

STRUCTURAL DESIGN OF MINI-UAVs WITH CONVENTIONAL AND ALTERNATIVE MATERIALS

Zeus Siqueira Bessoni, zeussiqueira@gmail.com

University of Brasilia - UnB

Manuel Nascimento Dias Barcelos Júnior, manuelbarcelos@gmail.com

University of Brasilia – UnB at Gama

Abstract. *The goal of this paper is to present the structural design of an unmanned aerial vehicle (UAV) using conventional and unconventional materials from the aerospace industry. In order to design each component of the aircraft as optimized and light as possible, a methodology based on analytical, numerical and experimental analyses will be developed. The aircraft design was devised according to the requirements for monitoring UAVs to be as optimized as possible taking into account every detail in design areas such as aerodynamics, structures, stability and performance. The work seeks to structure a methodology to create a product to be equipped with optical cameras and / or infrared and systems for navigation, control, positioning and real time data storage and transmission. The main application areas for the project are supervision, tracking and recognition. The aircraft can be employed to different kind of missions by the public sector such as soldiers, police officers, firefighters and by the private sector in general.*

Keywords: *Aircraft, UAV, unconventional materials, conventional materials, analytical analyses, numerical analyses and experimental analyses.*

1. INTRODUCTION

Inserted within the context of technological development, this project seeks from the development of a UAV (unmanned aerial vehicle) to empower students and universities to work in aerospace and develop national technologies and methodologies that can be used in Brazilian industry to manufacture products.

THE UAV is a vehicle that does not require an onboard human operator, employs aerodynamic forces to generate support, can be controlled remotely or automatically and can carry a lethal payload or not (U. S Army UAS Center of excellence, 2010; Dalamagkidis, 2009).

Due to its reduced cost compared to a conventional aircraft and the fact of not having a crew, the UAVs are gaining space within military applications since the First World War and in the civil field one can highlight the interest in Brazil from the year 2000 with the work between enterprises and universities for the construction of UAVs with 100% national technologies (Brig. Christopher, 1997).

The VANTs began as "smart bombs" used in the war and soon were gaining importance. Today we can highlight as main applications: the UAVs for monitoring, transportation, scientific research, attack, search and rescue, agriculture and livestock.

The work will be divided into three sections: analytical methods, numerical methods and tests. For the analytical methods, it will be used analytical, empirical and semi-empirical formulations for dimensioning of the main structures of the airplane. For the numerical methods, it will be employed finite elements to seek more realistic results than those achieved with analytical methods. The two methods will be compared and their results will be validated by experimental tests, static and dynamic, considering components separately, set of pieces and complete prototype.

From the comparison of these three steps, it will be developed a design methodology that seeks to unite lower cost, greater simplicity and better results.

2. METHODOLOGY

For structuring the methodology, it will be used an aircraft model, developed by the team involved in the project, which had its initial characteristics decided to contribute with the project development. These configurations were placed in an optimization program based on genetic algorithms that provided the preliminary configuration of the project.

THE optimization program uses analytical, empirical and semi-empirical formulas programmed in the MATLAB platform® (MATrix LABoratory) and the program AVL (Athena Vortex Lattice) to obtain estimates of the main information of the airplane as lift, drag, power required by the engine and payload and total masses.

Further analyses were made by the programs AVL and XFLR5 (a set of tools for profile, wing and plane analysis operating at low number of Reynolds based on theory of lift line, Vortex Lattice method and 3D panel method) in the aerodynamic and stability areas, resulting in the following characteristics:

- High wing monoplane
- Aspect ratio: 5.5

- Aspect ratio horizontal tailplane: 2.1
- Aspect ratio vertical tailplane: 1.5
- Wingspan: 3 meters
- Profile: clark y
- Wing root chord: 0.29 meters
- Wing tip chord: 0.03 meters
- Elevator Profile and rudder: NATION 0012
- Elevator chord: 0.20 meters
- Rudder root chord: 0.18 meters
- Rudder tip chord: 0.10 meters distance
- Distance from wing to tail assembly: 0.5 meters
- Estimate of engine traction engine: 110 N
- Estimate of empty weight (airplane + batteries): 2.5 Kg
- Estimate of total weight (airplane + equipment): 5.0 Kg
- Estimate of maximum total load to be transported: 7.5 Kg
- Safety factor load: 1.5
- Estimate of the payload compartment volume: 0.08 (diameter) x 0.16 (length) m.

