STRUCTURAL DESIGN OF DELTA WINGS OF AN EXECUTIVE SUPERSONIC AIRPLANE

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Abstract. *The technology of composites has been more and more acknowledged these days, with an ever-increasing study of its behavior, properties and applications. Following this tendency, this work presents the preliminary structural design of supersonic executive delta wings. This is a jet aircraft with wingspan of about 18 m. Two types of primary structure are analyzed: one made of carbon fiber and another of aluminum. Several models of finite elements have been created to help the conceptions and analyses of the primary structures in order to obtain initial proposals with low weight. Tension and stability criteria were checked in both solutions. The results are presented, compared and discussed.*

***Keywords**:* Composite Materials, Delta Wing, Structures, Supersonic

1. INTRODUCTION

If from times to times the civil aeronautic industry conceives projects that change the way passengers fly, whether it is shorting distances, increasing comfort or decreasing prices, a parameter which has been a constant barrier, in the commercial or executive sector, is the limited speed of subsonic and transonic flights. An exception to the rule was the Anglo-French aircraft Concorde, which would have routes over the oceans in a cruise in a speed of mach 2, but was a huge commercial disaster due to the extremely high cost of the its operation; and it's no longer being used. The Russian aircraft, Tupolev-144, followed the same concept of the Concorde, but it didn't get to be used in commercial airlines. Trying to overcome this obstacle, a varied range of projects and studies of executive supersonic aircrafts has aroused in the main companies in this field of aviation. Considering the high cost operation per passenger, these aircrafts attend to a public that demands a shorter time flight and are willing to pay its price. Therefore, the target aimed are business people that make long trips on business and for whom idle time spent on flights or airports end up being an expensive solution. During a simulated example, a business person residing in New York who needed to close a deal personally in London, would manage to take off form his city, work in the afternoon in London and be back by the end of the evening at home; all possible due to the economization of over 7 hours on its round-trip in an aircraft with the speed of 1.6 mach. The objective of the presented aircraft, named Strider SBJ, the main project of the eighth class of the Program of Specialization of Embraer (PEE), is exactly the study of this type of aircraft, presenting its economical feasibility and possible technical solutions of the project (Fig.1).

Not long ago, the ever increasing participation of composite components in aircrafts had been an appeal in marketing and technological domain rather than in business profits; and in the contemporary scenario, they play an important role on the weight reduction of aircrafts and, consequently, on the recurrent cost of their operations.

This study has for an aim the creation of an preliminary design of the primary structure of an aircraft wing all made of composite (Fig. 1); product of the work developed by the eighth class of the PEE; and comparison to the same design in aluminum.

Figure 1: Strider: The project developed by the 8th class of PEE.

2. DELTA WING

Figure 2 shows the structural model developed to the project, disregarding details such as connections, links and other details that did not make part of the objective. The studied part is represented by the color green, but differently form the analysis model, the wing structure below shows the exclusion of stringers and ribs in the areas determinate to the landing mechanism. The part of the wing which is represented in blue is a secondary structure that was not part of the analysis.

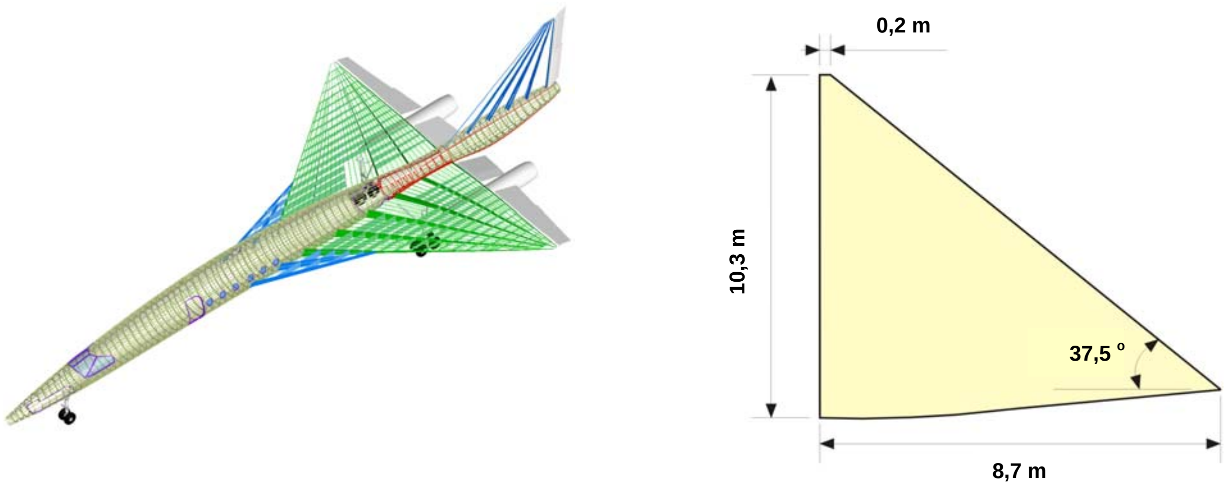


Figure 2: Structural skeleton of the Strider (left) and dimensions of the structure (right).

