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MATERIAL SELECTION FOR OPTIMIZATION OF A RADIO-CONTROLLED AIRCRAFT SPAR USING SANDWICH-TYPE HYBRID COMPOSITES

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Abstract. *The SAE Brazil AeroDesign challenges engineering students to design and build a radio-controlled aircraft, providing a knowledge exchange platform. Material selection is crucial in this process because the aircraft needs to align good mechanical resistance with low height and cost. The use of advanced composites, such as sandwich-type hybrid composites, in reinforced aircraft parts is growing due to their mechanical properties. This study aims to select the best sandwich composite material and its shape to size the structure of a radio-controlled aircraft's spar. Ashby's methodology was used to choose the best combination of core, resin, and fiber, and the digital logic approach is used to select the best material combination based on bending mechanical tests. The core was composed by balsa wood, while the resins were polyester and epoxy, and the fiber were carbon and glass fibre. The Schrenk approach was used to determine active forces on the wingspan, and structural tests were conducted to validate the material selection and size calculations. Based on these results, five mechanical properties were selected to represent the adopted design requirements: bending stress, shear stress, and modulus of elasticity were rated as provided to maximize spar strength and minimize deflection, while density and cost were appreciated as unsatisfactory properties to minimize mass and cost of the component. The box-type spar, composed of a balsa wood core coated with carbon fiber laminated with epoxy resin, was selected as the most suitable to meet the design requirements. The efficiency of the applied methodology was validated through developed simulations. The study demonstrates the importance of material selection in optimizing developed components used in the manufacturing of radio-controlled aircraft, as well as the effectiveness of Ashby's methodology and the weighted factor analyse in choosing the most suitable composite material to meet design requirements.*

Keywords: *Material selection, Ashby's methology, Weighted factor Analyse.*

1. INTRODUCTION

The SAE BRASIL Aerodesign competition is a challenge launched to engineering students with the main objective of providing the exchange of techniques and knowledge of aeronautical engineering through practical applications and competition between teams. The participating teams are involved with a real case of development of aeronautical projects, from their conception, detailed design, construction, testing, and optimization (SAE-Brasil, 2023).

The process of designing a component initially goes through the design stage. This step decides which materials will make up the aircraft and the manufacturing process that will be used. According to Ashby (2011), the number of materials available to the designer is about 160'000 or more. Therefore, the selection of materials is an important activity of this process, which can significantly affect the success or failure of the final product (Jahan *et al.*, 2011).

For projects focused on the development of aerospace components, materials should be selected to provide weight reduction and better performance for the final product (Jayakrishna *et al.*, 2018). Therefore, the segments of an aircraft must be properly designed to ensure the success of the component. According to FFerrante (2013), the selection process is not limited only to the choice between materials of different nature and properties. The analysis should be extended to meet the shape of the component, evaluating the influence of the form factor on the mechanical properties to be met and, at the same time, the best viable format for manufacturing. The selection of shapes of a structure can be used as a means of increasing mechanical efficiency (Ashby, 2011).

The use of advanced composites in structural parts of aircraft grows every year, due to the excellent mechanical properties that this material gives to the component designed and to allow flexibility in the design of complex parts with specific local properties (Rezende and Botelho, 2000). Among the hybrid composites, there is the sandwich type, that consists of two thin layers of rigid blades of low thickness with a core of greater thickness, composed of a less dense material and with less resistance. With this, a composite is obtained with the resistance of its external blades, resistant to traction and compression, and with the characteristics of its core with high flexural strength and low weight (Gama, 2020).

Therefore, such a configuration presents itself as an excellent option in the application in spars of radio-controlled aircraft.

According to Rodrigues (2014), the main components present in the aircraft structures are: fuselage, wings, empennage, landing gear and the powertrain. The spars are the main structural component of the wing and need to resist the shear, bending and torsional loads of the aerodynamic forces acting on the wing of the aircraft during flight. However, at the ultralight design stage, it is necessary to design equipment that is as light as possible and is still rigid enough to ensure the aerodynamic efficiency of the wings (Ashby, 2011). Some authors study the influence of the cross-section of the spar on the structural efficiency of the aircraft. Santos *et al.* (2023) analyzed the sizing of a spar with rectangular section while Silva *et al.* (2012) compared the design of a box shaped spar with a tubular carbon spar, considering the final mass of the wing, maximum load supported and the manufacturing time. Chaves and Kieckow (2006) developed a spar of composite material and low weight resistance, composed of carbon fiber and epoxy resin.

