STRUCTURAL DESIGN OF AN UAV FUSELAGE USING TOPOLOGY OPTIMIZATION METHODS

Daniel de Oliveira Andrade*, William Corbelli*, Rodrigo de Sá Martins*, Ramón Rodrigues Vieira de Queiroz*

***Universidade Federal de Minas Gerais**

Keywords: *Structural Optimization, Structural Design, Topology Optimization, Discrete Optimization.*

Abstract

Aircraft weight reduction is one of the greatest challenges of the aeronautical sciences, including the unmanned vehicles. This reduction represents fuel economy and better performance. In this paper, in order to design effective structures a optimization procedure was used. The topology optimization was used it characterize and determine the optimum distribution of material into the domain. After that, a size optimization was set to finish the structural design. Finally, the results were compared with the same component, that was design without the optimization tools.

1 Introduction

The current paper was motivated by the competition SAE AeroDesign Brazil. Such competition is a challenge proposed to engineering students, whose main goal is to foster the diffusion and exchange of aeronautical engineering techniques and knowledge. Thereby, the student can be involved in a real case of aeronautical development project, since its inception, detailed design, building and tests.

The airplane analyzed in this paper is classified in the regular category, which the main objective is to design a plane with the highest payload. The structural efficiency is a very important parameter, since the payload is the maximum take-off weight less the aircraft empty weight.

The differential adopted by the team was a modification in the airplane tail, previously composed only by one carbon tube (fig. 1), resulting in a less structural efficient structure to resist torsion and bending.

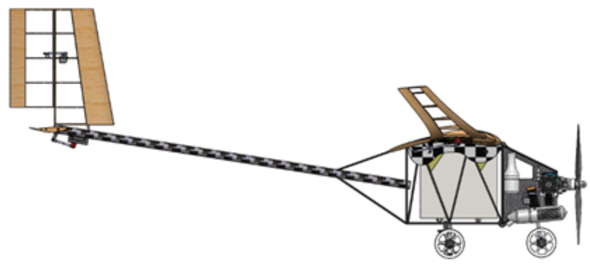

Fig. 1 UFMG 2015 airplane.

Such configuration was replaced by a truss cone. In this case, a topology optimization can be very beneficial to the structural design, since there are an infinite number of possible architectures.

2 Structural Optimization in design

Structural optimization can be generally defined mathematically by the following [1]:

Find $\mathbf{x}$, that minimize $f(\mathbf{x})$, subject to $\mathbf{g}(\mathbf{x}) \leq \mathbf{0}$.

Where f (objective function) is a scalar, $\mathbf{x}$ (design variable) is a vector of n components and

g (constraints) is a vector of m components.

There are several methods for structural optimization developed over the years. Several commercial software have the algorithms implemented and linear programming are usually used to find the solution ([2] and [3]). Other kinds of algorithms, such as genetic (like the one performed by (like the one described by [4] to design Skeleton Structures) or ant colony (developed by [5] can be used to solve the optimization problem.

The methodology shown in this paper is based in [6]. [6] divided the optimization in two parts, the first one is a topology optimization, followed by a discrete size optimization. Using Optistruct [2], the design could only be performed in two steps.

Since the problem was divided in this two parts, there is no easy way to know that the solution is global optimum. To perform the whole design with one optimization analysis, stress constraints should have been taken into account. [7] developed a very robust method to take into account the final geometry of the component, but his analysis was performed only in two dimensions.

2.1 Topology Optimization

In this paper the topology optimization is performed by minimize the compliance which is equivalent to maximize the stiffness. Maximizing the stiffness using a constant volume in a design space, it is possible to find the best load path [8].

Selecting the compliance as the objective function and the relative density of each finite element ψ as a design variable, the optimization problem can be rewritten as:

$$Minimize \int_{\Gamma} F^i z^i d\Gamma \rightarrow \int_{\Omega} \psi(x) d\Omega < V_0 \qquad (1)$$

and a side constraint $0 \leq \psi(x) \leq 1$.

Where F^i is the force, z^i is the displacement, Γ is the loaded boundary, Ω is the physical domain and V_0 is the volume fraction.

