DESIGN AND MANUFACTURING PROCESS OF A UAV COMPOSITE WING SPAR

Pablo M. N. Araujo [1, 3], Thiago R. Costa [1, 3] and Eduardo C. Silva [2, 3]

(1) Department of Mechanical Engineering, Pontifícia Universidade Católica do Rio de Janeiro, Brazil

(2) Department of Electrical Engineering, Pontifícia Universidade Católica do Rio de Janeiro, Brazil

(3) AeroRio, Pontifícia Universidade Católica do Rio de Janeiro, Brazil

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Abstract

This paper presents the design and manufacturing process of a lightweight UAV composite wing spar, aiming at achieving a high structural efficiency. The study introduces a real UAV wing geometry, designed to the 2016 SAE Brazil Aero Design competition, and evaluates its aerodynamic loads. Different possibilities of feasible cross-sections are compared aiming to maximize the moment of inertia per area. The mechanical properties of traditional aluminum alloy for aerospace applications are compared with those of polymer matrix composite materials. An analytical dimensioning procedure is presented for structural sizing and the Tsai-Wu failure criterion is used to calculate structural margins of safety for the composite parts. The manufacturing process of the spar is detailed, which uses the vacuum bagging lay-up technique, unlike the traditional method. The mold is a high-density foam used as the structure core. The adopted methodology lead to a reliable wing spar with optimized mechanical properties, having a high strength-to-density ratio. The AeroRio's team reached the second place in the 2016 SAE Brazil Aero Design competition.

1. INTRODUCTION

The recent advances of new computational technologies, software development, telemetry links and small autopilots have contributed to the popularization of UAVs (Unmanned Aerial Vehicles) for end users and enterprise applications. A UAV can be classified into three groups: autonomous, semi-autonomous and remotely controlled aircrafts. That includes all types of multi-rotors, fixed wing, and VTOL (Vertical Take-off and Landing) drones that do not require a pilot inside of them. A recent market research pointed out that the global drones market revenue was worth US$ 6.8 billion in 2016 and is expected to grow up to US$ 36.9 billion by 2022. These vehicles can have several applications for different industries, they can carry special camera sensors capable of taking pictures in order to build relevant mapping models of a specific land, helping farmers, agronomists and geographers in making decisions

[1-2]. They also can carry payloads as delivery boxes [3] or even engineering sensors for high risk offshore inspection of oil and gas constructions [4].

Many of today's engineers' tasks are associated with designing and manufacturing new products with low cost and in short periods of time. Such tasks are possible due to modern computational systems, that are capable of assisting in the design process and evaluation of new composite materials characteristics. Polymer matrix composites are commonly used in modern industry due to their low manufacturing cost and satisfactory mechanical properties and are usually produced in the form of symmetrical and asymmetrical laminates. In turn, these materials, when reinforced by continuous fibers, show: low weight, high strength, high stiffness, corrosion resistance and damping capacity of vibrations. Thanks to their high strength/weight and stiffness/weight ratios, they are used in the automotive, sports and aerospace industries; in order to allow the construction of lightweight structures.

This paper presents the design and manufacturing process of a lightweight UAV composite wing spar, aiming at achieving a high structural efficiency. The wing spar was optimized in order to maximize the team’s score in the SAE Brazil 2016 Aero Design competition. The most suitable materials were selected and combined in order to produce composite material with optimized structural performance. The wing spar sizing process is carefully described and the mechanical properties are meticulously evaluated, by analytical analysis.

These studies were conducted at the AeroRio Laboratory, which works on the design and development of unmanned aerial vehicles, such as fixed wing aircrafts and multi-rotors. The group develops multidisciplinary research projects, counting on the collaboration of professors from several engineering departments and with the participation of about 25 undergraduate and graduate engineering students. The team participates in national and international competitions, being three-time champion of SAE Aerodesign Brazil in the Advanced class (2012, 2013 and 2017), and recently, in 2018, the team reached the second place in the SAE Aerodesign East, one of the most important worldwide Aerodesign competitions.

