STRESSES AND DISPLACEMENTS ANALYSES ON LAMINATED COMPOSITES IN UNMANNED AERIAL VEHICLE WINGS

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Abstract. *This work presents a finite element analysis to assist the design of an unmanned aerial vehicle wing. As in regular aerospace applications, the use of composite materials, here as a laminated configuration, was mandatory. Structural analyses in ANSYS commercial software were performed to compare different lay-up configurations to the wing skin, covering a solid plastic foam core, obtaining displacement and stresses distributions for the different layers. Modeling techniques were applied to obtain a very well controlled finite element mesh, combining solid, layered shells and other special types of finite elements. The objectives include defining procedures to easily model a given wing geometry, with the loads prescribed and different composite configurations as number of layers, orientation angles, and physical orthotropic data.*

Keywords*: Unmanned Aerial Vehicles, Layered Composites, Finite Element Analysis*

1. Introduction

Unmanned aerial vehicles, UAVs, are a class of aircraft that has been shown to be most useful in several military and civilian applications. An academic final course project, at Instituto Militar de Engenharia, had the objective to develop an entire real prototype of a reduced dimensions vehicle. This project involved the aerodynamic design of fuselage and wings, to a specified geometry, that could be used to carry some equipment required. The fabrication, together with Centro Tecnológico do Exército, should use layered composite materials, providing high strength with the lowest weight possible. A few lay-up configurations, as some possible materials to be used were previously selected. To the wings study, in particular, some finite element analyses were performed to help to compare these initial possibilities. ANSYS commercial software provides an special element to model layered composites, varying its orthotropic material properties, layer thickness and winding angles to direct fibers.

Wings are to be made with a layered skin over a central solid core. This second, in low-density plastic foam, should provide the aerodynamic shape, besides contributing to structural resistance. The layers, with composite unidirectional fibers and a resin reinforcement, can be modeled in different directions, majoring the strength where required. To have a configuration capable to respond to several loads, more layers can be added to achieve a tailored design. At a first insight, there would happen tension and compression in wing regions, due to bending. Torsion can also act, from aerodynamic resistance forces.

2. The UAV Project

With a great variety of applications for an UAV, some were selected as main tasks for the prototype. It should have the capacity to take aerial photographs of the terrain and indicate some fixed points previously chosen. To make this easier, the vehicle should have a steady flight. A commercial piston motor should accomplish propulsion. Classical solutions (Anderson, 1991) were adopted in design of fuselage and stabilizers, presenting conventional geometry pattern. All the internal equipment totalized 10 Kg of mass to be carried by the UAV.

To impose a major stability in flight, it was selected a “high-wing” positioning, above the center of mass of the aircraft, in the fuselage. Wings geometry has a trapezoidal shape. The reason is to permit some aerodynamic efficiency, in low velocity (Torenbeek, 1976), with also an easy of construction. The choice for the airfoil profile considered low drag and momentum applied to the wings. After considering all the basic aspects in the aircraft design (Guerra and Teixeira, 2003), with its total weight, a geometry for the wings was finally defined. Total length of each wing is 1475mm, with cords of 357mm in the junction with fuselage and 120mm on the free edge. Control surfaces were also defined in project, but not considered in wings structural analyses.

2.1. Materials Data and Specifications

The materials definitions also considered easy of acquiring, easy of use and fabrication, besides its capacities to stand for all the service loads. UAV should have good conditions of repairing and maintenance. Solid core selection was an EPP polypropylene foam, having low density. It presents a major capacity in absorbing impacts, imposing a higher rusticity to military applications. For the layered composite materials, E-glass unidirectional fibers, class UF 0240 were chosen. They will be bonded with an Epoxy base resin, DER 324. It permits a good conformability and wetness to reinforcements, permitting more adherence and higher loads acceptance (Chawla, 1998).

Two lay-up configurations were initially proposed. Finite element analyses were used to compare their response to considered loads and to help to conclude about their acceptance. With a model obtained, the idea for future was to easily change lay-up data and get the new results, analyzing every new proposal. The use of longitudinal reinforcements is also another option. However, total final weight for the aircraft is a limiting parameter.

