization task, for each layer, both thickness and orientation are used as design variables. Compliance, stiffness described by displacements and failure index values are used as constraints during the procedure. Results are obtained by utilizing extensive use of automatization tools involving Python scripting in both ANSA pre-processor and META postprocessor. They include both thickness and failure index distribution over the surfaces.

TECHNICAL PAPER -

1. INTRODUCTION

UAVs (Unmanned Aerial Vehicles) are aircrafts that do not require a human pilot on board. Instead, they are controlled remotely by a human operator or are programmed to operate autonomously. UAVs come in a variety of sizes, from nano, spanning less than 10 cm and weight 200 grams to super heave, weighting more than 20000 kilograms and span more than 10 meters [1]. They are used for a range of purposes, including military operations, aerial photography, mapping and surveying, search, rescue, and delivery services. Despite their extensive use, high manoeuvrability, cost-efficiency, they are still limited in terms of endurance, flight autonomy and flight time to perform their missions. The structural weight must be kept as low as possible because it directly affects all characteristics of the vehicle [2].

Wings are major elements of an aerial vehicle producing most of the lift forces required for all stages of flight. Bending and torsional loads are acting, resulting wing deformations which affects the strength and the aerodynamic characteristics. The wing is formed by three major structural elements, skin, spars, and ribs. Skin is responsible to maintain the external surface of the wing during all phases of flight. Spars are the principal structural members of the wing. They are placed from the fuselage to the tip of the wing taking over most of the forces. Ribs are structural crosspieces of the wing extending from the leading edge to the trailing edge of it. They reinforce locally the skin from buckling phenomena and transfer the loads from the skin to the spars.

In this paper, a structural optimization process of a wing will be presented. Flight load cases are assumed and CFD simulations are employed to introduce pressure loads to the model. Manufacturing constraints are considered during the task. The optimization procedure includes translational and failure index constraints. Main goal is to minimize weight of the wing and at the same time, controlling its deflection. Smart software tools are employed, since for each iteration, a new FE model has to be created, and results are obtained automatically.

2. REFERENCE AIRCRAFT PLATFORM

The RX-3 UAV is the experimental prototype which was developed as a result of the DELAER project and is used as a reference platform for the scope of this study. Its mission is to perform aerial delivery of lifesaving supplies, which are stored in its cargo bay, to islands and mainland territories in Greece [3]. It is based on the Blended-Wing-Body configuration (BWB) where the wings smoothly blends into the main body (center body) of the aerial vehicle. Through a careful sizing of its outer wing and center body, the platform is inherently stable and no empennage component is used. Therefore, the BWB features a reduced wetted area and, consequently, a higher aerodynamic efficiency, when compared to a conventional tube-and-wing configuration. The three-axis control is achieved through a combination of elevons, i.e., combined elevator-aileron control surfaces located at the horizontal part of the outer wing, and ruddervators, which are placed on the winglets act as a combined rudder-elevator control surface. Fig. 1 presents the main characteristics of the RX-3. Its control surfaces are depicted with red colour.

Parameter	Value
Length	4.15 m
Wingspan	7.15 m
Maximum take-off weight (MTOW)	190 kg
Payload	40 kg
ICE Powerplant	54 hp
Max speed	250 km/h
Cruising speed	180 km/h
Endurance	2 hours
Range	130 km

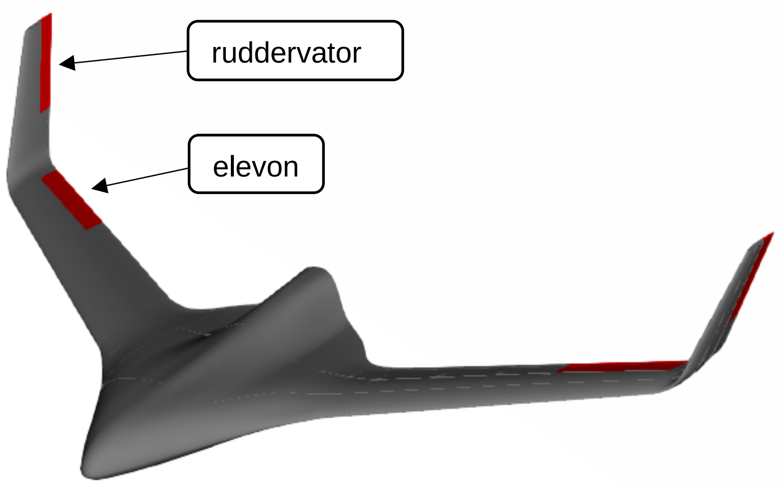


Fig.1: Rx-3 UAV key characteristics [4].