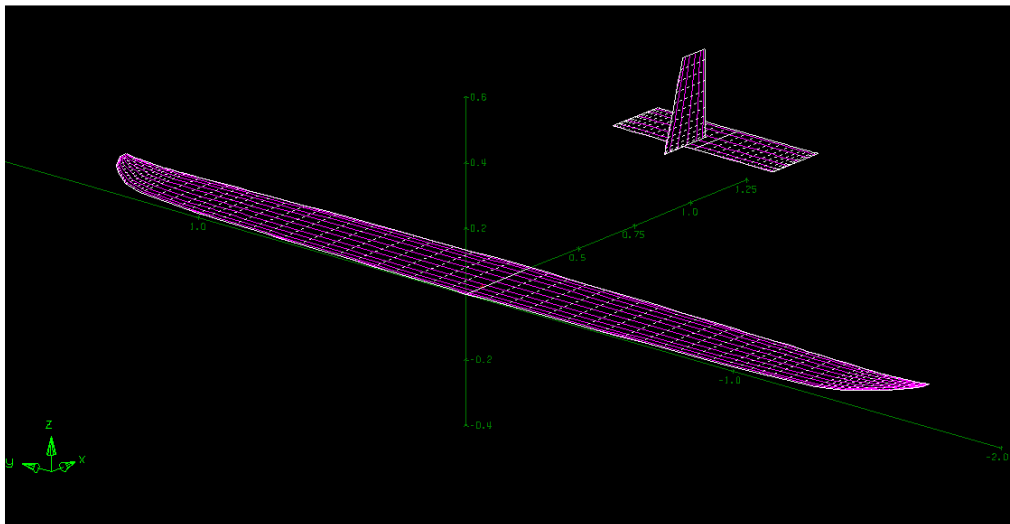


Figure 1. Aircraft Picture inside the program AVL.

Aiming ease operation, low cost and performance, the aircraft was designed as a central tube where are connected the tail tube, the engine and the wing spar tubes. The tail planes are connected at the end of the tail tube. All these components were designed to be made with commercial tubes.

To simplify the execution of the structural calculation, the aircraft was divided into 5 parts: engine tube, central tube, wing spar tubes, rudder and elevator tubes and tail tube.

The distribution of the load on the wing allows for this to be concentrated at the point where the moment is constant, regardless of the angle of attack, becoming into a vertical force upwards and a moment that tends to bring the airplane nose upward, the wing spar tube was placed at that point. Due to the materials that the profiles and the surface of the wing are built, employed only to keep the shape, these were disregarded in structural calculations because they have a much smaller influence on resistance of the wing than the spar tube, and also they can lead to higher level of complexity in the calculations. The same analysis can be made for the tail planes.

The wing and rudder spar tubes were treated as uniform section cantilever beams clamped at the central tube and trail tube, respectively, and their external diameters were limited by the maximum thickness of the wing tip, rudder and elevator profiles. The tail tube was dimensioned as a uniform section cantilever beam clamped at the airplane central tube. Its outer diameter was limited to 5cm. The engine tube was dimensioned as a uniform section cantilever beam clamped at the airplane center tube and has its internal diameter limited by the outside diameter of the engine that will be placed inside the tube.

MATLAB program routines were created to compute and determine the lighter set of structural elements that endures the load imposed to the aircraft. The routine can choose over a range of commercial tubes of different external diameters and thicknesses made of steel, aluminum, carbon fiber, Kevlar and glass fiber.

Each routine calculates the tensions acting on the component using the criterion of Von Mises and Tsai-Hill failure criteria for the metallic and composite materials respectively, in order to discover the lighter tube that withstands the loads with a safety factor of 1.5. The second criterion for selection of tubes is the deflection. The routines calculate the deflection suffered by the tube and these must be smaller than a specific limit in order of not jeopardizing aircraft aerodynamics.