2.1. Layout

According to the description seen in military aircrafts, nearly all the layout of the structure of the wing was made empirically, always taking as a basis the existing airplanes. The dimensions of the structure followed the picture below as a root chord of 10355 mm, a semi-span of 8720 mm and a tip chord of 244 mm (Fig. 2). Also, it has been defined that the initial project would be developed with 6 converging spars, 17 ribs and 50 stringers. All these components distributed regularly through out the span and chord.

The stringers have section shape "I" and the distance among them vary in a way that the maximum distance is close to 400 mm and the minimum 200 mm. The distances given result in 5 stringers among spars, approximated to the quantity found in aviation. The distance among them begins in the 400 mm and, through out the converging semi-span, this distance reduces itself until it reaches the 200 mm. From that point on, some stringer is interrupted and we are back to having 400 mm distance among them. Moreover, it is important to notice that on Figure 3 this interruption on the stringers is always made coincidently with the rib, avoiding problems of tension concentration of the skin. The discontinuity of some stringers has for an aim the reduction of the structure weight when they are no longer necessary.

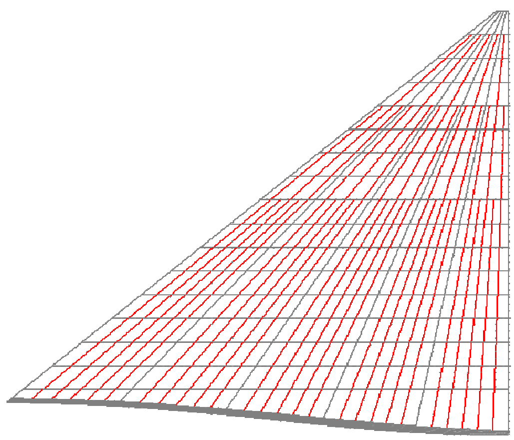


Figure 3: Structural model with spars, ribs and stringers (red)

In this stage of the initial project, nor the ribs or the spars have a weight relief whole and fuel passage. The space of the landing gear was considered from the beginning of the project, influencing the spaces given among the spars. With the regular division of the wing's components, the space among the ribs ended up being uniformly 0.486 m. The skin plate, limited by two spars and two ribs reached its maximum dimension of 0.486 m of width by 2.10 m of length, dimension that indicated that a further attention to the stability criteria should be given. These figures were defined with basis on some dimensions of previously researched airplanes with delta wings.

2.2. Loads

The loads were analyzed on the wing came from the aerodynamic pressure, of the distribution of the weight of the structure, of the fuel and also of the weight of the engines. The "aerodynamic group" was responsible for the analysis, which was later reassigned to the "structure group" as input data. Some points of the flight profile were selected and some parameters of the status corresponding to the flight, such as Lift Coefficient (CL) and the number of mach identified. These parameters were used as a starting point to the "aerodynamic group", aiming to find the distribution of pressure on the wing for this specific case. (Fig. 4)

