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COMPARATIVE STRUCTURAL ANALYSIS OF ALUMINUM AND COMPOSITE WING OF PASSENGER AIRCRAFT

Radoslav D. Radulović [1], Milica P. Milić [2], Xun Fei [3]

[1]University of Belgrade, Faculty of Mechanical Engineering,
Department of Mechanics, Kraljice Marije 16, 11120 Belgrade, Serbia
e-mail: rradulovic@mas.bg.ac.rs
[2] University of Belgrade, Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade, Serbia
e-mail: mmilic@mas.bg.ac.rs
[3] University of Belgrade, Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade, Serbia
e-mail: feixunlalala@gmail.com

Abstract:

This paper focuses on the conceptual design and structural analysis of winglets attached to the wings of passenger planes, with the aim of improving aircraft performance by reducing fuel consumption and increasing range. Winglets, which are upward and outward extensions of the wings, function by mitigating the drag induced by wingtip vortices. This study underscores the criticality of the winglets' design, as it must strike a balance between structural integrity and lightweight construction. To achieve these objectives, the study proposes the utilization of aluminum and composite materials in a thin-walled construction. Aluminum offers favorable strength-to-weight ratios, rendering it a commonly employed material in aircraft construction. In contrast, composite materials exhibit exceptional strength-to-weight ratios and excellent resistance to corrosion, making them highly suitable for lightweight constructions.

Key words: Conceptual design of wing, Static structural analysis, Composite and Aluminum material.

1. Introduction

The design of modern passenger aircraft wings has evolved to incorporate winglets, which are an essential feature for enhancing overall performance. Winglets, as extensions positioned upward and outward at the wingtips, serve the primary purpose of reducing fuel consumption and increasing the range of the aircraft. This study focuses on the conceptual design and structural analysis of winglets, with a specific emphasis on achieving the desired goals of fuel reduction and range enhancement.

2. Wing model for the structural analysis

One crucial aspect of the Finite Element Method (FEM) pertains to the subdivision of the domain. In this context, the utilization of Computer-Aided Design (CAD) software proves valuable as it facilitates the definition of an object's three-dimensional shape and enables the subdivision of the object into appropriately sized elements based on the desired mesh. The mesh, serving as a three-dimensional grid that outlines the elements, can be tailored to the specific problem at hand. It may comprise uniformly sized and shaped elements such as cubes or pyramids, or it can encompass elements of varying shapes and sizes across different regions of the domain.

By employing the finite element method, the model's behavior can be effectively visualized under designated boundary conditions. This software package offers notable advantages, including cost reduction in production and testing processes, as well as the optimization of geometry and weight. Such benefits are derived from the ability to accurately simulate and analyze the model's performance, enabling engineers to make informed decisions regarding design modifications and improvements.The first step is to import the model saved in the stp to softwear using the Import function. The model is scaled by a factor of 1000, in order to obtain the true dimensions of the model. View of the wing model is shown on figure 1.