The best 6 tubes of each component (3 metal and 3 composite) selected in analytical step will be simulated in the program ANSYS® trying to get closer to the maximum of the imposed conditions in the previous step. The tensions and deflections suffered by beams will be examined and these will serve as basis for experimental test comparison. Several numerical beam and shell elements and different simulation methodologies are used to identify which has the best cost benefit, results compatible to reality and lower computational cost.

The tests will be divided into 3 parts: static, dynamic and flight tests, and these will be executed with pieces separately, assemblies and prototypes. The static tests will be done with the fixed components by distributing weights over them to emulate the steady aerodynamic loads experienced in order to better compare the real conditions to the ones calculated analytically and simulated numerically. The dynamic tests shall be made by imposing conditions similar to flight with loads varying in intensity and direction. The flight tests will be done with prototypes equipped with onboard telemetry. At all tests, the components studied will be equipped with strain gauges in order to measure the acting tensions. In addition, all deflections and displacements will be measured for comparison reason. The experimental data collected in every test will be considered as reference values.

As a second design line, in parallel to the first design process using conventional materials, a whole new process is repeated following the same steps as the first, but now employing alternative and recycled materials. It will be used materials that seek to unite low cost and low impact on the environment (recyclable and biodegradable) without harming the performance of the airplane. By using these materials, UAVs can become much more accessible and still engage in world politics of environmental preservation. The selected materials to be tested are: bamboo, cardboard, styrofoam, plastic bags, PET and aluminum cans.

The biggest problem of working with these materials from a dimensioning point of view is the lack of information about their properties. When there is information on the properties of the materials, these are estimates without assurances that the components used have properties within the ranges of values specified and follow a standard of quality expected. This is due to the fact that these materials have several utilities where those properties are not so relevant, and also, they do not need to be produced or processed with a high quality level as is required for materials in aeronautic applications. In the case of bamboo, for being a live material that suffers the influence of the environment, the properties are variable from plant to plant.

In this work, it will be used properties estimated (from bibliographies) and these will be compared after to data of experimental tests in order to find an analytical and numerical dimensioning consistent to the reality. The bamboo will be used in 5 structural parts which will be dimensioned: engine and central tube, wing spar tubes, rudder and elevator tube and tail tube, and it will be treated as a composite beam with unidirectional fibers with longitudinal properties varying in each layer. Bamboo beams will be dimensioned first by analytical methods and then by numerical methods.

In addition to the problem of dimensioning using alternative materials, there is still the practical problem where some of the materials are degradable, which requires a special treatment in relation to the attack of pests, moisture, excessive heat, exposure to sun and weather. For this, it will be used varnishes and techniques for the preservation of these materials.

4. STRUCTURAL DESIGN

4.1 STRUCTURAL LOADS

The first step of the structural design is the determination of flight envelope and the aircraft loads. The flight envelope is expressed as a graph of the load factor by the speed and follows the patterns of the FAR 23 standard.

According to the FAR standard, planes so-called "normal" must have a load factor limit that are below 3.8, second Raymer (1992) the characteristic values for the same type of aircraft are between 2.5 and 3.8. For this project it was adopted n_{max} equal to 2.5 due to the fact of being an UAV and operating primarily for flights plans leveled without major maneuvers (Rosa, 2006).

According to the FAR standard, the negative load factor must be at least -0.4 times the positive load factor. For this project it was adopted a negative load factor of -1.

The maximum speed of the aircraft in strait flight predicted in preliminary calculations is 28 m/s which leads the maximum speed of the aircraft in diving presented in the diagram to be 42 m/s. By using this information one can calculate the whole envelope of flight maneuvers.

The calculation of the gust envelope used gust speeds (U_{de}) of 3.6 m/s and 2.4 m/s for the speed limits of cruising and diving respectively.