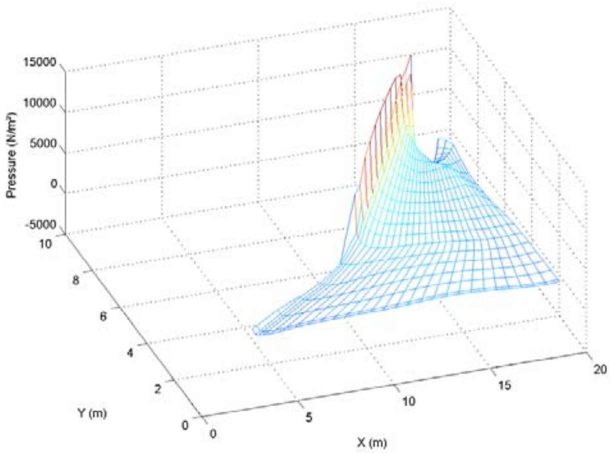


Figure 4: Distribution of the pressure of the aerodynamic on the semi-wing

Then, the wing was divided into transversal sections through out the span, according to the position of the ribs in the structural configuration of the wing. From the distribution of pressure, the center of pressure of each section of the wing is obtained. The pressure is so integrated through out the area and the corresponding force is applied on the respective centers of pressure of each section. This way, it is possible to estimate the forces through out the extension of the wing, due to the aerodynamic distribution of pressure (Fig. 5). These forces, before applied to the model, are multiplied by the load factor of 2.5, maximum load factor to the envelope of positive flight to passenger transportation aircrafts, according to FAR-25 (2009).

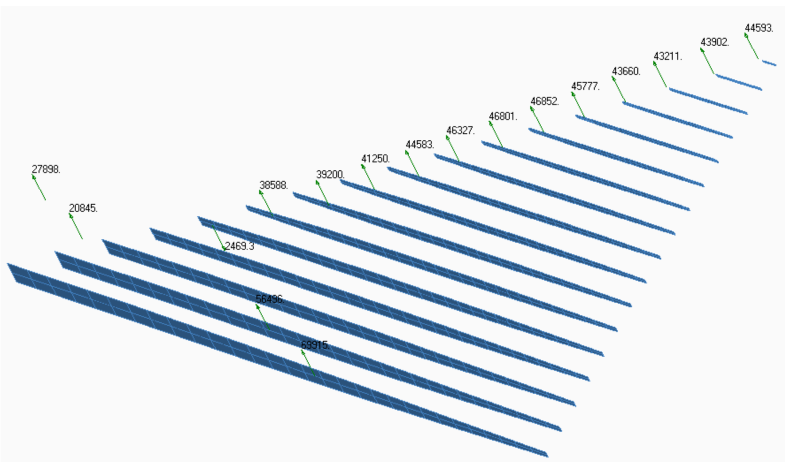


Figure 5: Distribution of effort resulting (N) of the aerodynamic pressure on the rib

In order to simplify the calculus, it was established that the weight of the structure varies linearly with the span, and in the same way was the distribution of fuel done. The two prior weights plus the weight of the engines are subtracted from the aerodynamic forces, but maintaining the results at the same point of application. To acquire the values of efforts and resulting moments of the use of the aerodynamic forces, a beam crossing the span and the semi-wing and passing through the middle points of the rib chords, was created. The loads generated were connected to the respective middle points via RBE3. The graphics of Figure 6, presented below, have on their abscissas the numbering of the ribs, being the basis represented by section 1 and the 17 ribs numbered from 2 to 18.