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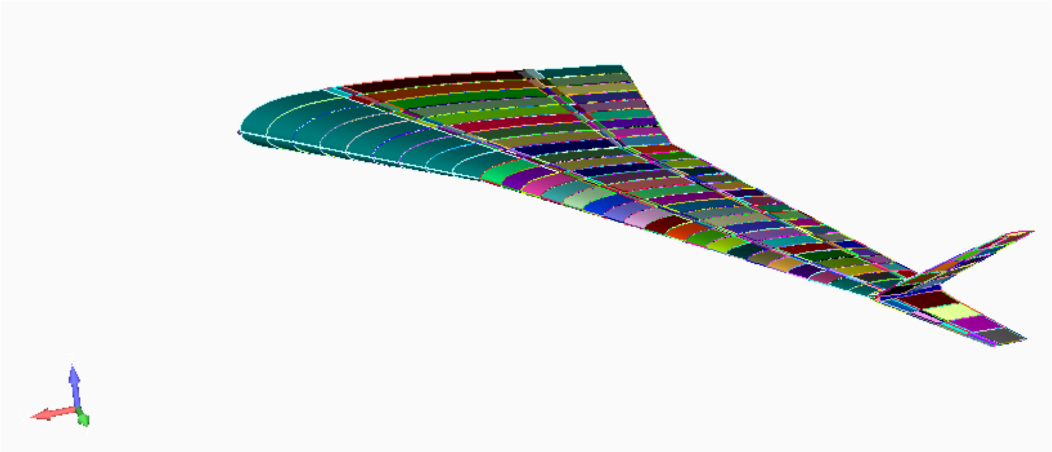
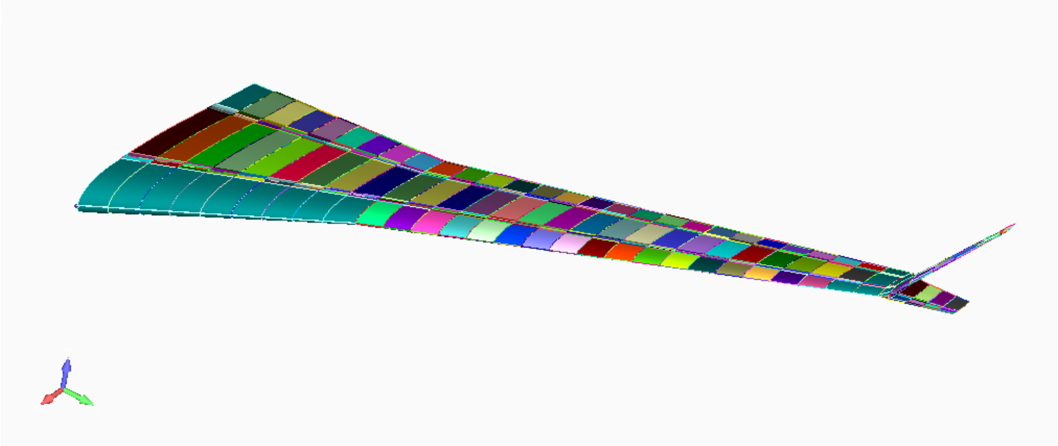


Wing model - Figure 1.



Wing model - Figure 2.

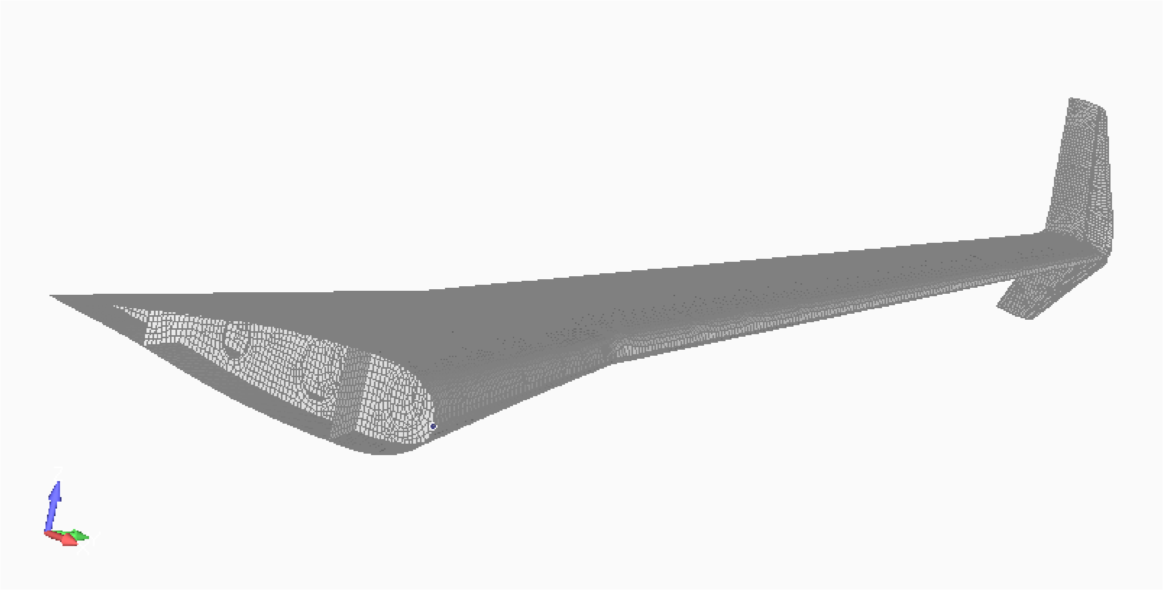
3. Allocation of materials and formation of a network of finite elements mesh

The process of material definition for an aluminum wing differs from that of a composite wing. For aluminum, it suffices to input specific parameters pertaining to the chosen aluminum material. On the other hand, for a composite wing, the process involves layering the laminae of the selected composite material.