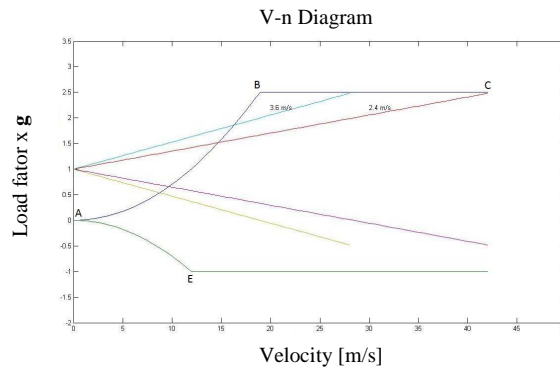


Figure 2. V-n diagram calculated for the project

By having the aircraft load factors; one can calculate the loads that each component of the aircraft undergoes. The loads used for preliminary calculations of the components of the aircraft were estimated in different subproject areas: aerodynamics, stability and propulsion.

4.2 ANALYTICAL DESIGN

The analytical design was divided into four parts: wing, tail tube, engine tube and stabilizer. Each of these components was designed according to criteria of deflection and maximum stresses for metallic and composite materials. For the whole analytical design, it was employed a safety factor of 1.5 (FAA, 2011).

All loads were computed by the AVL program, simulating the whole aircraft for leveled flight and landing conditions. The larger loads were employed, among all flight conditions, for designing.

For all the calculations it was used a system of coordinates where the direction X is normal to the cross-section of the beam, and the Z-direction and the Y-direction define the cross-section plane.

For the metallic materials, it will be used the Von Mises failure criterion and the method of superposition to find the maximum deflection. For the composite materials, it will be used the Tsai-Hill failure criterion, because it is one of the most accepted, together with the superposition method also to find the maximum deflection.

All beams of composite material were considered made with only one layer of tissue balanced bi-directional (0°, 90°) and were treated as orthotropic composites. The properties of the materials have been adopted as average taken from the bibliographies (Mendonca, 2005; Neto and Pardini, 2006).

For the calculation of the wing, it was disregarded the influences of the profiles and coating as structural components leaving only the spar element. The spar was positioned at one fourth of the wing chord, where it is located approximately the aerodynamic center, also, where the moments generated by the lifting forces remain relatively constant. Even considering the spar as a single structural element, it is known that both the profiles and the coating of the wing influence increasing its stiffness and resistance, however, as this influence is much smaller than that of the spar element, this can be considered as a safety factor for the wing, Figure 3.

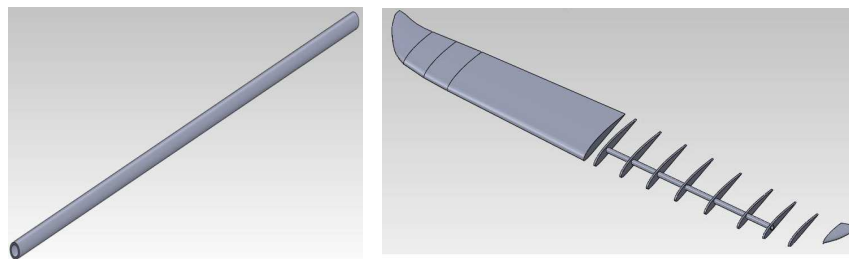


Figure 3. Difference between the real and the ideal wing

The spar element was treated as a beam in balance clamped at the wing root. For constructive reasons and seeking the greater inertia possible, it was adopted a uniform circular cross-section a long of the span and its outer diameter is limited by the contour of the profiles.

It was created a program in MATLAB (Matrix Laboratory, interactive software for high-performance numeric computation) where a range of commercial metallic and composite tubes with different outer diameter and thickness, both limited by its outer diameter smaller than the maximum thickness of the profile of the tip of the wing. In order to determine the lighter possible tube that withstands any tension with a safety factor of 1.5 and a maximum deflection of 0.15m, without modifying the aerodynamics of the wing.

The steel tubes were placed basically for comparison and are often heavier than the pipes made of other materials. The aluminum tubes have excellent results, have a low cost, but are not the most lightweight, are an alternative to cheapen the project if the tolerances of weight are not as restrictive. The tubes of carbon/epoxy are present in most of the components as the best choice, with excellent mechanical properties that combine low weight and high stiffness, ideal characteristics for aerospace components.