2. DESIGN PROCESS

The wing design presented in this paper was optimized for the SAE Brazil 2016 Aero Design competition. This competition has encouraged students to design and build lightweight UAVs to carry heavy payloads. The competition score leads teams to design high efficiency structures. For instance, the MTOW (Maximum take-off weight) is limited to 30 kg and the flight score increases with payload, so the competitors try to reduce the aircraft empty weight to increase payload capability.

2.1 Wing Geometry

The wing design begins with the selection of the best airfoil for the UAV propose. Then, it is important to define the wing type (elliptical, rectangular, delta) and main dimensions, such as: wingspan, root and tip chords, taper ratio, sweep and twist angle, dihedral, etc. The XFLR5 software was used to design and estimate airfoil performance, which uses the Xfoil code to calculate lift, drag and moment curves of the selected airfoil. Figure 1 shows some of the main wing components, highlighting the ribs and the wing spar.

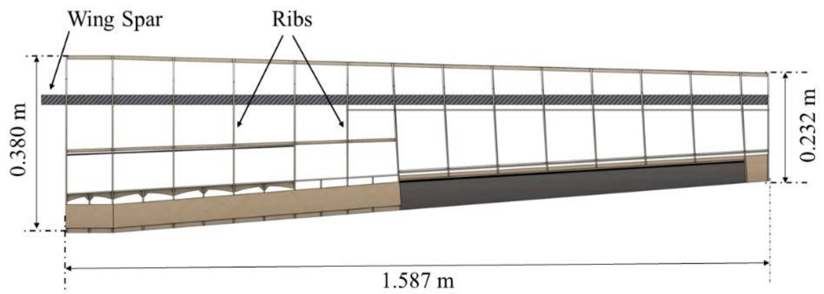

Figure 1: Wing layout

In order to relieve weight, the wing is made of thin plywood and balsa ribs covered with a tape skin. Ribs are just secondary structures, responsible for transferring load to the spar, which should be designed to withstand the aerodynamic loads.

2.2 Aerodynamic Loads

Aerodynamic forces should be estimated before wing design. XFLR5 was used to simulate important data of the 3D wing, as well as, lift and twisting moment loads along the wingspan. Distributed loads are calculated using the MTOW, however, during a maneuver those forces should be exceeded by a limited load factor n_{lim}, which represents the ratio between the aerodynamic force and the weight of the airplane. Miranda [5] recommends a maximum positive n_{lim} factor of 2.5 and a minimum negative of -1.0, for unmanned aircrafts. For design and analysis, the ultimate load factor n_{ult} is considered with a safety factor of 1.5.

$$n_{ult} = 1.5 \times n_{lim} \quad (1)$$

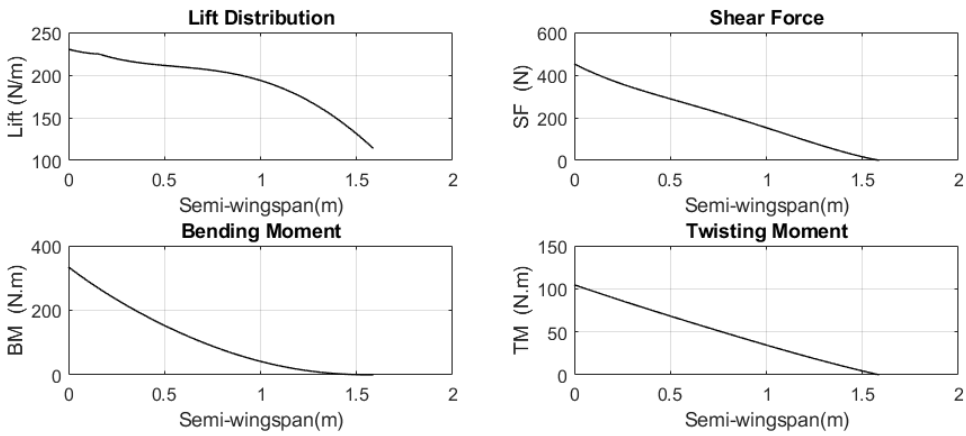

Figure 2: Wing Loads

2.3 Cross-section Design

The lift distribution along the wingspan is the most relevant load causing a large bending moment on the spar. To design an efficient spar, the cross-section should be chosen carefully, to maximize its moment of inertia. Because of the lay-up technology available in the laboratory, a cross-section geometry that could be manufactured using vacuum bagging technique was selected. Figure 3 shows a wing rib and the space available to the spar.