Following the material selection, the subsequent step involves defining the properties in the dedicated section. Here, the thickness of the wing is established and assigned to each respective part of the structure. Subsequently, a finite element mesh is generated to facilitate further analysis. The mesh's appearance, as well as the size of the individual elements comprising the mesh, are determined in the Mesh section.

Lastly, the Boundary Conditions section is defined, encompassing the specification of external forces, moments, and restraints acting upon the structure. These boundary conditions are imposed upon the generated mesh, as depicted in Figure 3, to accurately represent the real-world operating conditions of the wing structure.

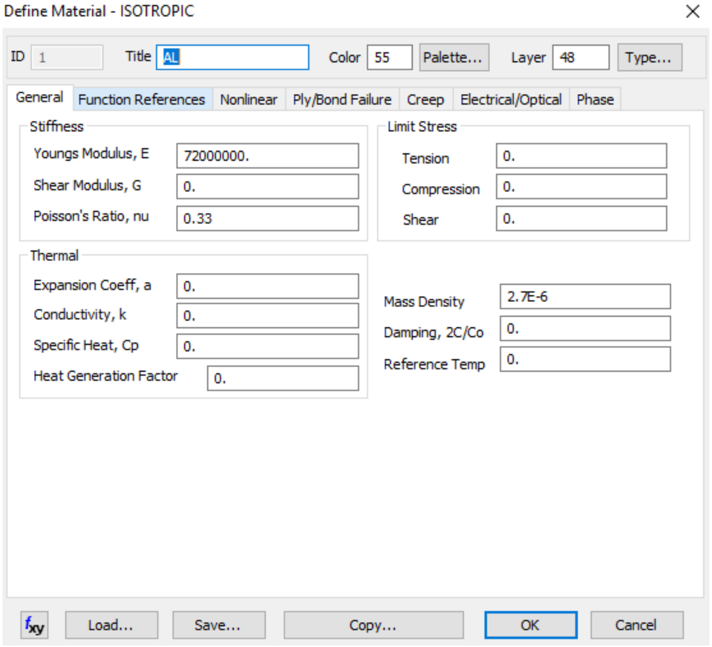
Wing mesh - Figure 3.



Wing mesh – Figure 4

4. Aluminum wing

The selected aluminum will be assigned as a material



Define Material - ISOTROPIC

ID 1
Title AL
Color 55
Layer 48

Stiffness
Youngs Modulus, E 72000000.
Shear Modulus, G 0.
Poisson's Ratio, nu 0.33

Limit Stress
Tension 0.
Compression 0.
Shear 0.

Thermal
Expansion Coeff, a 0.
Conductivity, k 0.
Specific Heat, Cp 0.
Heat Generation Factor 0.

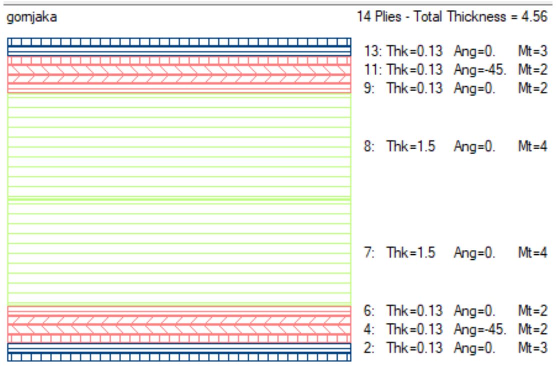
Mass Density 2.7E-6
Damping, 2C/Co 0.
Reference Temp 0.