Lay-up data includes the angle the fibers are to be winded, in respect to wings longitudinal axis. Each layer can have its own angle and thickness. The total skin thickness will account every single layer. They were considered perfectly bonded to each other. The first lay-up suggested included only one layer, winded on longitudinal direction. This could impose a major resistance to bending action. A second one, to stand more twisting over this direction, added more layers on different angles of 45^o. Options were set as [0^o] and [+45^o, 0^o, – 45^o]. These angles are referred to the wing longitudinal axis, transversely to the UAV fuselage axis. The material is the same for every layer, with a 0.38mm thickness.

Unidirectional fibers are usually made in orthotropic or transversely isotropic materials (Jones, 1975). These present different properties depending on the directions considered. Orthotropic data have 3 mutually orthogonal principal directions, with a different strength property for each one. Transversely isotropic class is a small simplification of the other, having equal values in one plane directions, with an orthogonal axis to this plane presenting a different property.

For the current material configurations, layered composites present a transversely isotropic form and the foam core was considered isotropic. Some relevant data for the finite element analyses are presented in Tab. 1.

Table 1. Some Numeric Data for Material Models

MATERIAL MODEL 1 – Isotropic	(FOAM CORE)
Young’s Modulus	125 Mpa
Poisson’s Ratio	0.32
Ultimate Strength in Traction	2.1 MPa
Ultimate Strength in Compression	1.2 MPa
MATERIAL MODEL 2 – Transversely Isotropic	(COMPOSITE LAYERS)
Axial Young’s Modulus	39 GPa
Transverse Young’s Modulus	8.6 GPa
Poisson’s Ratio in-plane	0.28
Shear Modulus	3.8 GPa
Axial Ultimate Strength in Traction	1080 MPa
Axial Ultimate Strength in Compression	620 MPa
Transverse Ultimate Strength in Traction	39 MPa
Transverse Ultimate Strength in Compression	128 MPa
Shear Ultimate Strength in-plane	89 MPa

In previous table, it also can be seen some strength capabilities. It is clear that for some directions there is a great privilege. If layers are formed with the unidirectional fibers aligned to a specified axis, there will be a greater resistance while transversely values are much lower. To avoid a possible weakness, more layers can be stacked oriented with these other directions. The overall resistance should be obtained by reasonable methods (Herakovich, 1988), (Jones, 1975), considering lay-up data and material properties for all layers.

2.2. Loads Prescribed

For the loads chosen in the UAV structural design, a condition of initial flight take-off was determined as the most crucial. This considers an attack angle of 15^o over the wings. A method based on the extended theory for sustained line (Baldoino and Bodstein, 1995) was used for the load prescription in this stage. Computational calculus make possible to obtain sustaining and pitching coefficients distributions over longitudinal axis of wings span (Anderson, 1991).

Based on data as wings geometry, UAV velocity in take-off, air density in the altitude used and others, results for lift forces and pitching momentums can be reached. The first one is applied on the bottom areas of the wings. Pitching momentums act due to airfoil shape. Their application is along a line, located at 25% of every cord, over the wing length, clockwise over the fixation at the fuselage. Both loads can be plotted as curves over the wings spans. From the lift forces distribution and having the bottom surfaces areas defined, another distribution of pressures can be defined.

Figure 1 shows pressures, in Pa, from the lifting forces, as a distribution in longitudinal direction. Transversely, distributions are constant and equal to each value in this curve for a specified point over span, between 0 and 1.475m. To simplify this load imposition, an integration of this distribution of pressures, over section areas defined was done to achieve average values, to be applied constant. Based on figure 1, seven division points over longitudinal direction were chosen, trying to approximate this curve as linear segments and obtaining area divisions on bottom surface of wings.

Figure 2 presents pitching momentum, in N.m. Zero values on span are the junctions with UAV.