This study is focused on the structure of the wing module of the reference platform. Two spars are placed inside the wing, on the 33% and 67% of the leading edge respectively. Each spar's cross section is chosen a "C" type, due to its combination of high bending stiffness and its manufacturability. A total number of 9 ribs, evenly distributed on the wing is chosen. The internal configuration is presented below (**Fig.2**).

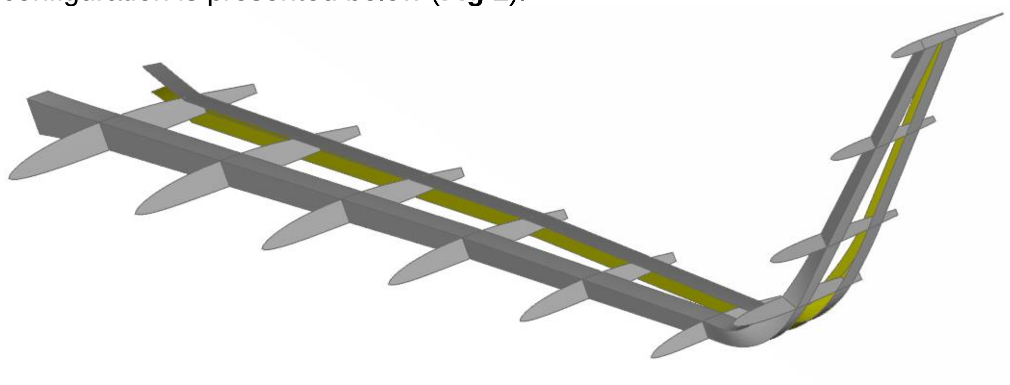


Fig.2: Internal structure.

3. FE MODELING AND OPTIMIZATION

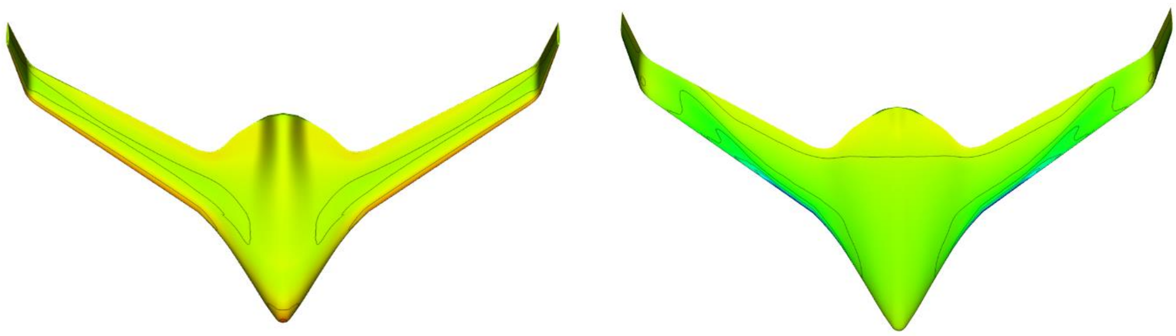
Geometry clean-up and mesh generation

The CAD software used for the structural design is Autodesk Inventor 2023. The geometry is translated to the ANSA pre-processor using iges neutral files including the assembly's part hierarchy. The skin, spars and ribs are connected using triple cons for simplicity. Quad-dominated mesh is generated using 15mm element length resulting in a total number of 2118 triangular and 48619 quadrilateral high-quality elements.