2.2 Size Optimization

Selecting the final component mass as a objective function and putting Buckling and Stresses as constraints it is possible to size the structure with the architecture found in the topology optimization. Or:

$$Minimize \int_V \rho dV \rightarrow \begin{cases} \sigma < \sigma_u \\ \lambda \leq FS \end{cases} \qquad (2)$$

Where ρ is the material density, V is the volume of the component, σ is the maximum stress in the analysis σ_u is the strength limit of the material, λ is the buckling eigenvalue and FS is the buckling factor of safety. In this case, the design variables are the members cross sections, being discrete due to the fact that they are chosen from finite available tubes.

3 Structural Design

The first step in the structural design is the determination of loads. In this case, the loads are mainly aerodynamic coming from the horizontal and vertical stabilizers.

The fuselage was divided in two parts (fig. 2). The truss distributions are calculated analytically in the part 1, since the loads are mainly from the wing, landing gear and cargo compartment (fig. 3). The part 2 will be design space in the topology optimization developed in this paper.

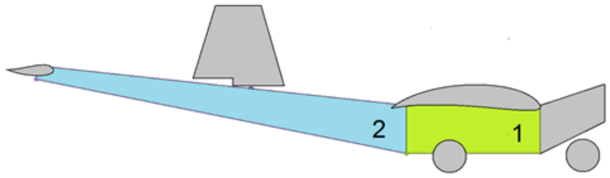

Fig. 2 Design space.

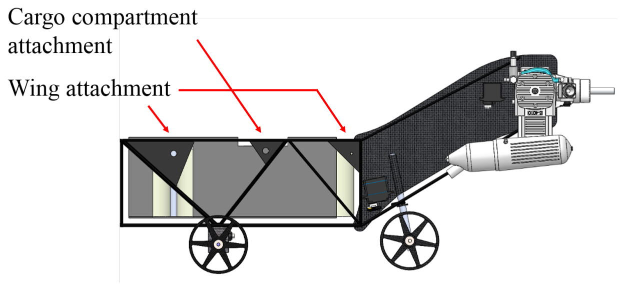

Fig. 3 Cargo bay detail.

The truss cone was idealized as a triangular geometry. This configuration does not need diagonal web members, therefore, is more structural efficient than a rectangular shape (fig. 4). Besides that, the truss cone is manufactured by three separated planes (fig. 5). Thus, it is preferable to idealize the design space as plane elements.

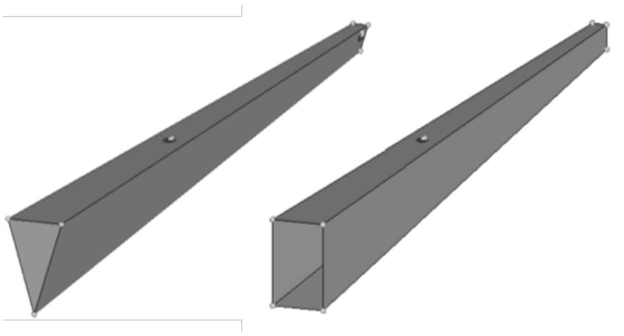

Fig. 4 Tail geometry.

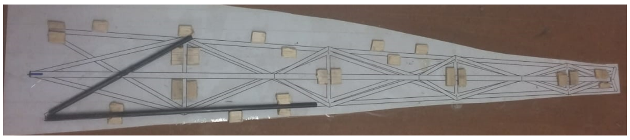

Fig. 5 Truss manufacturing.

The regular class aircraft's from 2017 SAE Brazil AeroDesign Competition had to fit into a cone with 2900 mm of diameter and 750 mm of height. Therefore, the vertical stabilizer was thereabout placed in the middle of the truss cone (fig. 6)

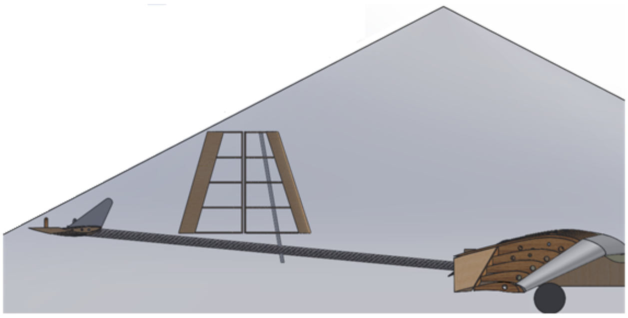

Fig. 6 Cone restriction.

Two different types of attachments were proposed for the vertical stabilizer, shown in fig. 7 and fig. 8.