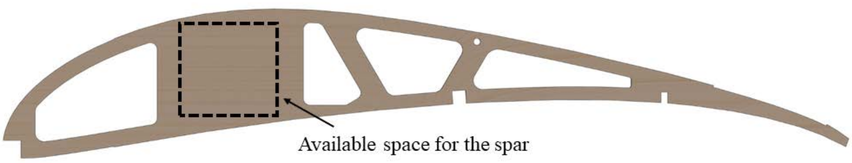

Figure 3: Wing rib

Aiming at maximizing spar strength, three feasible thin-wall cross-section geometries, depicted in Figure 4, are compared: circular, rectangular and I-shaped. For comparison purposes, all of the analyzed geometries have a unitary area (A = 1 a.u.^{2}), the same thickness (t = 0.0806 a.u.) and height (h = 4.0299 a.u.). The height of the circular cross-section is equal to its diameter, so d = 4.0299 a.u.. For maintaining the area equal to 1 a.u.^{2}, the width of the rectangular and I-shaped cross-sections were defined as b_r = 2.3349 a.u. and b_t = 4.2692 a.u., respectively. Table 1 presents the comparison between the torsion constants and moments of inertia of the cross-section geometries highlighted in Figure 4.

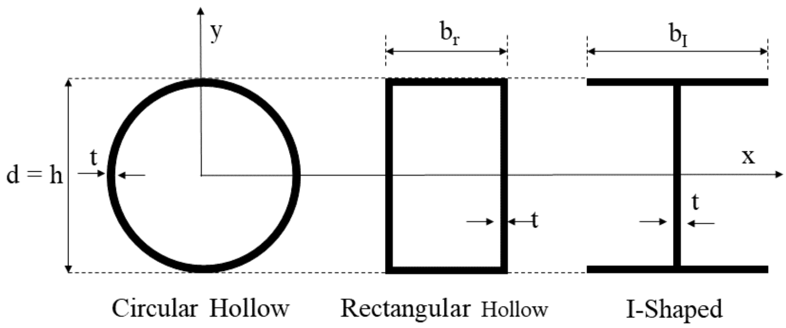

Figure 4: Cross-section shapes

Table 1: Cross-section comparison

	Symbol	Circular	Rectangular	I-shaped
Torsion Constant	K	3.9009	2.2423	0.0022
Moment of Inertia	I_{xx}	1.9505	24.000	23.284

Table 1 shows that the circular hollow cross-section is better to withstand twisting moments, because of its higher torsion constant. However, the rectangular thin-wall cross-section has a higher moment of inertia along the X-direction, almost 12 times larger than the circular section. Considering that the spar should resist bending moments rather than torsion moments, the rectangular thin-wall cross-section is chosen.

3. MATERIAL SELECTION

A high strength lightweight material should be chosen to the wing spar, considering the aerodynamic loads, calculated in section 2.2, and the cross-section geometry selected in section 2.3. Table 2 shows the comparison between an aerospace isotropic aluminum alloy, 7075-T7451 [6], with three polymer matrix composite materials: CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass Fiber Reinforced Polymer) and KFRP (Kevlar Fiber Reinforced Polymer) [7]. As carbon, glass and kevlar reinforced polymers are used in thin-wall structures, their properties are evaluated for plane stress state [8]. These materials are orthotropic and woven in orthogonal directions, which implies equal mechanical properties along the fibers directions.

Table 2: Mechanical properties of the analyzed materials

	Symbol	Unit	CFRP	GFRP	KFRP	7075-T7451
Ult. Tensile Strength 0°/90°	X_t/ Y_t	MPa	600	440	480	524
Ult. Comp. Strength 0°/90°	X_c/ Y_c	MPa	570	425	190	524
Young's Modulus 0°/90°	E_1/E_2	GPa	70	25	30	71.7
Ult. In-Plane Shear Stren.	S	MPa	90	40	50	303
In-Plane shear modulus	G_{12}	GPa	5	4	5	26.9
Major Poisson's Ratio	ν_{12}		0.10	0.20	0.20	0.33
Density	ρ	kg/m^3	1600	1900	1400	2830
Comp. Strength/Density	r	MNm/kg	0.356	0.224	0.136	0.185