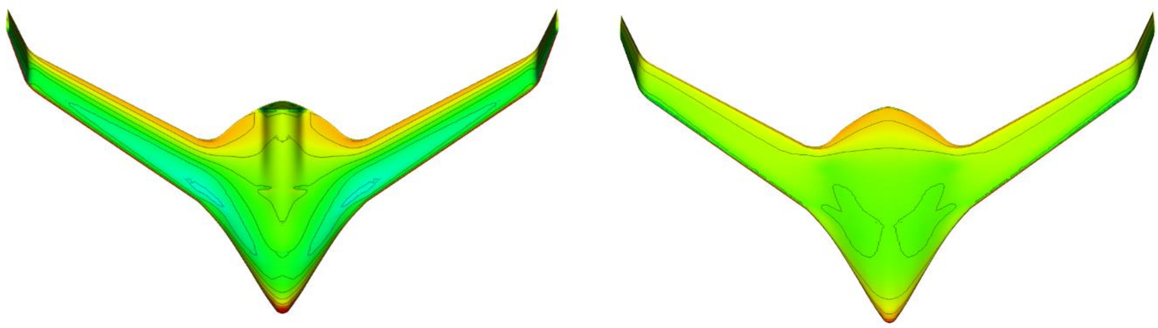
Flight loads and boundary conditions

Three flight load cases are considered for the study. At first, pressure results in Pascals are presented for the upper and lower surfaces of the vehicle (**Fig.3**).

- Maximum Speed (Angle of Attack: 0º, Load factor: 1.69 g's)



- Maximum Positive Turn (Angle of Attack: 8º, Load factor: 3.23 g's)



- Maximum Negative Turn (Angle of Attack: -8º, Load factor: -1.56 g's)

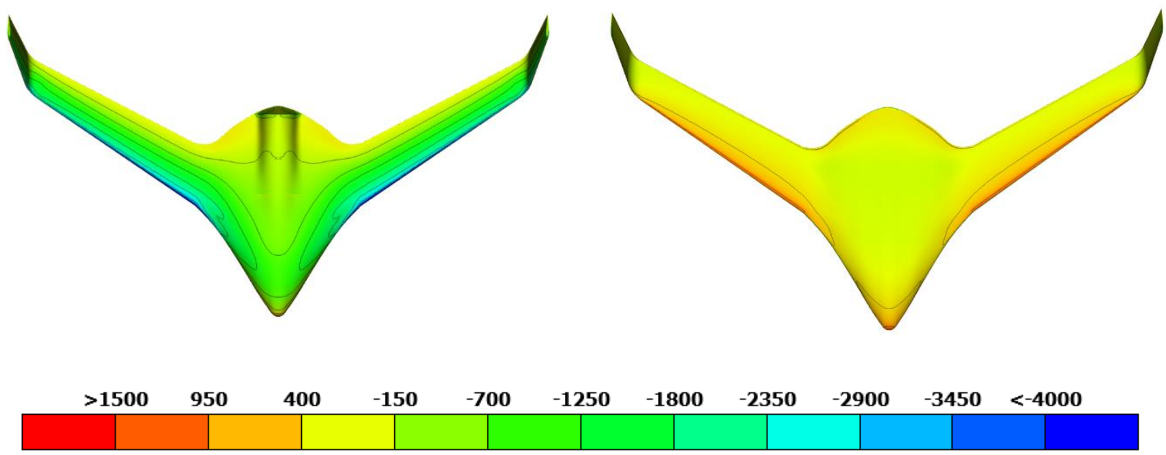


Fig.3: Pressure results in Pascals for the upper and lower surface (Upper surface is placed in the left-hand side and lower in the right).

Pressure results are mapped from the CFD simulation files to the structural mesh. Due to the incompatibility between the CFD and the structural mesh, mapping is carried out by using scripts from the Python collection library included in ANSA. In addition to pressure, acceleration loads are created for each load case using DLOAD-GRAV entities considering the angle of attack and load factor.

The mass of two sub-systems describing the control surfaces actuators (including servo actuators and the links) are placed in the wing, assuming a weight of 1.5 kilograms for each sub-system. They are described by MASS entities and connected to the wing and the winglet using COUPLING entities. The spars on the wing's root are considered fixed during the analysis. **Fig.4** presents the MASS (magenta spheres), COUPLING (blue "spider") entities and the boundary conditions (blue points).