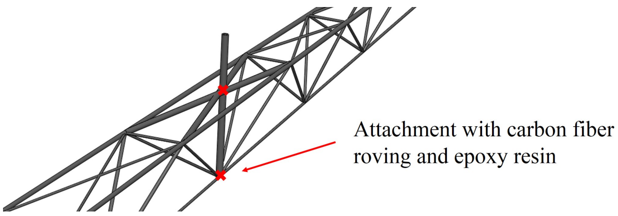

Fig. 7 Vertical tail attachment type 1.

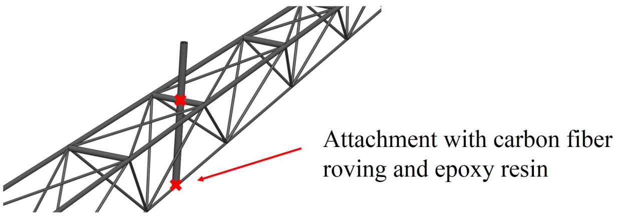

Fig. 8 Vertical tail attachment type 2.

The SIMP method (Optistruct topology solver) is only available for isotropic materials [2]. Therefore, the carbon fiber was assumed isotropic. This is a valid approximation, since the trusses are designed to mainly resist axial loads and the carbon fiber tubes are unidirectional and pultruded.

3.1 Truss Topology

The optimization objective is minimize the compliance of the structure. Thus, only the members who most contribute to the stiffness of the structure will be kept. The optimization constraint is the volume fraction. Higher values of volume fraction tend to concentrate mass, creating large members. Lower values can overlook some members, making the structure incomplete.

The criteria to choose the best volume fraction was the uniformity and size of the members. A manual bisection method was used in an interval from 0.3 to 0.1 to converge the volume fraction value. In the both cases (fig. 9 and fig. 10), the chosen value was 0.12, which was closest to a truss like structure.

The chosen results are exported to the CAD though the OSSmoth with a threshold value (minimum density of element) of 0.15. The trusses are sketched, exported to a STEP file and imported back to the Hypermesh.

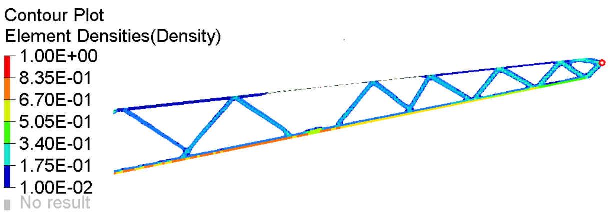

Fig. 9 Topology optimization (First type of attachment).

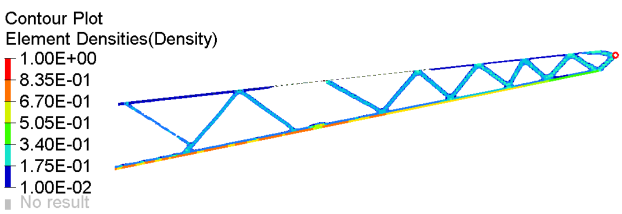

Fig. 10 Topology optimization (Second type of attachment).

3.2 Final Layout

After the structural architecture was obtained for the two kinds of vertical stabilizer attachments, the final layouts were obtained using a discrete size optimization. Tab. 1 shows the available tubes for the tail truss.

Table 1 Available Carbon Tubes

Tube	Otter Diameter(mm)	Inner Diameter (mm)
1	5	3
2	4	3
3	4	2
4	3	2
5	2	1

The finite element model was built using the results from the topology optimization. Fig. 11 shows the finite element model, highlighting the the constraints and loads.

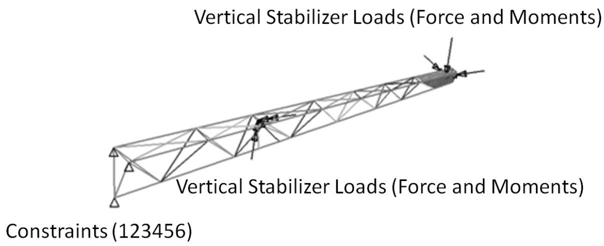

Fig. 11 Analysis setup

To apply the size discrete algorithm, there is an extra difficulty: the discrete design variables are entangled, that is, the inner and outer diameter for each tube are related. To simplify the optimization, an analysis was performed using only the smallest tubes. The stress analysis is shown in fig. 12.