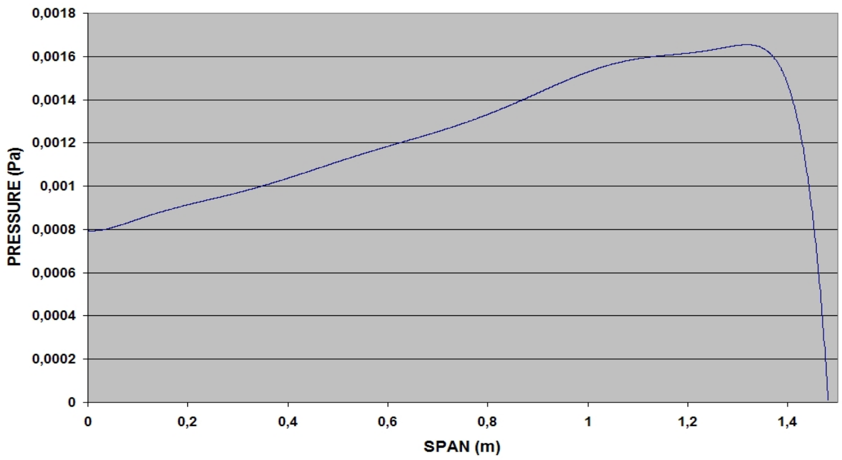

Figure 1. Pressure Longitudinal Distribution

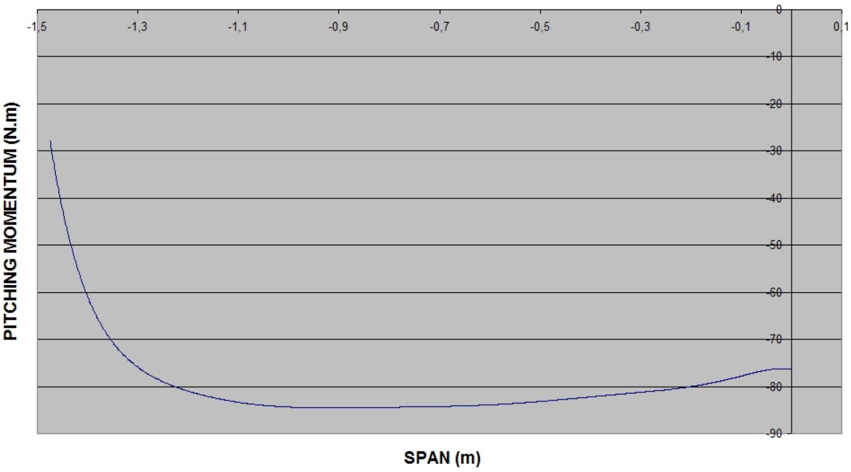

Figure 2. Pitching Momentum Distribution Over the Wing Span

3. Finite Element Modeling

The first phase to have a finite element model in ANSYS software was to import an initial three-dimensional CAD file. Some adaptations were previously made with special objectives. The intention on FE model is to have a 100% mapped mesh, to use quadrilateral shells and hexahedral solid elements. This will also easy the conjunction of both types of elements, to model the perfect bond, by hypothesis, of layered skins with central solid core. A division of wing volume, over the length, at 25% of cords was required to make possible the application of momentum at this specified location. Since both types of loads are distributed over the wings, the seven transverse divisions mentioned on pressures simplifications were used in overall model.

The finite elements chosen, available in software for structural mechanical analyses, were, at first, SHELL99 and SOLID95. SHELL99 is a layered shell for composite modeling, permitting up to 250 layers and requiring mid-side nodes, configuring an 8 node quadrilateral element. This makes necessary higher order solid elements, as SOLID95, for core modeling. This will permit the perfect cohesion in the use of multiple attributes meshes. Unfortunately this increases the overall number of nodes. The use of techniques for mapped meshes helps to control the complexity of the model. An accentuated curvature is pronounced in the wing front border. Problems with mid-side nodes positioning arise if a course mesh is created on that region, since the intermediate nodes follow the straight direction between the others. Some refinement was needed and used to improve the modeling of the curvature.

A final mesh was obtained considering aspects of modeling relevant details, able to receive all loads, totally mapped and yet, with the total number of elements and nodes controlled. Figures 3 and 4 show solid model, with divisions created to easy load imposition, and the complete finite element mesh. All exterior areas contain shell elements surrounding solid core modeled with the brick elements. Mapped meshes easy the perfect match using same nodes for both finite elements.