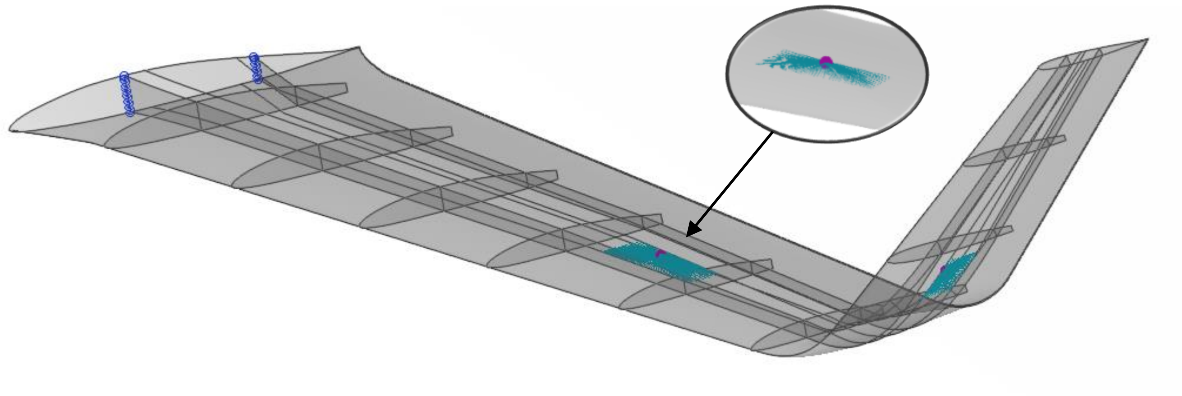


Fig.4: MASS, COUPLING, and boundary conditions entities.

<u>Material properties</u>

The wing is composed entirely of composite materials. Two types are used and presented below (**Table 1**).

Table 1: Material properties.

Type	Density [tn/mm^3]	E_1 [MPa]	E_2 [MPa]	v_{12} [-]	G_{12} [MPa]	G_{13} [MPa]	G_{23} [MPa]
Twill	1.52 10^{-9}	61000	61000	0.05	2800	2800	2800
	t [mm]	X_t [MPa]	X_c [MPa]	Y_t [MPa]	Y_c [MPa]	S [MPa]	
	0.25	995	-750	870	-700	80	

Type	Density [tn/mm^3]	E_1 [MPa]	E_2 [MPa]	v_{12} [-]	G_{12} [MPa]	G_{13} [MPa]	G_{23} [MPa]
Uni-directional	1.60 10^{-9}	100000	8000	0.05	4500	4500	4500
	t [mm]	X_t [MPa]	X_c [MPa]	Y_t [MPa]	Y_c [MPa]	S [MPa]	
	0.25	1000	-550	20	-20	80	

The material orientation in the model is an essential parameter for the simulation of composite materials as it determines the reference direction. For the skin and spars, the main direction is defined along the width of the vehicle. Considering the rib elements, they are defined vertically to the cross-section of the wing.

<u>Thickness configuration</u>

The **Table 2** illustrates the layout configuration and the group of the design variables.

Table 2: Laminate configuration.

Area	Sub-area	Orientation values	Thickness values	Orientation allowable values	Thickness allowable values
Skin	-	45/0/45	Const.	Const.	Const.
Ribs	-	45/DV_{1UD}/45	0.25/DV_2/0.25	0, 22.5, 45, 67.5, 90	0.05, 0.25, 0.5, 0.75, 1.0
Spars	Flanges	45/0_{UD}/45	0.25/DV_3/0.25	Const.	0.05, 0.25, 0.5, …, 2.0
	Webs	45/0/45	Const.	Const.	Const.

As presented, the laminate configuration of the skin surfaces is constant during the analysis. The configuration of the ribs is consisted by two outer 45º plies and one unidirectional ply in the middle. Thickness and orientation variables for the middle ply are defined as a group of design variables (DV_{1UD} and DV_2). The configuration of the spars is separated into two sub-areas. First, the layout of the webs which is constant. Second, the layout of the flanges which is consisted of two external plies oriented to 45º and one unidirectional ply. The thickness of the unidirectional ply is defined as a group of design variables (DV_2).