An interesting parameter to choose a material for high structural efficiency is the ratio between strength and density. As shown in Table 2, CFRP has the largest ratio, besides, it has almost the same Young's Modulus of the aluminum alloy. These aspects lead to the selection of the CFRP to compose the UAV spar. To prevent the laminate from bucking, a high-density foam is used as a core. It also facilitates the manufacturing process, because the laminate can be laid-up directly on the core. Divinycell H45 foam is chosen due to its machinability, mechanical properties and low weight. Table 3 shows its main mechanical properties.

Table 3: Mechanical properties of the core material

	Symbol	Unit	H45
Ult. Tensile Strength	X_t	MPa	1.4
Ult. Comp. Strength	X_c	MPa	0.6
Young's Modulus	E	MPa	50
Ult. In-Plane Shear Stren.	S	MPa	0.56
In-Plane shear modulus	G_{12}	MPa	15
Density	ρ	kg/m^3	1600

4. STRUCTURAL SIZING

As the lift forces generate a bending moment on the wing, it is important to minimize bending stress. Consequently, the cross-section height should be as high as possible, without compromising each rib strength, maximizing the moment of inertia. As rib maximum thickness varies along the wingspan, the cross-section height of the spar should also be variable. Figure 5 represents the typical cross-section of the composite spar, made of two materials: CFRP, and a high-density foam, H45, as described in section 3. The wing spar flanges are made of *2n* CFRP layers, while webs have only *n* layers, it designedly occurs because of the lay-up method that will be detailed later section 6.

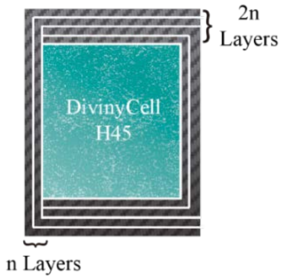

Figure 5: CFRP layers and core

A methodology was created in order to determine the number of layers *n*. All aerodynamic loads considered are used as inputs, the spar is discretized into various sections, and bending and torsional moments are calculated for each correspondent section. Initially, the algorithm considers *n* equal to one ply, then, tensile, compressive and shear stress are evaluated for both materials. Next, the Tsai-Wu criterion is used in each critical zone to evaluate laminate failure [8-9]. In case of failure in one of the materials, another ply is added and *n* increases in one unit. Then, all stresses are calculated again and the failure reevaluated. The process continues until it converges in all of the analyzed wing sections. The result is a file containing the number of plies required for each section, and the length of each ply along the spar to be used in the lay-up. The number of plies varies from 1 to 3, along the webs of the designed wing spar. The first ply has 3.176 m length, the second 1.700 m and the third 0.186 m. Consequently, it should be noted that the number of plies varies from 2 to 6 along the flanges, since there are two plies in the flanges for each ply in the webs. Some assumptions are: composites are macroscopically homogeneous and orthotropic, linearly elastic, initially stress free, free of voids and complete bonding at interfaces. Loads of each material are calculated assuming the same deflection, for bending and twisting, according to (2) and (3), respectively. Analytical formulas and equations for bending stress, shear stress and torsion constant are used [10-11]. Figure 6 shows the compressive and shear stress in CFRP and H45, along the semi-wing span.

$$BM_{CFRP} = \frac{BM\ E_{CFRP}\ I_{CFRP}}{(E_{CFRP} I_{CFRP} + E_{H45} I_{H45})} \tag{2}$$

$$TM_{CFRP} = \frac{TM\ G_{CFRP}\ K_{CFRP}}{(G_{CFRP} K_{CFRP} + G_{H45} K_{H45})} \tag{3}$$

where: BM is the bending moment, TM is the twisting moment, E is the Young's modulus, I is the moment of inertia, G is the shear modulus and K is the torsion constant.