The negative point of these tubes is the price and fragile behavior, its use in components considerably increases the cost of the aircraft. An alternative to the carbon tubes are the Kevlar® tubes, which do not have properties as appropriate as the carbon, but can be an alternative in search of a price reduction. The fiber glass tubes have the worst mechanical properties between the fibers, but are easily found and present costs much lower than the other two fibers, and may, like the aluminum be an alternative to cheapen the project when the weight restrictions are not very critical.

Based on preliminary analytical calculations and results found, it was made a pre-selection of the materials that will be used in aircraft. These materials also will be validated and optimized with subsequent numerical simulations. Parties of the aircraft that did not go through the process of analytical design were selected on the basis of the materials commonly used in aircraft of the same size. With respect to alternative materials, there was pre-selection, some materials will be tested and rated for verification of their possible use in aircraft.

4.3 NUMERICAL SIMULATIONS

For the numerical simulation, it was used the software ANSYS 13.0 workbench because it is a program with excellent reputation in the area of numerical simulations and presents results compatible and reliable, and has an more intuitive interface.

For the structural problems, the program uses the FEM (Finite Element Method). This consists in discretizing into smaller elements the piece to be examined. Each element can be considered as a spring that has stiffness, size and properties. The governing differential equations are locally linearized over each element and the combination of the local linear systems of equations into a global system of equations subject to boundary conditions completes the modeling process.

The simulations will employ elements of automatic type (the software selects the best element) and a tetrahedral one. The tetrahedral meshes will be divided into 3 cases: the first with maximum refinement, the second with intermediary refinement and the last with minimum refinement. Results of equivalent Von Mises stress and maximum deflection will be obtained to be compared to the analytical ones.

For simulation of the wing structure, it was considered a tube clamped at the wing root and subjected to lift and drag forces, and an applied moment applied located on a point over the wing span, Figure 4. It was considered an acceleration of 2.5 times the gravity acceleration ($2.5 \times g$) as load factor.

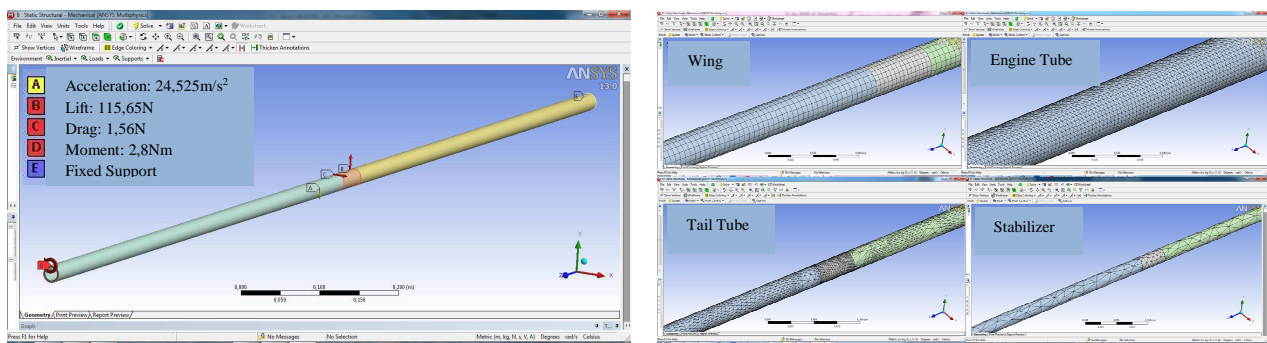


Figure 4. Boundary conditions employed for the wing structure simulation and meshes for the four structure designed, respectively: wing, tail tube, engine tube and stabilizer