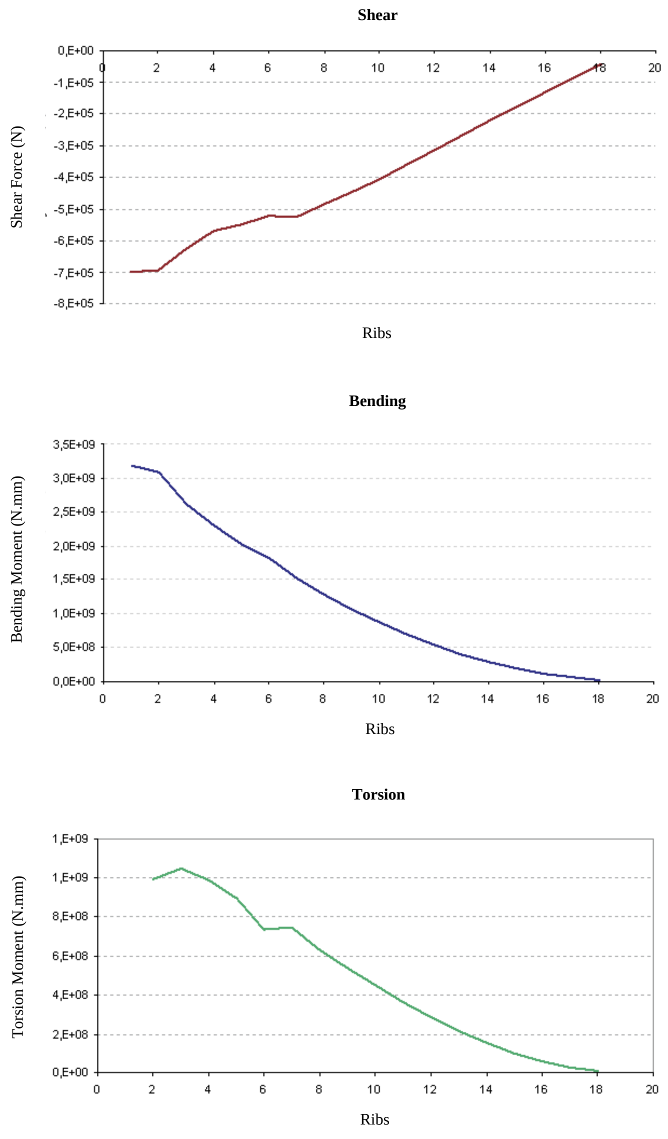


Figure 6: Loads Diagrams

3. STRUCTURAL MATERIALS

3.1. Composite

Among all the materials used in the “Industry”, the recommendation of the aeronautic professionals who work with such technology was to use the graphite-epoxy of an average tape width of 0.15 mm. The elastic and endurance properties of the orthotropic material, as Modules of Young (E) and shear (G), Poison Coefficient (Ni), Axial Tensions (T) and of shear limits (S), used in all the composite projects are presented on the Tables 1 and 4. The numeric sub-indexes represent the axis of the main orthogonal tensions and the alphabetic determinate the type of tension, compression (c) or traction (t).

Table 1: Mechanical Properties

E_1 (MPa)	E_2 (MPa)	Ni_{12}	G_{12} (MPa)	T_{1t} (MPa)	T_{1c} (MPa)	T_{2t} (MPa)	T_{2c} (MPa)	S_{12} (MPa)
152500	12050	0.31	4970	2276	1455	95	265	107

3.2. Metallic

The main doubt about the metallic wing was regarding the kind of aluminum to be used in its components. In the metallic projects of conventional aviation there is a concern with the final price of the aircraft, therefore, in the areas of the components with less structural load, the aluminum used is of a less noble alloy and, thus cheaper. As the study of the manufacturing cost of the wing will not be done in this work, and knowing that the composite material is more valuable than the metallic, the use of aluminum 7475 T7351 was adopted in all the components of the wing. The mechanical properties of the aluminum depend on the width of the plate and orientation of the grains. For this research, in order to maintain the use of only one material, even when there is the reduction of width of the skin or of the stringers through out the span, it was decided to adopt a plate with a average width of 0.25" (6.35mm) to the whole model. The orientation of the grains on the plate also influence on the properties, the longitudinal orientation of the grains was chosen for it demonstrates a greater endurance than the others. The elastic isotropic properties and the mechanical properties of the Aluminum used are exposed on Table 2 (RICE, 2001).

Table 2: Mechanical Properties

E (MPa)	G_{12} (MPa)	Ni_{12}	F_{tu} (MPa)	F_{ty} (MPa)	F_{cy} (MPa)	F_{su} (MPa)
71016	26889	0.33	489	413	420	282

4. FEM MODEL

The finite elements model was made on Nastran 2003. The mesh was formed from elements of the plate QUAD4 of maximum side of 350 mm.

The restrictions of displacement of the model were simplified for nodal fixed constrain. The areas these restrictions were applied were the basis of contact of the spar with the Stub and the contact face of the skin with the fuselage.

The forces calculated by the loads group are placed on discrete point and must be transmitted to their respective ribs. The method used was the transmitting of these efforts to the nodes of the components thru the use of rigid elements. The principle is based on the application, on the nodes of the component, of loads that simulate the same resultant force and moment to the applied force on the independent node. The rigid element, used by the Femap program and also used in the analysis of the structure of the wing, is called RBE, which is divided into RBE2 and RBE3, (MSC,2001), where RBE3 is the rigid element used in this work.

The structure was optimized based on two criteria of failure. The first to be observed was the Tsai-Wu, specific criteria for composite. This method generates a failure index to each ply, but also a failure index to the analysis of the whole laminate. This index must be smaller than the unit; otherwise, the respective area is failing. During the carried out simulations, it was decided not to evaluate the delaminating failure, in other words, in the CAE program used the value of the parameter "Bond Shear Allow" used were of great magnitude so that the results of this failure were so small that would not interfere on the final result. The program also requires a parameter of the method which was adopted as being Tsai-Wu Interaction = -0.5, common value in bibliography about composite analysis. From the moment the structure was approved, the second criteria to be applied would be the buckling failure. This criteria indicates the position of buckling and generates an index that represents the actual amount of load that can be applied without structural failure. Once the parameters an limits of tension have been informed to the program, both criteria are given on the post-processing of Nastran. Analytical calculus of a complex structure, such as the one in question, was initially disregarded.