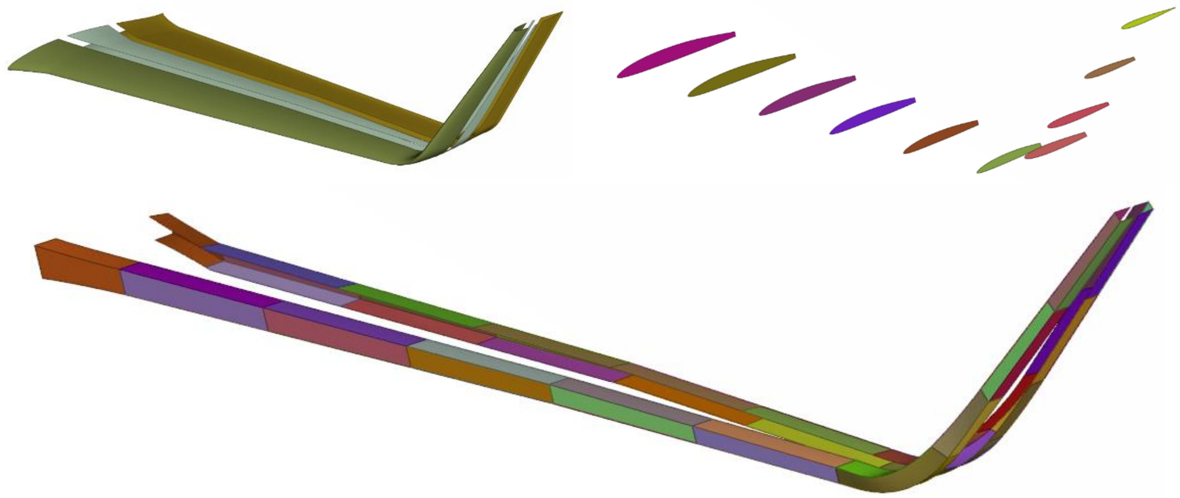


Fig.5.: Skin, spars, and ribs properties definition. The distribution of the properties is illustrated in terms of colour variance.

As described in **Fig.5**, the spars are divided along the width of the wing into 9 sub-properties. Furthermore, the flanges are divided into upper and lower surfaces. Thus, the total number of design variables of the spars are 36. In addition, the design variables describing the ribs are 18 containing both thickness and orientation variables resulting a total number of 54 variables for the analysis. The initial values for both the thickness and orientation design variables are chosen as the minimum allowed values, 0.05 for the thickness and 0º for the orientation variables. In fact, 0.05 mm thickness value is not reasonable, but 0 mm thickness value is not acceptable in the laminate property card.

Constraints

Two different types of constraints are imposed to the optimization:

- **Translational displacement (*dz*)**
  This constraint is imposed to control the deflection of the wing due to bending. The maximum value is frequently defined as a portion of the vehicle's wingspan, usually below 5%.
- **Failure Index (*F.I.*)**
  This constraint is imposed to control the strength of the model by introducing an upper bound to the Max Stress Failure index criterion.

Optimization problem description

The optimization algorithm used is named NLPQLP which is a special implementation of a sequential quadratic programming (SQP) method. Proceeding from a quadratic approximation of the Lagrangian function and a linearization of constraints, a quadratic programming subproblem is formulated and solved. The mass of the structure is obtained by reading a text file created on each iteration by the execution of a Python script from ANSA in batch mode. The optimization problem is mathematically summed up below:

$$minimize \quad weight$$

$$subject\ to:$$

$$-100\ mm \leq dz \leq 100\ mm$$
$$Failure\ Index\ \leq 0.9$$

$$and$$

$$DV_{1UD} = 0, 22.5, 45, 67.5, 90$$
$$DV_2 = 0.05, 0.25, 0.5, 0.75, 1.0$$
$$DV_3 = 0.05, 0.25, 0.5, \dots, 2.0$$

Considering that the above constraints, must be satisfied for all load cases, thus the total number of constraints for the optimization procedure is 6.

4. RESULTS

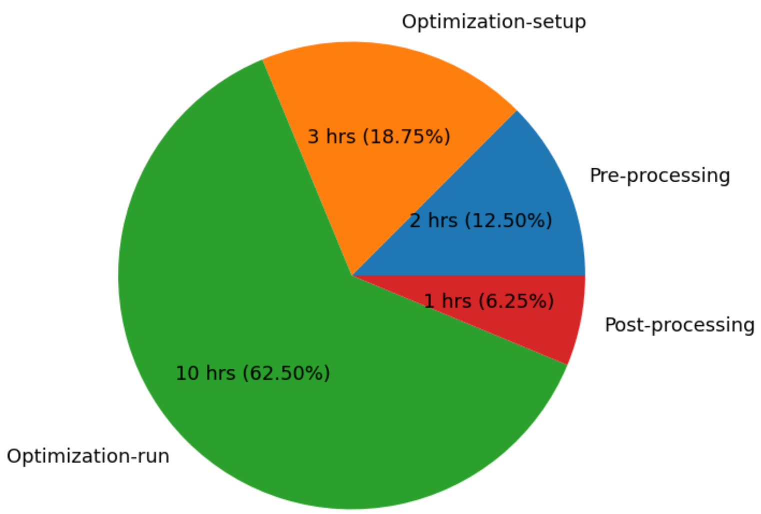


Fig.6: Total run time.