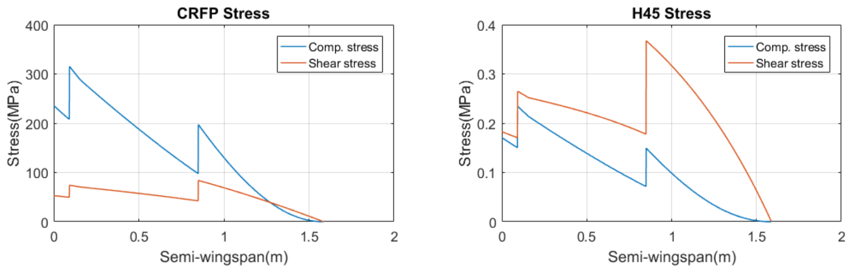

Figure 6: CFRP and H45 critical zone stress

5. MANUFACTURING

A vacuum bagging lay-up technique is used to manufacture CFRP. The propose process aims at maximizing the moment of inertia, by increasing the number of layers in the flanges, which is possible by splitting the process into two parts. Fist, the lay-up is made on one side of the core, resulting in a C-shaped CFRP laminate with n layers. After trimming, the core is rotated and the carbon woven is laid-up on the other side, producing another C-shaped laminate with an overlap of $2n$ layers in the flanges, and only n layers in the web.

Since the wing spar is manufactured for a unique UAV, the lay-up is made directly on the core, because this procedure eliminates the machining of hard material molds. The core is machined from a 20 mm wide plate, since it has more machinability than MDF or aluminum, saving CNC (Computer Numerical Control) machine usage time. A mold overhang of 3 mm is cut on a laser CNC machine, preventing the carbon fabric fillet from removing material from flanges area, as depicted in Figure 7.

During the lay-up, an epoxy resin of the same weight of carbon fiber is mixed to wet the fabric. Besides, a breather and a release film are used between the vacuum bag and the fabric to absorb excess of epoxy. The result of this process is a 0.25 mm ply with approximately 35% of epoxy resin and 65% of carbon fiber in weight, at a vacuum of -600 mmHg. Figure 7 shows the first step of the lay-up procedure.

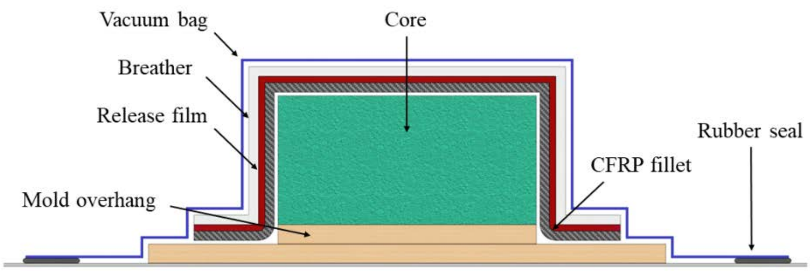

Figure 7: Vacuum bagging draft

6. CONCLUSIONS

Polymer matrix composites are widely used in modern aviation industry due to their high strength-to-weight and stiffness-to-weight ratios. In this paper, authors present the procedure to obtain a wing spar for a fixed wing UAV, with optimized mechanical properties. The proposed technique allowed the fabrication of a lightweight composite wing spar based on a high-density foam core reinforced with carbon fiber layers.

The wing design process was performed taking into account the optimization of the flight score, according to the rules established in the SAE Brazil 2016 Aero Design competition. The process involves the airfoil selection, the definition of the wing type and of its main dimensions. Besides, the aerodynamic loads were calculated along the wing span, such as: lift distribution, shear force, bending and torsional moments. A rectangular cross-section geometry was chosen for the wing spar aiming at maximizing spar strength, because it provides the highest moment of inertia among the analyzed cross sections.

The selection of the materials used in the wing spar lead to the comparison of the mechanical properties of an aerospace aluminum alloy, 7075-T7451, and three polymer matrix composite materials: CFRP, GFRP and KFRP. CFRP was selected due to its high strength-to-density ratio. Besides, a high-density foam was used as core to prevent the laminate from bucking.

The proposed methodology used to determine the optimal number of CFRP layers considers the aerodynamic loads and the Tsai-Wu criterion to evaluate laminate failure. The analytical calculations of the CFRP an H45 stress are presented along the wing span. The manufacturing process of the wing spar is also described.

The wing spar described in this work was used in the AeroRio's aircraft during the SAE Brazil 2016 Aero Design competition, where the team reached the second place of the Advanced Class.

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