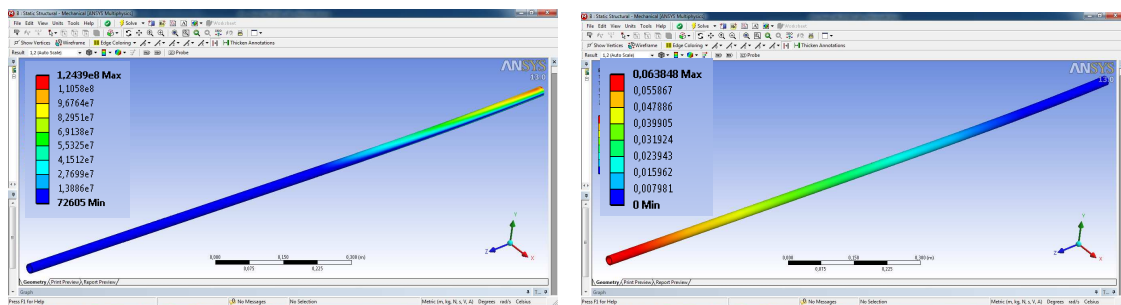


Figure 5. Stress and deflection results for the tail tube element

The first results obtained with the numerical simulation showed great difference compared to the analytical results, especially those regarding the stress, Figure 6. One of the reasons for this error was the boundary condition at the clamped wing root. To solve this problem, rather than simulate half wing, it was simulated the whole wing, and the wing was clamped over a significant area at the root, the piece inside the fuselage, to avoid stress concentration. It was also used an interactive method of convergence with the objective to improve the results. The procedure of simulating the complete wing considerably improved the results, reaching an error for deflection of 6.22 %.

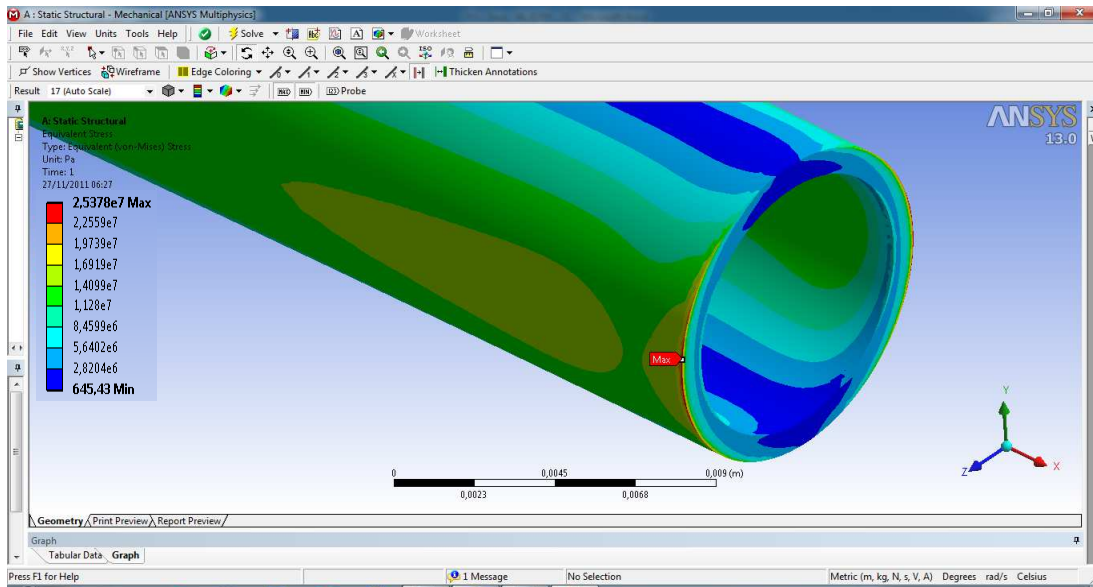


Figure 6. Stress concentration problem at the clamped root edge

Despite the problems of stress concentration found in the numerical simulation, it was possible to find satisfactory results in comparison to the analytical ones. The best results achieved for the tail tube were 0.13% error of deflection, and for the rudder and the elevator were obtained only stress results due to their small displacement and the error were: 1.34 % and 1.9%, respectively.