Total clock time required for all steps of the process is 16 hours. On **Fig.6** the portion of the time required for each process is described. All processes were carried out in an i7 3rd generation CPU (4 cores / 8 threads) and 64GBs of RAM. The chart does not include the time needed for the CFD simulations. The iterations of the optimization were carried out in series. It's clear that both pre- and post-processing procedures demand only around 20% of the overall time. Objective function values are presented versus iterations in the next diagram (**Fig.7**).

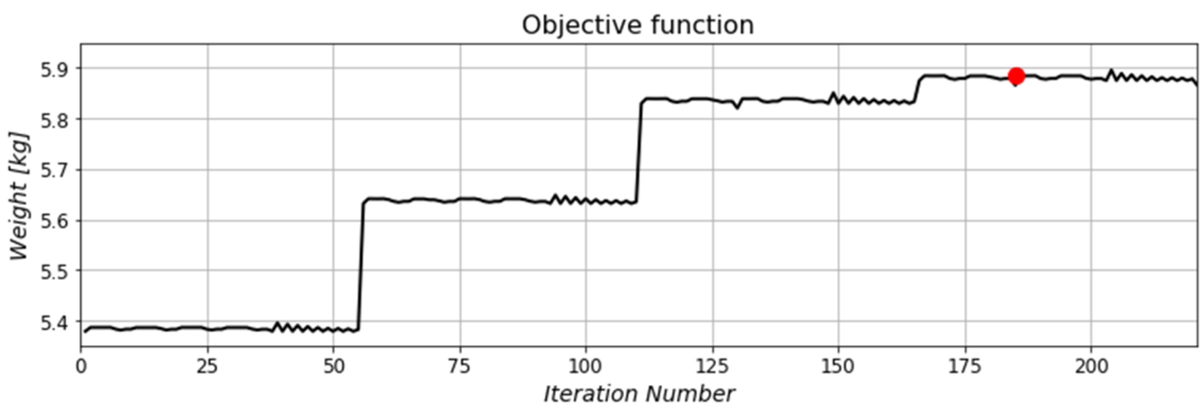


Fig.7: Objective function values.

As mentioned, the initial thickness values are the minimum allowed for each design variable. As a result, the first iterations produce solutions with minimum weight but violate the constraints. During the optimization the thickness values are increased to fulfil the constraints, so the total weight is increased. Next, constraint values are presented versus iterations (**Fig.8**).