5. DESIGN AND ANALYSIS OF THE COMPOSITE STRUCTURE

From an initial model, until the result of the optimized model presented in this chapter, there had been many tentative that will not be presented for not being representative. Even before the initial model, other simpler models had been made intending, with some quick simulations, to reach a model which demanded less work. The optimization, however, was limited to width variation of the components. Based on the belief that the limiting criteria is the buckling, and also on the results of the initial model not shown in this article, the decision was for the optimization of the structure using this criteria. For the optimization procedure, the option was to tackle the problem on the spot of occurrence; and then, with the happening of new failure criticism, solve it until the obtainment of a superior index and also close to one. The main components worked on to reach the accomplishment of the criteria were upper skin and the upper stringers.

5.1. Configuration

The increase on the width, one of the procedures used to inhibit the buckling failure, is a consequence of the increase in the quantity of plies. Therefore, there were some preoccupations to be considered: to put more plies trying not to significantly alter the proportion of the orientations and maintain the wider areas with the maximum value of width within the acceptable limits. The laminates of the components were kept, as shown on Table 3.

Table 3: Laminates

Components	Laminates
Upper Skin	$[90_{(2)}/0_{(4)}/90/0_{(4)}/45/-45/45/-45]_s$
Lower Skin	$[90_{(2)}/0_{(4)}/90/0_{(4)}/45/-45/45/-45]_s$
Upper stringers	$[45/-45/0_{(4)}]_s$
Lower Stringers	$[45/-45/0_{(4)}]_s$
Spars 1, 2 e 3	$[90/0_{(5)}/90/0_{(5)}/45/-45/45/-45]_s$
Spars 4, 5 e 6	$[90/0_{(5)}/90/45/-45]_s$
Ribs	$[45/-45]_{10}$
Caps	$[45/-45/0_{(4)}]_s$

On the stringers, on the other hand, which were modeled as beams, it is necessary the generation of isotropic properties of the composite material in order to allow the use of the bar components, and be able to follow the initial proposal of having stringers integrated to the skin and, therefore, from the same material. For this adaptation, the "Laminator" was used. It is a commercial software that uses the theory of the classic laminated plate, together with the input of elastic and endurance properties of the composite material, the orientations and sequences of the laminate to generate as an output the values of apparent properties of the laminate (The Laminator, 2008). The difference in the property of compression of the lower and upper stringers is due to the fact that stringers have distinct section, as shown on Table 4.

Table 4: Endurance Properties

Beam Components	Width (mm)	E_1 (MPa)	T_{1c} (MPa)	T_{1t} (MPa)
Upper Stringers	1,8	108900	-160.6	1230
Lower Stringers	1,8	108900	-43.2	1230

To simulate a reduction on the width through out the span of the semi-wing, the skins were divided into 3 areas with different properties, so to make a discrete reduction of the width. Figure 7 shows these 3 areas represented in different colors on the upper skin of the model.

The upper stringers were also divided into 3 different properties, as the skin, starting from the root chord, the biggest section, to the tip chord, the smallest section. (Fig. 8)

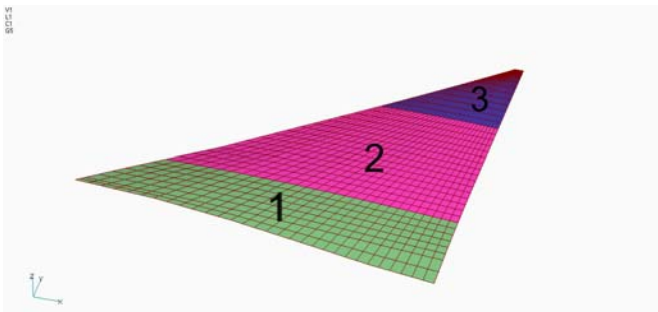


Figure 7: Division of the properties on the upper skin of the model

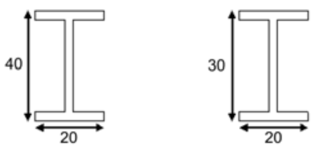


Figure 8: Optimized stringers of upper skin a) root, b) tip (mm)

5.2. Results

The total displacement of the wing end up being 0.65 m on the tip, resulting in a coefficient between displacement and span of 0,075.