4.4 TESTS

Two prototypes of low cost were built with the objective of serving as platform for static and dynamic testing; testing slots and constructive techniques; testing the use of alternative materials; and on flight testing for data acquisition. One of the prototypes is made of the aeronautics industry materials donated by the enterprise ALLTEC, and the other is made of recycled materials and bamboo donated by CPAB (Center for Research and Application of Bamboo and Natural Fibers), both using onboard electrical equipment conventional UAVs, Figures 7 and 8. The prototypes were designed in program SolidWorks and constructed in the workshop of the aerodesign team Draco Volans from the University of Brasilia, Figure 8.

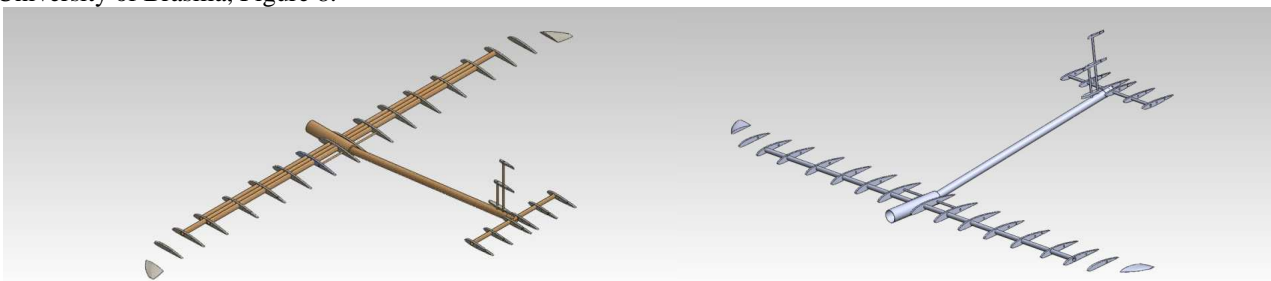


Figure 7. CAD of the conventional and alternative designs



Figure 8. Prototypes of the conventional and alternative materials

For comparison purpose static tests were executed with both prototypes in order to validate analytical calculations and numerical simulations and to have more data for comparison. The tests were applied to the wings of two distinct ways, with weights concentrated at the point of force application and with weights distributed mimicking the distribution of forces during a flight. In the tests were measures the maximum deflection of the wing with the maximum weight estimated, Figure 9.

The results found in the tests were very consistent with the expected. For concentrated weight, it was found a deflection of 65mm and for the distributed weight 50mm of deflection. The analytical results indicated a maximum deflection of 45.5 mm and numerical results were closer to the experimental tests showed, an average of 63.2 mm. The tests with concentrated weight had results closer of the one in simulations with a difference of 1.8 mm, and the tests with distributed weight had results closer to the ones of the analytical calculations with a difference of 4.5 mm.



Figure 9. Experimental test with concentrated and distributed weight

From the design and construction done, it was possible to devise a methodology for preliminary structural design of UAVs. The process must begin with the preliminary draft of the aircraft. Once the preliminary project is ready, it should be made simplifications in project, substituting complex structures like wing, stabilizer and fuselage into simple structures like tubes and beams.

After the necessary simplifications are made, it must be made the conversion of aerodynamic loads into punctual load over simple beam element and the definition of the support of the simplified structure. Another point to be raised is the geometric restriction, for instance what is the length the structure must or may have, and what are the maximum and minimum external and internal diameters. These restrictions are usually obtained by the thickness of the profiles, types of slots, size of fuselage and size of the payload compartment.

Once all these data is collected, analytical formulas can be used for the calculation of the beam elements. To improve the process, these equations must be programed to optimize the desired results, as for example, reduction in weight and cost. Commercial tubes can be "tested", and their choice may lead to significant reductions in the final price of the aircraft.

For the construction of prototypes for the validation of aerodynamic parameters and flight data acquisition, the analytical design is enough. To obtain a more structurally optimized aircraft, it is necessary to go further and employ numerical simulations to design the beams by using preferentially software based on well-known FEM. The numerical

results must be compared to the ones obtained analytically. From the simulations, one can see more easily both critical regions and the ones little requested. The objective is to change the structures by removing material from regions less requested thus achieving the reduction of the total weight of the aircraft.