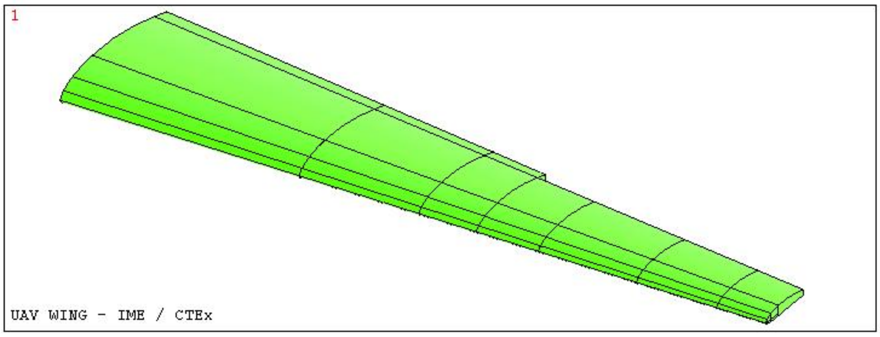

Figure 3. UAV Wing Solid Model with Longitudinal and Transverse Divisions

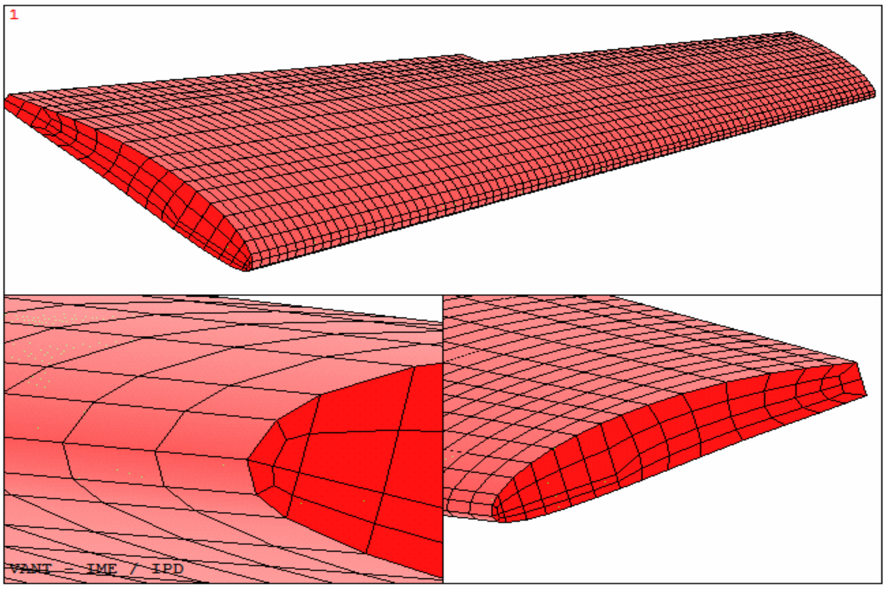

Figure 4. Finite Element Mesh. Entire Wing and Details of Front Border and Free Lateral End

4. Structural Analyses Simulated

As mentioned before, there are two lay-up configurations to be analyzed, with just one or three layers. Initially, only base pressure was applied to the wings, as it was previously expected to be the most severe. Another case added pitching momentums. Static analyses were performed. Pressures were simplified, adopting constant values between the seven transverse divisions in solid model. Tab. 2 shows its numeric approximations and where are the division points over wing span. These values were obtained from initial longitudinal distributions presented on figure 1.

Table 2. Pressure Load Values and Division Locations

Divisions / Lengths	Average Pressure (Pa)
1 (0 to 0.5 m)	953
2 (0.5 to 0.75 m)	1201
3 (0.5 to 0.875 m)	1347
4 (0.875 to 1.0 m)	1466
5 (1.0 to 1.205 m)	1577
6 (1.205 to 1.372 m)	1605
7 (1.372 to 1.475 m)	797