Defining material - Figure 5

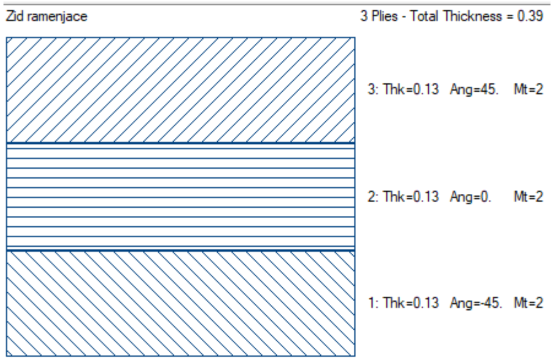
Element	Type of element	Cross section	Thickness [mm]	Material
Ribs	Plate	Rectangle	1.5	Aluminum 7075 T6
Front wall of spar	Plate	Rectangle	3	Aluminum 7075 T6
Rear wall of spar	Plate	Rectangle	2	Aluminum 7075 T6
Upper skin	Plate	Rectangle	1	Aluminum 7075 T6
Lower skin	Plate	Rectangle	1	Aluminum 7075 T6
Back spar	Plate	Rectangle	2.5	Aluminum 7075 T6
Front spar	Plate	Rectangle	3.5	Aluminum 7075 T6

Assigning the thickness and material to the elements of the structure – Table 1

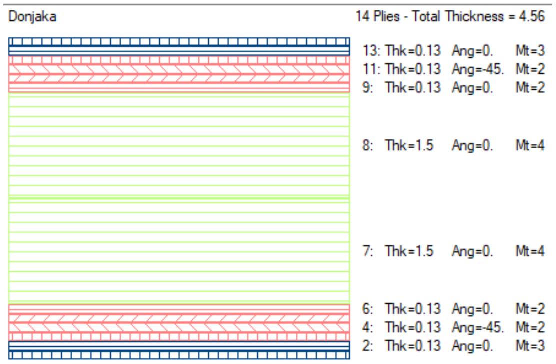
5. Composite wing



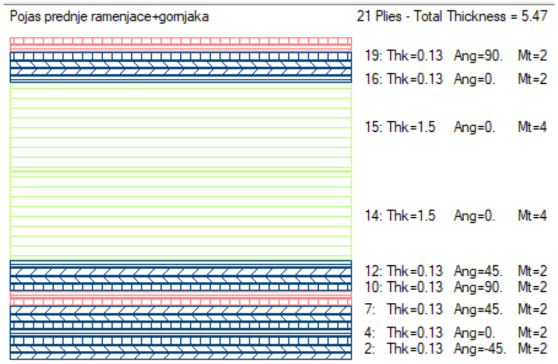
Layers of materials on the upper skin
Figure 6



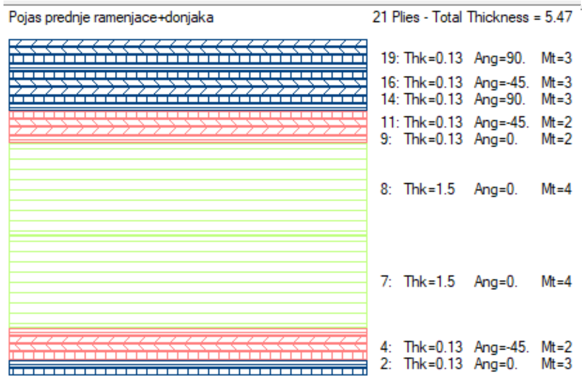
Layers of material on the wall of spar
Figure 7