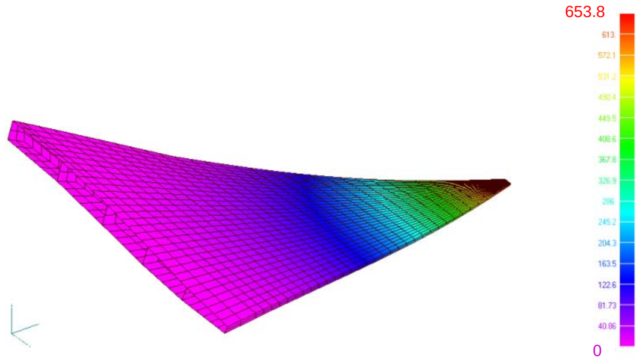


Figure 9: Total displacement of the model

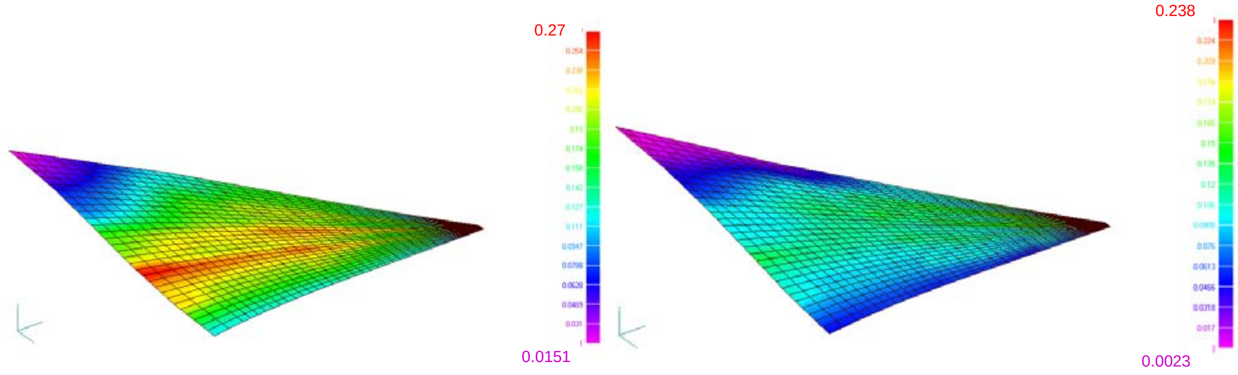


Figure 10: Tsai-Wu criteria for lower (left) and upper skin (right)

The results of the Tsai-Wu criteria show a super dimensioning of the components, not presenting any area of the wing that had similar condition to critical in these criteria. Figure 10 shows the result of the Tsai-Wu to lower and upper skin respectively. With this configuration, after re-dimensioning of the structure resulting from some steps, the buckling index resulted in 1.0006, above and close to the critical value of the unit, solution considered satisfactory. The Nastran solution is shown on Figure 11.

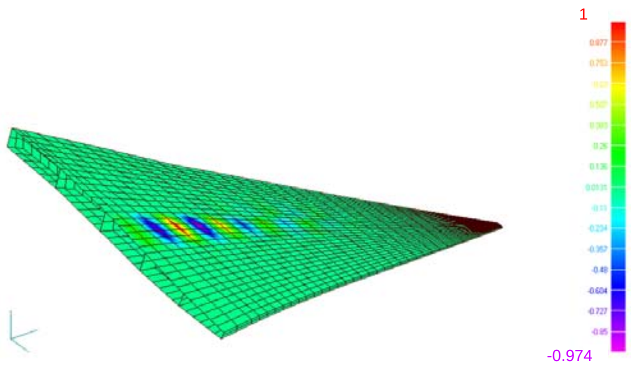


Figure 11: Buckling eigenvalues of the optimized model

Considering Graphite-Epoxy density of 1550 kg/m^3, as shown in Gardner, 2008, and disregarding some elements of the wing such as horizontal caps, relief holes and fuel passage in ribs and spar, among other, the mass of the structure is approximately 1532 kg.

6. DESIGN AND ANALYSIS OF THE METALLIC STRUCTURE

The delta wing made in aluminum came up as a natural option to the comparison of results, and, because of this, the same simplified method of optimization that was used in the previous model to reach the semi-wing with exactly the same layout of the composite wing. Also, as in the procedure of the previous chapters, the optimization comes from an initially estimated model with some alterations on the width of the material of the many components, trying to satisfy the failure criteria adopted. Based on the results already seen, the stability criteria will be adopted, but its displacement will still be presented as a parameter of comparison to the composite wings.