The present study selects the best sandwich-type composite material, as well as its shape to later size the structure of the spar that composed the radio-controlled aircraft. The methodology of Ashby (2011) was applied for the selection of the best core and the best candidates to compose the fiber and resin. Subsequently, the digital logic method was used to select the best core-resin-fiber combination to be applied in the manufacture of the spar, considering its mechanical properties obtained through traction and bending tests.

2. METHODOLOGY

2.1 Load analyses and design

To start the dimensioning of the spar, it was necessary to determine the weighted factors as a function of the operating velocity of the aircraft. Then, the loads were determined along the wingspan from Prandtl's support line theory, by Schrenk's approach method (Silva *et al.*, 2012; Santos *et al.*, 2023). According to Rodrigues (2014), the Schrenk approach is based on the representation of an arithmetic mean between the load distribution originated by the wing model and an elliptical distribution for a wing of the same wingspan and area, presenting satisfactory and reliable results, being valid for any wing model under study.

From the load distribution determinate by the Schrenk's method, a loading function was generated. To determine the resultant efforts, the loads are integrated along the wing extension, been able to determine the maximum values of the bending moment and the shear force that must be supported by the spar (Hibbeler, 2010).

The safety factor (FS) was determined according to the methodology of Collins (2006) whose implementation occurs through penalty factors for each component of the aircraft. A semi-quantitative evaluation of the penalty factors was performed by assigning a penalty number (PN), ranging from -4 to 4, in which, for example, NP = 1 represents a slightly necessary change and NP = 4 represents an extremely necessary change. Positive values of PN show the need to raise FS and negative values show the need to decrease FS. The penalty factor (T) is calculated by:

$$T = \sum_{i=1}^{n} NP_i \ , \tag{1}$$

and the safety factor (FS) is calculated by:

$$FS = \begin{cases} 1 + (1 + 0.1T)^2 & , \, if \, T \geq -6 \\ 1.15 & , \, if \, T < -6 \end{cases} \tag{2}$$

The penalty factors were determined based on the accuracy of the calculation applied at each step of the process and the quality of manufacturing. According to Hibbeler (2010) and Niu (2011), from the maximum bending moment and knowing the geometric properties of the spar cross-section, the maximum bending stress (σ_{max}) that must be supported by the spar can be calculated by:

$$\sigma_{max} = \frac{M_{max} c}{I} FS \ , \tag{3}$$

in which M_{max} is the maximum bending moment, c is the distance of the neutral line and I is the inertia of the cross-section area. The maximum shear stress (τ_{max}) is calculated by:

$$\tau_{max} = \frac{V_{max} Q}{It} FS \ , \tag{4}$$

where V_{max} is the maximum shear force, Q is the first moment of area and t the width of section.

2.2 Ashby Method

Ashby's method for material selection initially proposes to relate the functional requirements, geometric parameters, and properties of materials to mathematical functions, to determine the material index. From this, it is possible to evaluate the mechanical behavior according to the request for loading or use of the material to maximize or minimize these properties. Consequently, the material with the highest performance index represents the best choice (de Souza *et al.*, 2017). Once these indices are defined, they can be correlated to the properties required in the project through Ashby diagrams, that is a grouping of the most diverse varieties of existing material families, arranged in graphs that integrate one or more properties to select the material that best meets the pre-established requirements.

For the application, five parameters were adopted for the material selection based on the specif application of a spar to a radio-controlled aircraft. The spar needs a high bending resistance and shear resistance, a high Young modulus to minimize strain during the flight, low density to minimize the aircraft weight and low cost.

The most common spar section forms in competitions, because they offer greater lightness and resistance, are tubular type, box shaped, partly hollow, or in the form of an I-beam (Rodrigues, 2014; Mira, 2013). To define the material index (M_i), we use the shape factor, presented in Ashby (2011) and Ferrante (2013). The geometry of the spar is box shaped, with 40 mm height, 20 mm width and 5.5 mm thickness, with a shape factor $\phi_B^e = 2.59$. The material index was:

$$M_i = \frac{(\phi_B^e \; \sigma_{max})^{2/3}}{\rho \; c} \; , \tag{5}$$

where ρ is the material density and c the material cost, that are qualities to be reduced. Resulting, by Eq. 5, in a yield curve of 1.5 to be used on the Ashby diagram.