Approximations for momentum values were also adopted, applied however inside the wing. There was a new problem in modeling, since the solid elements only offer displacement degrees of freedom, not allowing imposition of momentums that require rotational DOFs. A trick used was to consider some other elements available in software (Ansys Help System, V7.0). An added beam of low stiffness was created over the line of momentum applications, with BEAM4 elements. It permits to impose momentums over the longitudinal axis, adding rotational DOFs not included on solid elements. After this, just to transmit this load first to layered shells, MPC184 element was chosen. In seven internal points of the beam, aligned with the transverse divisions, these elements were positioned to act as rigid members. Only one point of the shell, in each section, was used to transmit load, on the upper border of the wing back. Its reason is that, as a rigid member, MPC184 would modify the deformation field if more points were "locked". There will still be a great modification in stress and strains results nearby seven points that rigid members connect to overall structure. A post-processing procedure was required to eliminate considered erroneous composite and solid elements, permitting result readings on the remaining wing regions. Figure 5 illustrates additional elements and its modeling procedures. Wings were shown only in bottom and back surfaces. Red lines represent the longitudinal axis, modeled with beam elements, and the seven transverse members, acting as rigid components just to transmit momentums. It can be noticed points which the rigid elements contact the composite shells, shown in red areas.

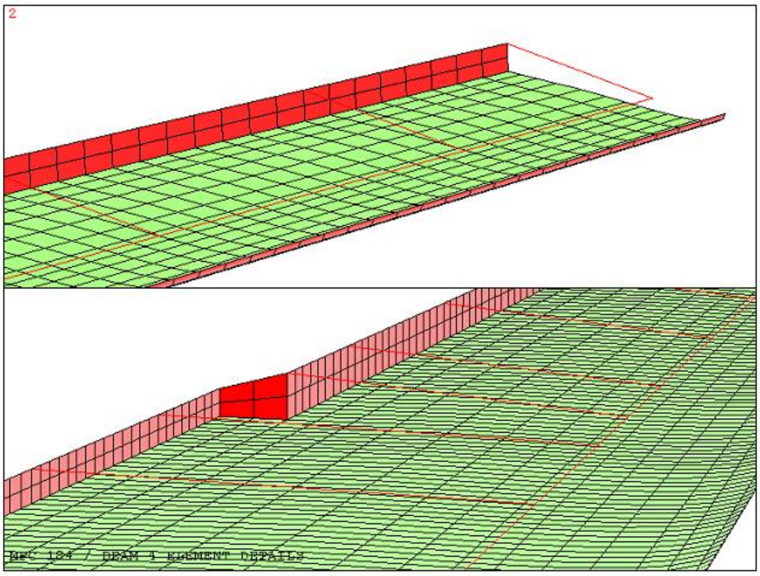

Figure 5. Details of Modeling Procedures: Elements BEAM4 and MPC184

There will be presented in this paper results for three analyses considered: Single layer lay-up/Pressure load, and 3 layers with only pressure and with both pressure and momentum applied. Some remaining definitions and considerations still need to be discussed. The scope of the work, at first instance, was more concerned in obtaining modeling approaches to overall problem than a very well detailed strength analysis. The static problem is simple, with loads not too severe. Failure of the materials was not considered. Since that, with an insight more to obtain a model capable to analyze different future configurations and to study stresses distributions over each layer, failure criterias were not yet adopted. Delamination was not either analyzed, nor interlaminar stresses. These considerations can be performed in finite element simulations, if required in the future.

5. Results

The post-processing involved the monitoring of stresses and displacements on the solid core and every layer. Elements present displacements in three global directions referenced as X, Y and Z. Vertical displacement, UY, presenting the higher values, can also cause fluttering with severe vibration to the wing. This component was the most important to be considered.

Output options on layered elements permit two forms of results: stresses can be shown in global directions, aligned with transverse, vertical and longitudinal axes of the wing, or in each layer principal directions. These are aligned with fiber direction, having the privilege of strength values, its transverse direction, and the orthogonal axis to layer plane. Both systems were used in the study of stresses fields. These differences can be obtained from linear transformations, with rotations in the winding angles considered for each layer (Jones, 1975; Herakovich, 1998). More attention was given to longitudinal and transverse components, as well as in-plane shearing stresses. Positive and negative values are obtained, showing traction and compression over different regions. For the solid core, Von-Mises equivalent stress was also monitored. Following tables 3 and 4 present some higher stresses, in each system and component considered, and maximum deflections, as vertical displacement, for every analysis performed.