6.1. Configuration

The optimized model had its final components width as follows on Table 5. The lower stringers had their width increased from 3.6 to 4.0 mm and the upper ones from 5.4 to 8.0 mm.

Table 5: Components width

Components	Width. max. (mm)	Width. mid. (mm)	Width. min. (mm)
Spars	25	20	10
Ribs	5	5	5
Upper stringers	12	11	10
Lower stringers	5	4	3

6.2. Results

The displacement of the tip of the semi-wing to the metallic model was within the expected interval; its values were close to 0.57 m, therefore with a coefficient between displacement and span of 0.065. Figure 12 shows this behavior.

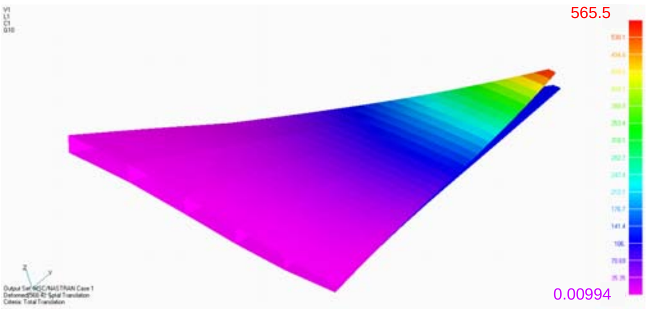


Figure 12: Total deformation of the metallic semi-wing

Figures 13 and 14 show the results of the Von Mises tensions, found in the main components of the wing. Having values of limit tensions of the material above 400 MPa, except for the rib found at the tip of the wing, all the other areas analyzed had satisfactory results.

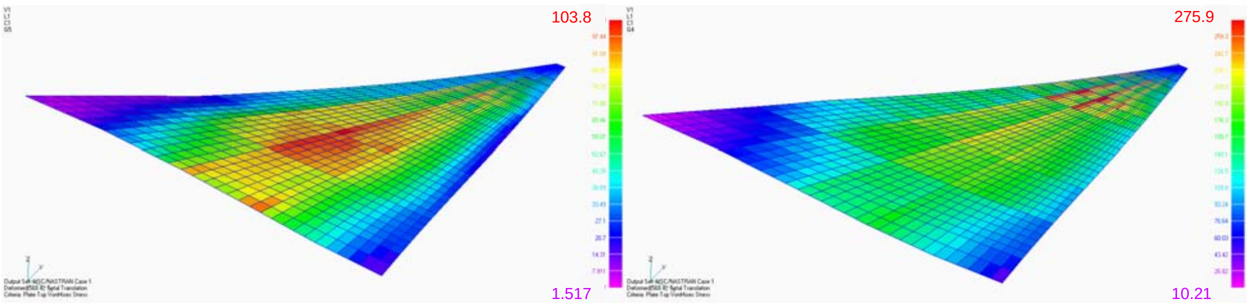


Figure 13: Von Mises tension on the upper (left) and upper skin (right)

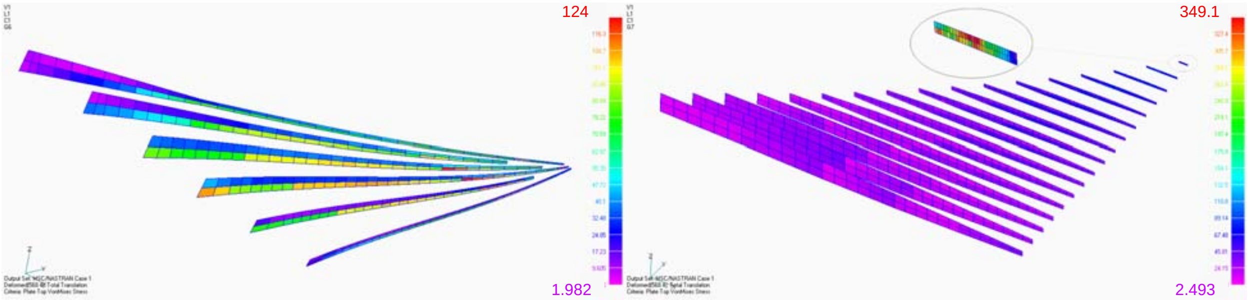
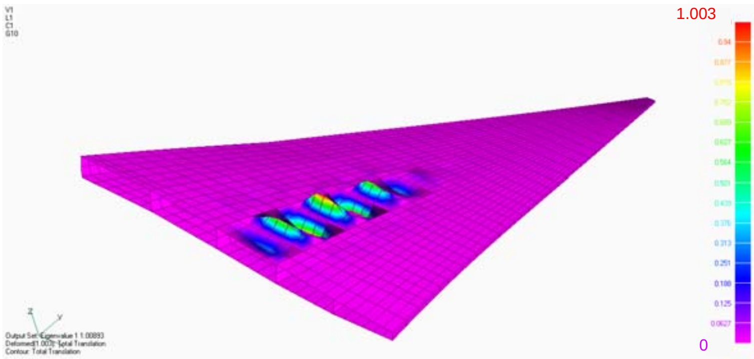