Layers of materials on the lower skin
Figure 8

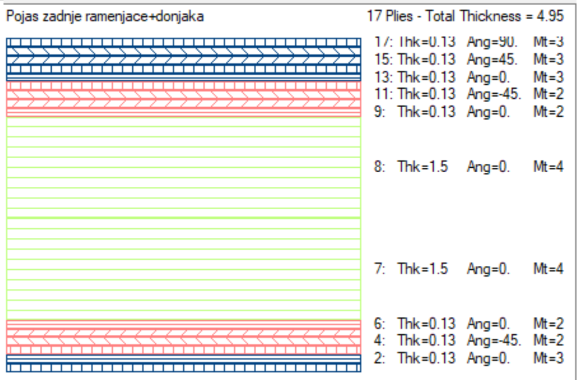


Layers of materials on the zone + upper skin
Figure9



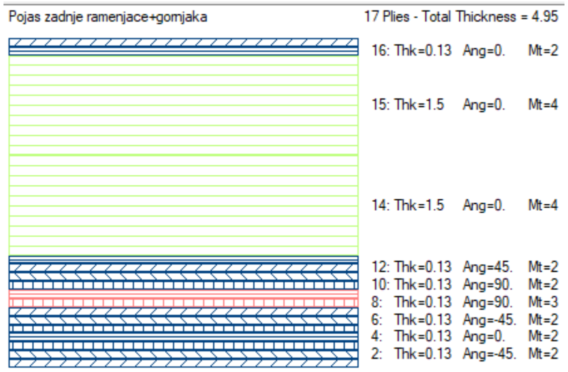
```
Pojas prednje ramenjace+donjaka          21 Plies - Total Thickness = 5.47
19: Thk=0.13  Ang=90.   Mt=3
16: Thk=0.13  Ang=-45.  Mt=3
14: Thk=0.13  Ang=90.   Mt=3
11: Thk=0.13  Ang=-45.  Mt=2
9:  Thk=0.13  Ang=0.    Mt=2
8:  Thk=1.5   Ang=0.    Mt=4
7:  Thk=1.5   Ang=0.    Mt=4
4:  Thk=0.13  Ang=-45.  Mt=2
2:  Thk=0.13  Ang=0.    Mt=3
```

Layers of materials on the zone+lower skin
Figure 10



```
Pojas zadnje ramenjace+donjaka          17 Plies - Total Thickness = 4.95
17: Thk=0.13  Ang=90.   Mt=3
15: Thk=0.13  Ang=45.   Mt=3
13: Thk=0.13  Ang=0.    Mt=3
11: Thk=0.13  Ang=-45.  Mt=2
9:  Thk=0.13  Ang=0.    Mt=2
8:  Thk=1.5   Ang=0.    Mt=4
7:  Thk=1.5   Ang=0.    Mt=4
6:  Thk=0.13  Ang=0.    Mt=2
4:  Thk=0.13  Ang=-45.  Mt=2
2:  Thk=0.13  Ang=0.    Mt=3
```

Layers of materials on the zone + lower skin
Figure11



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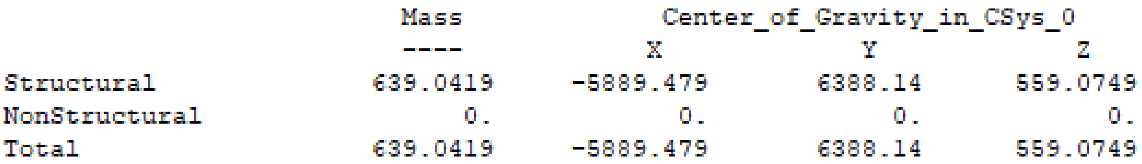
Pojas zadnje ramenjace+gornjaka          17 Plies - Total Thickness = 4.95
16: Thk=0.13  Ang=0.    Mt=2
15: Thk=1.5   Ang=0.    Mt=4
14: Thk=1.5   Ang=0.    Mt=4
12: Thk=0.13  Ang=45.   Mt=2
10: Thk=0.13  Ang=90.   Mt=2
8:  Thk=0.13  Ang=90.   Mt=3
6:  Thk=0.13  Ang=-45.  Mt=2
4:  Thk=0.13  Ang=0.    Mt=2
2:  Thk=0.13  Ang=-45.  Mt=2
```

Layers of materials on the zone + upper skin
Figure 12

6. Input of wing loads and contour boundary conditions for FEM analysis

In Figure 13 is shown the wing mass value in program after assigning material and thickness to each part of the structure. This established that the mass of the wing is the same as the mass of the wing of an airplane of real construction in kilograms, without fuel.