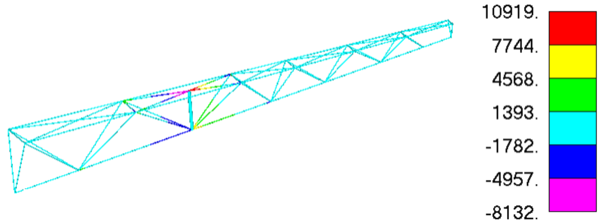

Fig. 12 Stress analysis of tail truss using the smallest tubes (Stresses in MPa).

According to fig. 12 and the allowable tensile/compressive stress of tab. 2, the safety factor can be calculated:

Table 2 Material Properties [9].

T300

COMPOSITE PROPERTIES**

Tensile Strength	255 ksi	1,760 MPa	ASTM D-3039
Tensile Modulus	19.5 Msi	130 GPa	ASTM D-3039
Tensile Strain	1.3 %	1.3 %	ASTM D-3039
Compressive Strength	230 ksi	1,570 MPa	ASTM D-695
Compressive Modulus	18.5 Msi	125 GPa	ASTM D-695
In-Plane Shear Strength	14 ksi	98 MPa	ASTM D-3518
ILSS	15.5 ksi	11 kgf/mm^2	ASTM D-2344
90° Tensile Strength	11.5 ksi	80 MPa	ASTM D-3039

$$FS = \frac{\sigma}{\sigma_u} < \frac{1570}{10919} = 0.14 \tag{3}$$

The buckling analysis was performed and the results are shown in fig. 13.

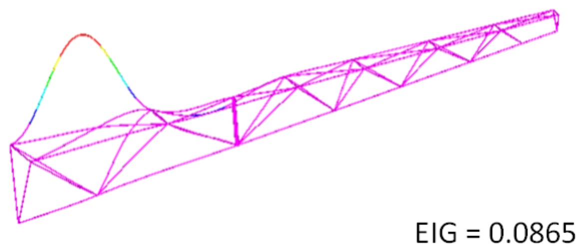

Fig. 13 Buckling analysis of tail truss using the smallest tubes.

Since the buckling eigenvalue is lower than the strength factor of safety, it was considered that the structure is dimensioned by buckling. Thus, it is assumed that the important design variable is the the inertia and not the cross-section areas. The tubes were changed by equivalent bars with the same inertia (fig. 14).

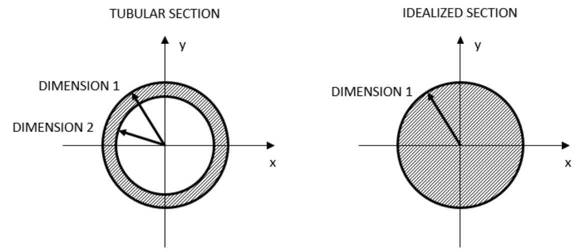

Fig. 14 Section transformation

$$I = \frac{\pi(D_{out}^4 - D_{inn}^4)}{64} = I_{eq} = \frac{\pi R_{eq}^4}{4} \tag{4}$$

$$R_{eq} = \sqrt[4]{\frac{(D_{out}^4 - D_{inn}^4)}{16}} \tag{5}$$

The equivalent radius for each tube are shown in tab. 3.

Table 3 Equivalent radius for optimization

TUBE	INERTIA (mm^4)	EQUIVALENT RADIUS (mm)
1	26.70354	2.415
2	8.890292	1.816
3	11.78097	1.968
4	3.19068	1.420
5	0.736311	0.984

Using the equivalent radius as a design variable, it is possible to set the optimization with discrete and independent design variables. For the first geometry, the results are shown in fig. 15.

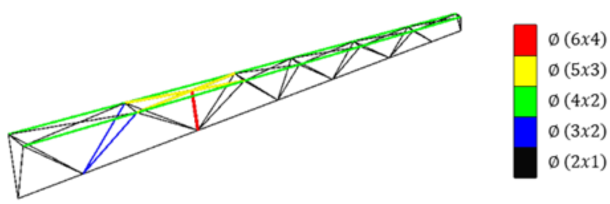

Fig. 15 Optimization results for the first structural architecture.

For the second geometry, the results are shown in fig. 16.