Table 3. Some Stress Values Obtained in Foam Solid Core and Vertical Displacements for Entire Structure

LAY-UP / LOADS	Longitudinal Global Stresses (MPa)	Transverse Global Stresses (MPa)	Von-Mises Equivalent Stress (MPa)	Vertical Displacements (m)
1 Layer / Pressure	– 0.669 + 0.533	– 0.298 + 0.237	+ 0.612	+ 0.1363
3 Layers / Pressure	– 0.129 + 0.104	– 0.098 + 0.084	+ 0.188	+ 0.0316
3 Layers / Pressure + Momentums	– 0.196 + 0.205	– 0.394 + 0.291	+ 0.507	+ 0.0442

In the core analyses, maximum values of vertical displacements were located at the tip of the free edges. Values of maximum compression and traction were located near the fixation with fuselage, on bottom and top of wing, as expected in a bending beam. In the further tab.4, regions of traction and compression varied upon number of layer. First three rows of results are related to global coordinates, while the following are in the system defined for a local system aligned with fiber orientation.

Bold numbers indicate the most dangerously values. All the results should be compared with material data in table 1. It should be reminded that a failure analyses was not performed. Comparison just gives an idea of how close results are to safety limits. Any result was close enough to strength limits, in compression or traction, on directions considered.

Two images, on figure 6, illustrate some stresses distributions. Left image shows selection of solid core, with Von-Mises equivalent stresses. The other one shows stresses distributions on layer 1 of the 3 layers, with only pressures applied, option. Regions of traction and compression can be easily seen in yellow or light blue colors. Similar plots can be obtained for every result in any layer.

Table 4. Stress Component Results for each Layer (MPa), in Global and Local Coordinates

Analysis Performed	1 Layer Pressure	3 Layers Pressures Only			3 Layers Pressures and Momentums		
LAYERS	[0°]	[+ 45°]	[0°]	[– 45°]	[+ 45°]	[0°]	[– 45°]
Components	Results in GLOBAL Coordinates						
Longitudinal Stress	– 57.4 + 83.9	– 28,7 + 22.5	– 12.1 + 23.6	– 31.4 + 33.5	– 27.7 + 47.3	– 28.6 + 61.9	– 57.4 + 52.1
Transverse Stress	– 71.1 + 56.4	– 22.6 + 19.8	– 15.2 + 14.7	– 23.8 + 24.7	**– 18.8** **+ 38.8**	– 24.8 + 21.4	**– 45.0** **+ 35.1**
In-plane Shear	– 15.4 + 23.0	– 14.6 + 10.7	– 4.24 + 5.04	– 8.19 + 17.2	– 33.1 + 31.5	– 14.3 + 14.8	– 31.1 + 35.4
	Results in LOCAL Coordinates – Layer System						
Longitudinal Stress	– 41.1 + 73.5	– 34.2 + 25.5	– 14.9 + 17.1	– 30.3 + 45.8	– 33.0 + 83.3	– 29.5 + 57.1	– 81.9 + 63.2
Transverse Stress	– 51.4 + 40.2	– 12.2 + 8.8	– 9.38 + 7.34	– 11.2 + 9.04	– 14.7 + 17.1	– 17.6 + 19.1	– 26.0 + 24.9
In-plane Shear	– 15.5 + 13.5	– 6.33 + 5.16	– 4.85 + 2.90	– 5.32 + 6.47	– 8.3 + 9.52	– 7.27 + 16.4	– 9.21 + 8.69