```
                      Mass              Center_of_Gravity_in_CSys_0
                      ----           X              Y              Z
Structural          639.0419    -5889.479       6388.14       559.0749
NonStructural             0.           0.            0.             0.
Total               639.0419    -5889.479       6388.14       559.0749
```

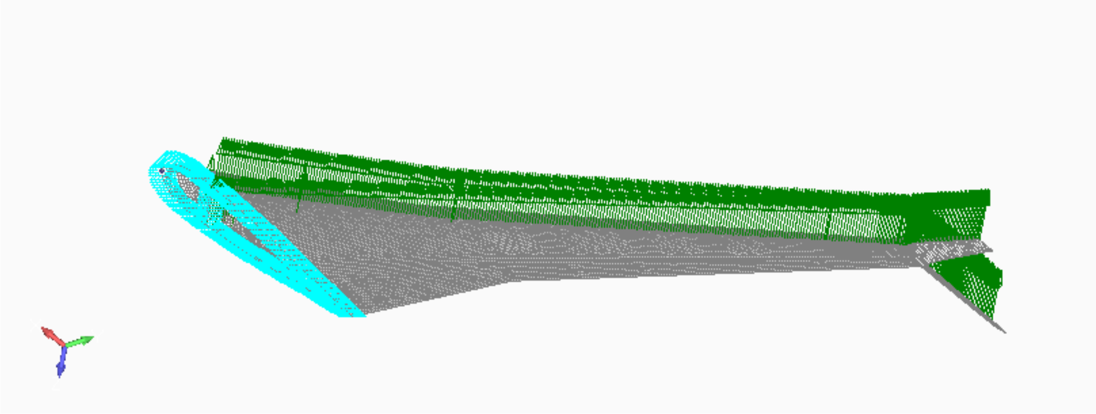
The mass of the wings in program after the assigned material – Figure 13

Subsequent to the preceding procedures, the subsequent stage entails inputting the necessary loads to prepare the model for static analysis. These loads are derived using the methodology described earlier within the Solid Flow software package. The accompanying image depicts the wing model with the applied load, a feature shared by both aluminum and composite wings. The load is introduced along the leading edge, specifically within the primary shoulder region, which bears the predominant weight of the entire wing structure.

$$F_{uk} = R_z = 154944.546[N] \tag{6.1}$$

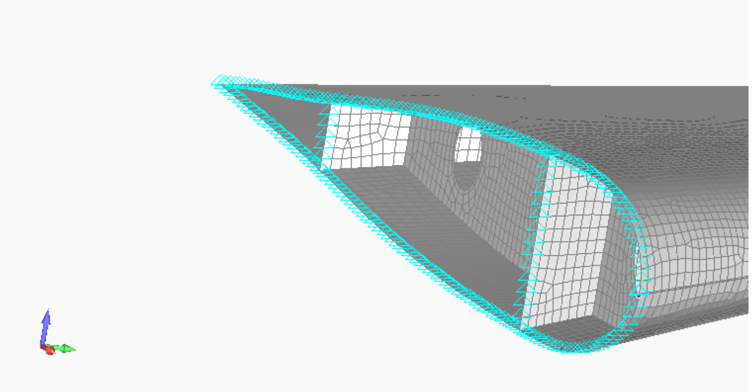
$$F_g[N] = 0.6 \cdot \begin{bmatrix} \frac{F_{uk}}{2} & \frac{F_{uk}}{3} & \frac{F_{uk}}{6} \end{bmatrix} = [46483{,}3638 \quad 30988{,}9092 \quad 15494{,}4546] \tag{6.2}$$

$$F_d[N] = 0.4 \cdot \begin{bmatrix} \frac{F_{uk}}{2} & \frac{F_{uk}}{3} & \frac{F_{uk}}{6} \end{bmatrix} = [30988{,}9098 \quad 20659{,}2728 \quad 10329{,}6364] \tag{6.3}$$



Wing model with load – Figure 13

The boundary conditions that are set represent the wing-fuselage connection, where in all analyses the wing is considered as a cantilever, fixed at one end.

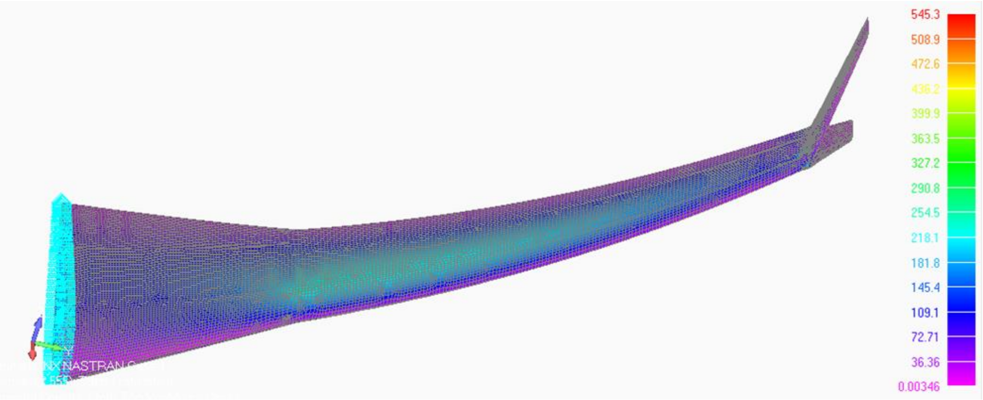


Constraint definition – Figure 14

7.Static analysis

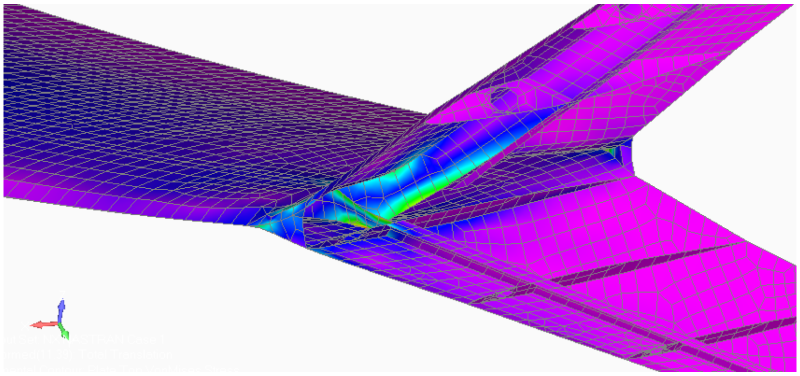
7.1.Static analysis for aluminum wing