Also, to improve the safety before flights, static and dynamic structural tests can be done to validate the results obtained in the analytical and numerical calculations.

5. CONCLUSIONS

The main goal of this work is the development of a methodology for structural dimensioning of UAVs which is simple, cheap and of quality, and can be used in other similar projects to design commercially competitive aircraft.

It is expected that the developed methodology be mostly based on analytical formulations and that results of numerical simulations be compatible to the analytical ones. Therefore, the numerical simulation will be used only to enhance the design quality, saving computational time and reducing costs when necessary. In addition, it is also expected that the analytical and numerical results are consistent to the reality, comparable to experimental data.

The methodology simplicity has the function of enabling the development of new projects in other universities and teaching centers which will allow for the expansion of the national aerospace research, the labor qualification for the aerospace industry and the introduction of the people to the aerospace environment in order to encourage the growth of the Brazilian aerospace industry and market.

The propose of using alternative materials is to find nonconventional solutions to current problems, instigating more research in this area to modeling of not commonly used materials to be able of manufacturing a much affordable and accessible product that can be widely used by police officers, firefighters, soldiers and other interested parties.

Finally, it is expected to construct two aircraft prototypes, one with conventional materials of the aerospace industry and the other with alternative materials 100% recyclable and with the lowest possible impact to the environment. These prototypes have the purpose to serve as the basis for the project of UAVs which may be marketed as products 100% national and also serve as platforms for teaching in universities.

5. REFERENCES

- ANAC, "Regulamento Brasileiro de aviação civil", Brasil, 2009.
- CASA, "Civil Aviation Safety Regulation", 2002.
- Cornswwey, Tobey M., "Advanced Composite Materials", Ohio, 1970.
- Dalamagkidis, K., Valavanis, K.P. and Piegl, L.A., "On Integrating Unmanned Aircraft Systems into the National Airspace System", Springer, 2009.
- Desktop aeronautics, "Aircraft Design: Synthesis and Analysis", Stanford, 2006.
- EASA, Joint Aviation Requirements.
- FAA, "Federal Aviation Regulation", UEA, 2011.
- Headquarters, U.S. Air Force, "Unmanned Aircraft Systems Flight plan 2009-204", Washington DC, 2009.
- International Conference of building officials (ICBO), "ACCEPTANCE CRITERIA FOR STRUCTURAL BAMBOO", California, 2000.
- International Standard," ISO 22156 - Bamboo Structural Design", 2001.
- International Standard, "ISO 22157 – 1 e 2 –Bamboo - Determination of physical and mechanical properties", Switzerland, 2004.
- Iscold, P.H, "Introdução às cargas nas aeronaves", UFMG.
- Janssen, Jules J. A., "Designing and Building with Bamboo", Technical University of Eindhoven, Netherlands, 2000.
- Lawrence, Kent L., "ANSYS® Workbench tutorial, structural & thermal analysis using the ANSYS workbench release 11.0 environment", Mechanical and aerospace engineering University of Texas at Arlington.
- Maj. Christopher and A. Jones, "Unmanned Aerial Vehicles (UAVs) an Assessment of historical operations and future possibilities", The research Department Air Command and staff College, 1997.
- Marçal, Vitor Hugo Silva, "Uso de bambu na construção civil, monografia de projeto final em engenharia civil", Universidade de Brasília, Brasil, 2011.
- Mendonça, Paulo T. R, "Materiais compósitos & Estruturas Sanduíche", Barueri – SP, 2005.
- Neto, Flaminio Levy and Pardini, Luiz Claudio, "Compósitos estruturais", São Paulo, 2006.
- Raymer, Daniel P., "Aircraft design: A conceptual approach", AIAA education series, 1992.
- Rosa, Edison da, "Introdução ao projeto aeronáutico", Florianópolis: UFSC/GRANTE, 2006.
- Shigley, J. E., Mischke, C. R. and Budynas, R.G., "Projeto de engenharia mecânica", Porto Alegre, 2005.

5. RESPONSIBILITY NOTICE

The author is the only responsible for the printed material included in this paper.