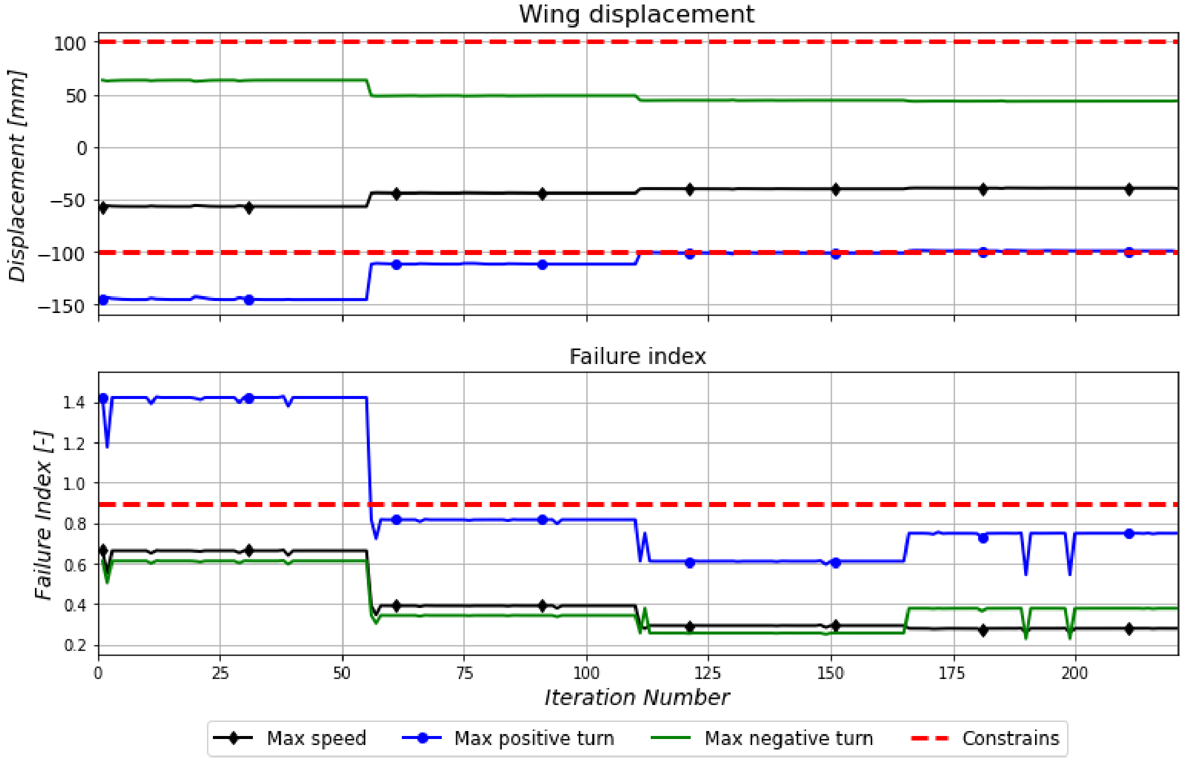


Fig.8: Constraints values.

As seen in **Fig.7** and **Fig.8** the "Max positive turn" load case is the most demanding case for all types of constraints. The mass of the wing starts from 5.4 kilograms and the optimal design is finalized to 5.9 kilograms, an increase of 10%. On the other hand, the change on the constraint values is more than 50% highlighting the robustness and the efficiency of the workflow.

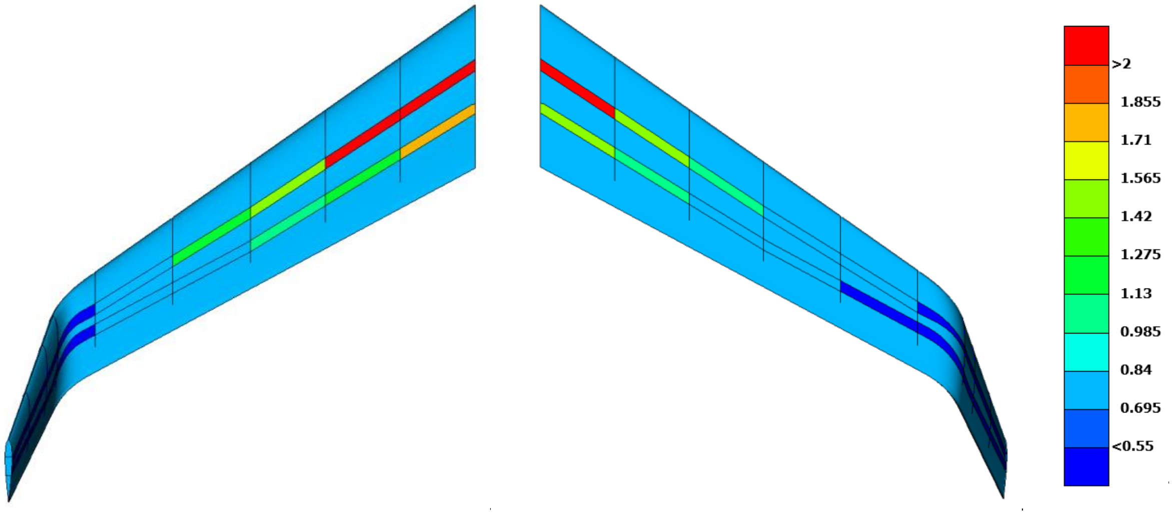
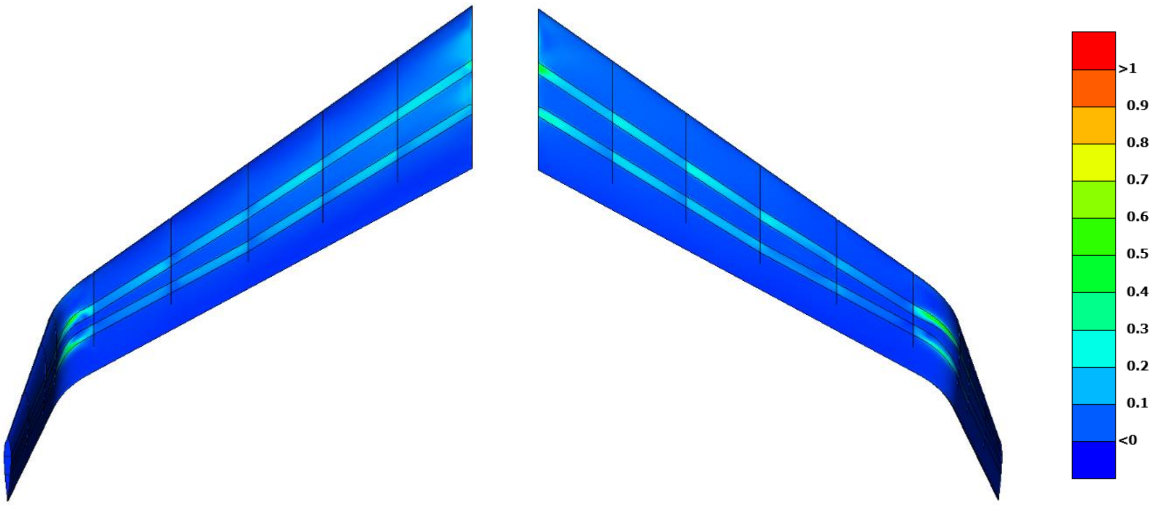