Figure 14: Von Mises tension on the spars (left) and ribs (right)

From the point of view of stability, criteria used for optimization of the model, the eigenvalue found was 1.00893, close to what was found in the composite model. The area where this value was found is shown on Figure 15 and coincides with the change of width of the skin, spars and ribs.

To aluminum 7475 T7351 density of 2790 kg/m3, alloy used in the entire metallic model, the value of the total mass of the semi-wing was approximately 3341 kg.



Picture 15: Buckling eigenvalues of the optimized metallic models

7. COMPARATIVES

The two models followed exactly the same layout, loads and mesh of the elements. The differences laid on the width of the plate components, the sections of the stringers. This comparative was divided into two parts; the geometric differences and the criteria results.

The alteration of the components width and the sectioning of the stringers were artifacts used for the optimization of the models. Both suffered the same process to reach a final model. Special care was taken on the modification of the composites width in order keep the percentage of the plies orientation.

Table 6: Skins width

Components	Width. A1(mm)	Width. A2(mm)	Width. A3(mm)
Upper skin - Metallic	12,0	11,00	10,0
Upper skin - Composite	7,5	7,2	7,2
Lower skin - Metallic	5,0	4,0	3,0
Lower skin - Composite	4,5	4,5	4,5

In the comparative of stringers is shown the beam dimensions, to the upper as much as to the lower of the two models. As we can see on Table 7, the lower stringers had the section maintained constant through out the span for the two wings, because their modification did not alter the weight or the results of the stability criteria significantly.

Table 7: Stringers dimensions

Stringers	Hr(mm)	Wr(mm)	Tr(mm)	Hp(mm)	Wp(mm)	Tp(mm)
Upper Composite	50	20	7,2	30	20	5,4
Lower Composite	15	10	1,8	15	10	1,8
Upper Metallic	30	20	7	40	25	8
Lower Metallic	30	15	4	30	15	4

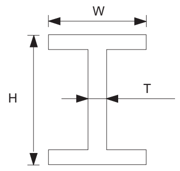


Figure 25: Beam dimensions

With two different types of material, the Von Mises criteria of the metallic wing and the Tsai-Wu criteria of composite did not appear in this comparative analyzes exactly because they are not shared by the two models, having nothing else to say but that in both models these criteria were complied. Moreover, even not being an evaluation criterion, the deflection of the wing is represented by Figures 9 and 12 which shows a similar behavior of the stiffness of both, with 0.65 m to the composite model and 0.57 m to the metallic. The stability criteria was limiting to both models on the central area of the wing and, therefore, the reason of the changes on their geometry. The objective of the optimization was to reach a superior value, but very close to 1, and the value 1.0006 was obtained to the composite wing, and 1.0089 to the metallic one. Both models had their critical areas found on the basis of the upper skin of the wing.

As the whole process of optimization aimed the lightest structure possible that would pass on the failure criteria, the mass of the structures was the expected final result and the most significant to the study of models. Once introduced the data of material density, the program of finite elements calculated the mass of the structures, weighing the metallic wing 3341 kg against a mass approximately twice as small of the composite wing, 1532 kg. It should be mentioned that the composite wing needs some additional artifices to accomplish the project of an aircraft, and the addition of these components should decrease considerably the difference of mass between the structures.

8. CONCLUSION

Using the same optimization criteria for both wing models, it was shown that the simplified structure of the wing made of composite came down to half the mass of the same structure made of aluminum. Although it was not part of the proposal of the group during the study, we must say that all the simplifications made penalize the metallic model in this comparison, once the aeronautic manufacturing technology of composite demands some attention to issues such as metallization (protection against storms) and affixation between composite components and metallic. These artifices add mass to the composite wing, decreasing the difference between the models, but as it was not part of the study, we do not have values to quantify this weight addition. However, it is shown that, when dealing with projects of different materials, they must be optimized from their conception.

9. ACKNOWLEDGEMENTS

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