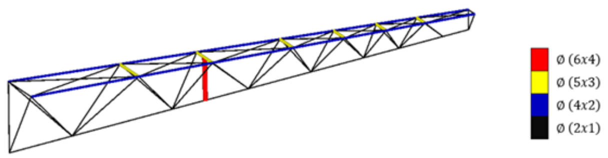

Fig. 16 Optimization results for the second structural architecture.

4 Discussion

The mass value of both structures found in this study were similar. The first model weight 54 g and the second one weight 51 g. Since the analysis performed in the optimization was an approximation (it used the concept of equivalent radius), it is necessary to check the strength of the final design (model 2). Fig. 17 shows the final analysis results.

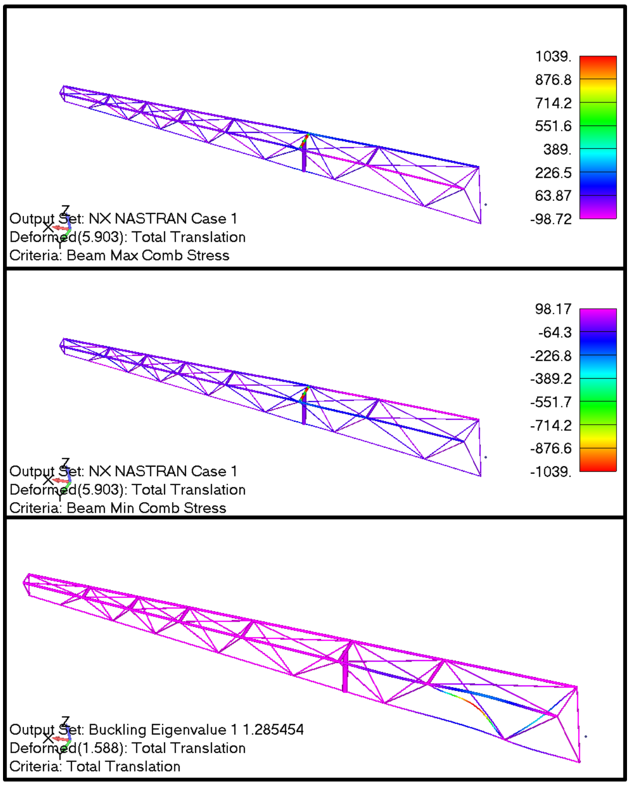

Fig. 17 Stress and buckling analysis of the final configuration.

The design of the same structure performed without optimization ended up with a 100 g tail truss. That means that the optimization process represented a 49% weight reduction.

5 Conclusions

In the present paper the following conclusion could be made:

- The optimization analysis was proven to be very effective when comparing the design of the tail truss with and without optimization analysis.
- The equivalent radius approach was very important to simplify the problem.
- A concise optimization process was essential to obtain the good results shown here.
- For further work, the authors recommend to redo the optimization with only one analysis (using an hybrid topology/size algorithm).

References

[1] William R. Spillers Keith M. MacBain. *Structural optimization*. 2009.

[2] Altair Engineering. *Optistruct User Manual*. 2017.

[3] R. J. Yang. Optimal topology design using linear programing. *Computers & Structures*, 52:265–275, 1993.

[4] Kevin Gillman Richard J. Balling, Ryan R. Briggs. Multiple optimum size/shape/topology designs for skeletal structures using a genetic algorithm. *Journal of Structural Engineering*, 132:1158–1165, 2006.

[5] Barron J. Bichon Charles V. Camp. Design of space trusses using ant colony optimization. *Journal of Structural Engineering*, 132:1158–1165, 2004.

[6] Dianzi Liu Osvaldo M. Querin, Vassili V. Toropov. Parametric optimization of a lattice aircraft fuselage barrel using metamodels built with genetic programming. In *The Fourteenth International Conference on Civil, Structural and Environmental Engineering*.

[7] C. Brampton J. Norato H.A. Kim R. Picellia, S. Townsend. Stress-based shape and topology optimization with the level set method. *Computer methods in applied mechanics and engineering*, 329:1–23, 2018.

[8] Martin P. Bendsœ. *Topology Design of Structures*. 1993.

[9] Torayca. Technical data sheet no. cfa-001. Technical report.

6 Contact Author Email Address

For contacting the authors, please refer to:
danielandrade.aero@gmail.com
corbelli.william@gmail.com
rodrigomartins@demec.ufmg.br
ramonrvq@gmail.com

Copyright Statement