2.3 Digital logic approach

The digital logic approach consists of defining the relative importance by establishing a weighting factor (α_i) for each performance goals of the material using a decision core (Souza, 2007). The weighting factor is determined by the construction of a performance matrix, which compares the different selected goals. A factor analysis is performed, comparing two different goals. The goal considered more important than the other on the comparison receives a higher positive decision index. In the case that the two goals are considered equally important, they receive the same index. The resultant positive decision for each goal is calculated by the sum of the index for each comparison of this goal with the others, and the weighting factor of each goal is calculated by dividing the positive decisions of this goal by the total number of positive decisions for all goals evaluated. After, on the material selection, the weighting factor of each goal is multiplied by a scaled value (β_i). When evaluating a list of candidate materials, one property is considered at a time. The best value in the list is rated as 100 and the others scaled proportionally (Dehghan-Manshadi *et al.*, 2007). For a candidate property that needs to be maximized, the scaled value is:

$$\beta_i = 100 \cdot \frac{numerical\ value\ of\ property}{maximum\ value\ in\ the\ list} \; . \tag{6}$$

For properties like cost and density, a lower value is more desirable. In such cases, the lowest value is rated as 100 and β_i is calculated as:

$$\beta_i = 100 \cdot \frac{minimum\ value\ in\ the\ list}{numerical\ value\ of\ property} \; . \tag{7}$$

Finally, is calculated a performance index (γ) for each material candidate, by:

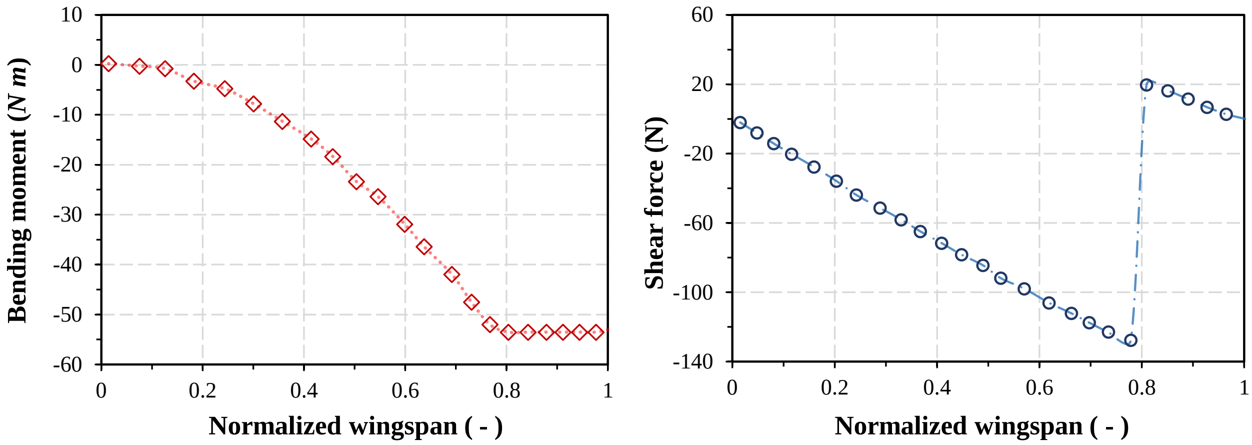
$$\gamma = \sum_{i=1}^{n} \alpha_i \beta_i \; . \tag{8}$$

The performance index is used to rank the candidate materials, the highest performance index indicates the best material performance for the application, based on the material goals and also the relative importance of those goals for the application.

3. RESULTS AND DISCUSSIONS

By the SAE Brazil competition requirement, the loads for the spar design were calculated. Figure 1 shows the bending moment and shear force along the wingspan.

Based on Eq. 2, the safety factor was $FS = 2.21$. Applying the maximum bending moment of Fig. 1a on Eq. 3 and the maximum shear force of Fig. 1b on Eq. 4, it were calculated the maximum bending stress and shear stress of $\sigma_{max} = 27.44$ MPa and $\tau_{max} = 1.12$ MPa, respectively. Those values were used in sequence as the limit values for the Ashby diagram.



(a) (b)

Figure 1: Distribution of (a) bending moment and (b) shear force along the wingspan for the spar design.

3.1 Core selection

Since most of the bending stress is supported by the coating, the composite core was selected to provide the lowest possible density to the spar. First, we used the software CES Edupack© Level 1 to determine which class of materials would best meet the material index requirement (Eq. 5) as it is illustrated in Fig. 2.