Following the completion of the static analysis, the acquired results encompassing the stress distribution and deformations of the aluminum wing enable a straightforward assessment of potential stress concentrations within the structure that could potentially induce plastic deformation. This determination is facilitated by referring to the predefined maximum stress threshold, specifically known as the critical stress, which serves as a decisive factor for identifying critical regions. In the scope of this project, the focus will solely be directed towards normal stresses, disregarding other stress components for the purpose of simplicity and clarity.



Characteristic cross section of wing – Figure 15

The value of the maximum normal stress in the construction is: 550 MPa
Wing deformation is: 12 cm

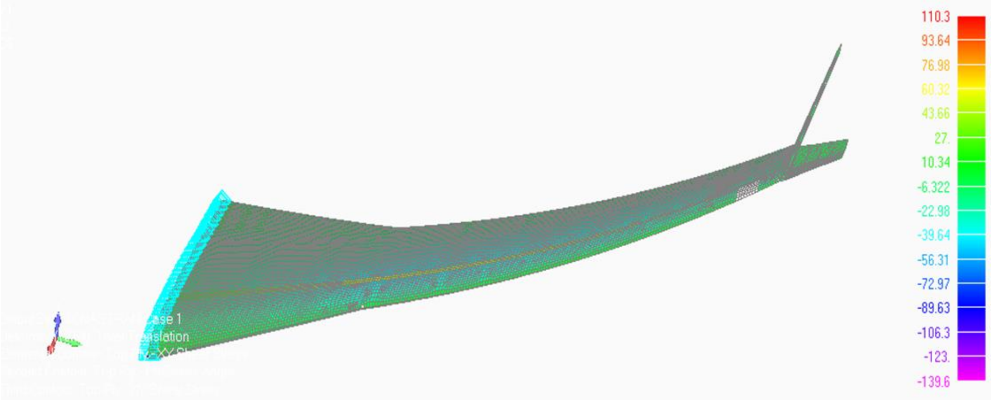


Characteristic cross section of wing – Figure 16

The results of the static analysis show that the stresses in the construction do not exceed the permitted values, except at the place of connection in between the winglet and the wing, where it is necessary to strengthen the construction.

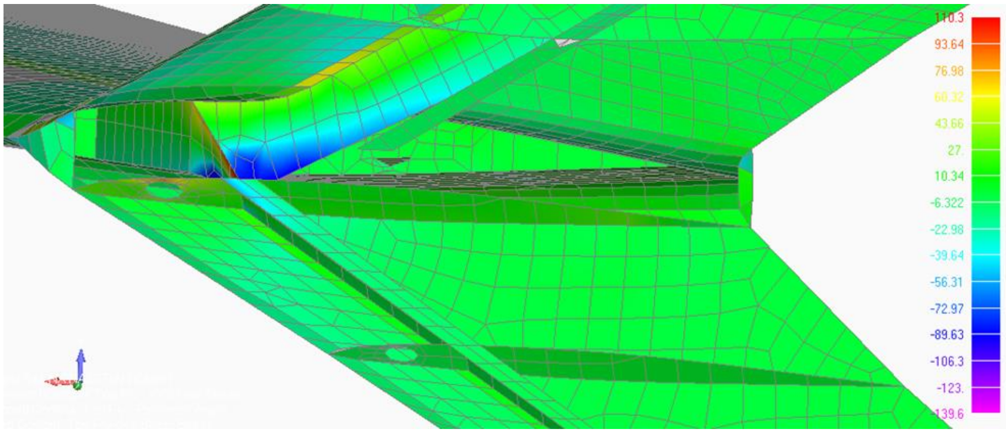
7.2.Static analysis for composite wing

When it comes to the composite wing, the structure of the composite laminate is such that the maximum allowable stress is not valid for the entire laminate, but it is necessary to consider each layer separately. The combination of multiple composite weaves leads to this, and then to read the stress state of those elements and to determine the limits within which these stress move.



Characteristic cross section of wing – Figure 17

The value of the maximum normal stress in the construction is: 110.3 MPa
Wing deformation is: 11.32 cm



Characteristic cross section of wing – Figure 18

8. Conclusion

The primary objective of this project is to gain a comprehensive understanding of the fundamental challenges encountered in wing element construction. The employed software programs facilitate the efficient and seamless modeling of the structural elements, as well as their subsequent analysis. Through the analysis process, the deformations arising from static loading are determined, and the corresponding stress values are evaluated directly on the elements themselves. In order to ensure that these stress values remain within permissible limits, specific elements are reinforced as necessary.