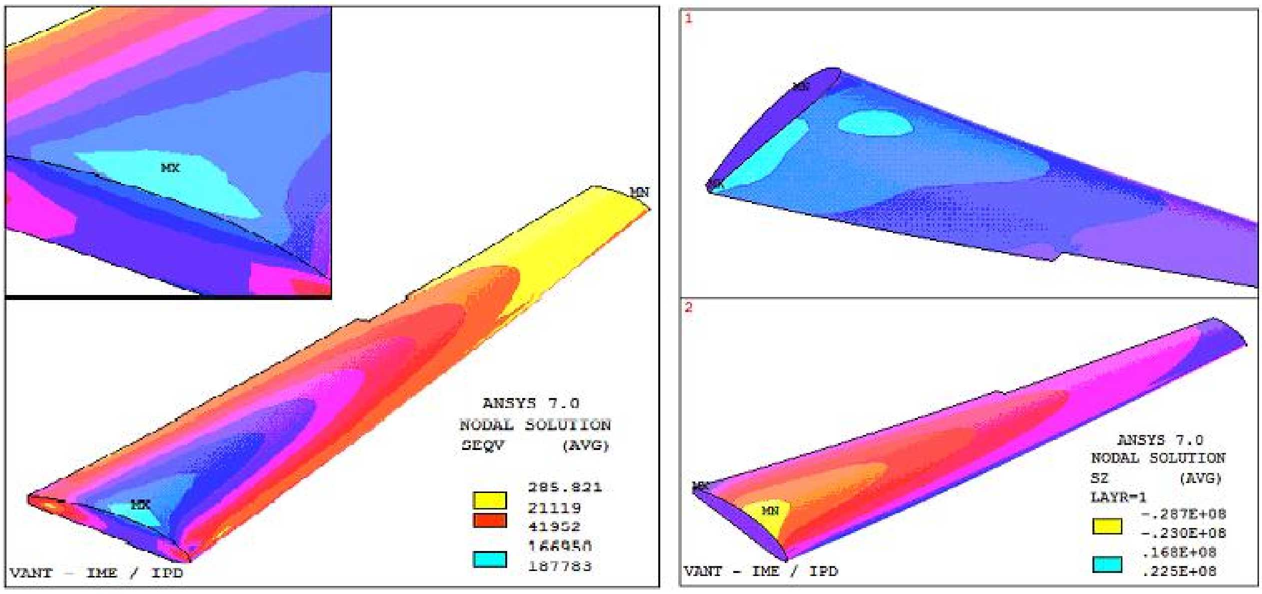

Figure 6. Examples of Von-Mises Equivalent Stress (Pa), on Core, in Left Image and Detail, and Longitudinal Global Direction Stresses, at Layer 1 of the Three Layers Option, on the Right (Bottom and Top Views).

6. Conclusions

The finite element analyses were used to compare different lay-up configurations and load conditions. Several considerations were taken into account to obtain a model capable to stand these options and to be useful to more cases to be tested in the future.

First case analyzed, with only one layer, did not present problems in stress values. As mentioned, the fibers chosen present a very high strength, at least in its principal axis. The problem was, however, with a great vertical displacement, about more than 13 cms. over less than 1.5 m. That was the reason the application of momentums was not performed. A great risk to impose vibrations and aerodynamic disturbances already compromised this option.

Considering 3 layers composite, both load conditions were compared. In terms of values, once again a critical value was not plotted. If so, problem should be revised adopting a failure criteria. Imposition of momentum changed a little patterns of stresses, increasing traction or compression in some different areas, but not at too high values, as shown in table 4. Results change from layer to layer, requiring a very detailed analysis of entire model.

In the core results, it was concluded that values are far from limits of safety. A very good class of foam material was selected, more expensive. It shows that a less noble choice could be used.

7. References

Anderson, J.D., 1999, “Aircraft Performance and Design”, Ed. McGraw Hill, New York, USA.
Ansys Help System, release 7.0, Ansys, Inc.
Baldoino, W.M.; Bodstein, G.C.R., 1995, “Comparative Analysis of the Extended Lifting-Line Theory to the Classical Lifting Line Theory for Finite Wings”.
Chawla, K.K., 1998, “Composite Materials Science and Engineering”, Springer-Verlag, New York, 1998.
Guerra, E.B. ; Teixeira, C.V., 2003, “Projeto Preliminar de um Veículo Áéreo Não Tripulado para Reconhecimento de Alvos de Artilharia”, Instituto Militar de Engenharia, Rio de Janeiro, Brazil.
Herakovich, C.T., 1998, “Mechanics of Fibrous Composites”, Ed. John Wiley & Sons, USA.
Jones, R.M., 1975, “Mechanics of Composite Materials”, Ed. McGraw Hill.
Torenbeek, E., 1976, “Synthesis of Subsonic Airplane Design”, Ed. Nijgh-Wolthers-Noordhoff, Rotterdam, Holland.

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