Fig.9: Thickness distribution.

Regarding the laminate configuration of the ribs, for all design variables, the resulting thickness is the minimum allowed (0.05 mm). The results are according to the theory where the ribs support the outer geometry of the wing locally than the wing behavior as a cantilever beam. Regarding the wing and the winglet, the figures (**Fig.9** and **Fig.10**) present the thickness and the failure index distributions respectively.



Upper surface Lower surface

Fig. 10: Failure index distribution in the “Max positive turn” load case.

5. CONCLUSIONS

Lightweight design is an extensively explored concept in many industries, especially in aerospace applications. Structures composed of laminate structures are multi-plied surfaces, described by many variables, at least two for each ply. By employing software-aided optimization tools, the design space is thoroughly explored and configurations that suit better to the imposed constraints are discovered. Manufacturing limitations are vital and counted on during the definition of the design variables.

To explore an optimum solution for the structural configuration of a wing element, the use of BETA CAE’s software suite is employed with the ABAQUS solver and the ISIGHT software, obtaining full compatibility between all software. The user effort for the whole optimization procedure is far smaller compared to the actual optimization run. Results demonstrate that the proposed design procedure’s outcome is a configuration that complies to all the constraints imposed. It was shown that ribs have negligible effect to the overall bending deformation of the structure. To minimize deflections in the wing the surfaces root should be stiffened.

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REFERENCES

[1] N. Elmeseiry, N. Alshaer, and T. Ismail, “A Detailed Survey and Future Directions of Unmanned Aerial Vehicles (UAVs) with Potential Applications,” Aerospace, vol. 8, no. 12, p. 363, Nov. 2021, doi: 10.3390/aerospace8120363.

[2] D.P. Raymer, Aircraft Design: A Conceptual Approach, 5 edition, Amer. Inst. of Aeronautics & Reston, VA, 2012.

[3] S. Kapsalis, P. Panagiotou, and K. Yakinthos, “CFD-aided optimization of a tactical Blended-Wing-Body UAV platform using the Taguchi method,” Aerospace Science and Technology, vol. 108, p. 106395, Jan. 2021, doi: 10.1016/j.ast.2020.106395.

[4] P. Panagiotou, D. Mitridis, T. Dimopoulos, S. Kapsalis, S. Dimitriou, and K. Yakinthos, “Aerodynamic design of a tactical Blended-Wing-Body UAV for the aerial delivery of cargo and lifesaving supplies,” in AIAA Scitech 2020 Forum, Orlando, FL: American Institute of Aeronautics and Astronautics, Jan. 2020. doi: 10.2514/6.2020-1958.