As a result of these efforts, critical phenomena, such as plastic deformations and fractures, are successfully mitigated throughout the structure. Consequently, the objectives of this project are achieved. Additionally, this outcome indicates that the material selection has been judicious, considering the optimal balance between mass and strength. Given the focus of this project on the comparative analysis of the aluminum and composite wing with the implemented winglet design, the final results are presented in the subsequent tables for comprehensive evaluation.

Aluminum wing	Composite wing
Wing deformation for the most loaded case of flight: 12 cm.	**Wing deformation for the most loaded case of flight: 11.32 cm**

Comparison results – Table 2

The static analysis was conducted under the most critical flight conditions, aiming to determine the comparative performance of different wing materials in terms of their deformation characteristics. The primary objective is to identify the material that exhibits superior resistance to deformation in this specific flight scenario. The optimal wing construction, in this context, corresponds to the one demonstrating minimal deformation under the identified flight conditions. It is noteworthy that the structural integrity of the wing is of paramount importance, and the absence of critical stresses that could induce plastic deformation or structural failure further validates the efficacy of this research endeavor.

The overarching goal of this study is to present a prospective methodology for preliminary analysis in the selection of suitable materials and structural elements during the conceptual design phase of aircraft wings. By evaluating and comparing the deformation behaviors of different materials, this work contributes to the development of a framework for informed decision-making regarding material selection in the initial stages of aircraft wing design.

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