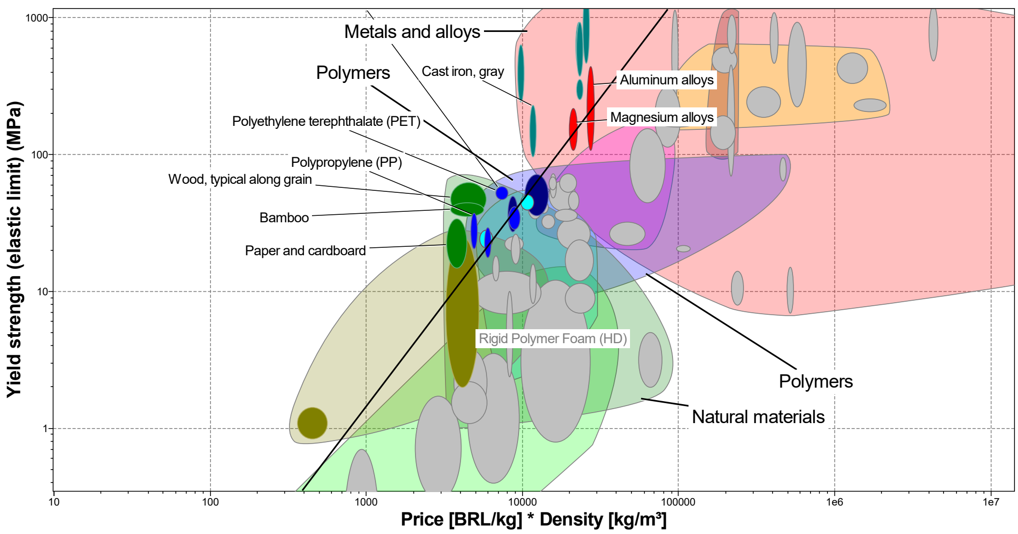


Figure 2: Ashby diagram for class of material selection.

As shown in Fig. 2, the class of natural materials, especially woods, are the material class with the best material index. In addition, metallic materials and alloys and some polymers also have a good performance. The metals and alloys are widely used in the aerospace sector due to their versatility and good mechanical properties. However, to simplify the study, the selection of the core was limited to natural materials due to its applicability on radio-controlled aircraft. To select the material for core composition, we verified the material in the wood class that presents the lowest density to minimize the mass of the core that makes up the spar. Figure 3 shows the wood class material evaluated.

According to Fig. 3, despite the high cost among the wood class, the balsa wood (*Pyramid Ochroma*) is the material that presents the lowest density, being this the material selected for the composition of the spar core. In addition, the cork

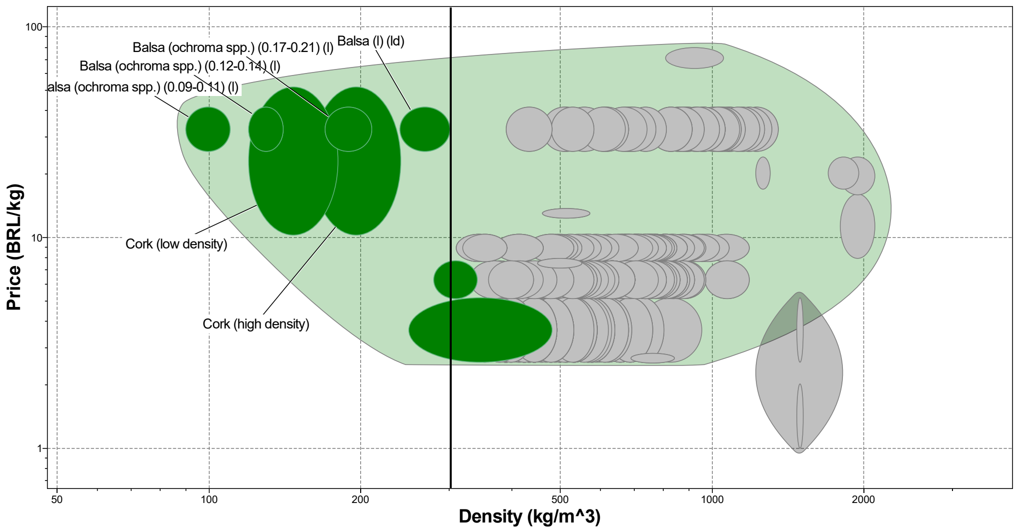


Figure 3: Representation of an interface between two arbitrary fluids.

also shows to be a viable candidate for the composite manufacturing.

3.2 Fiber and resin selection

The fiber for making the coating of the chosen core was determined based on the material index defined in Eq. 5. Figure 4 illustrates, among the class of fibers, the materials that best meet the material index and the selected limitations.

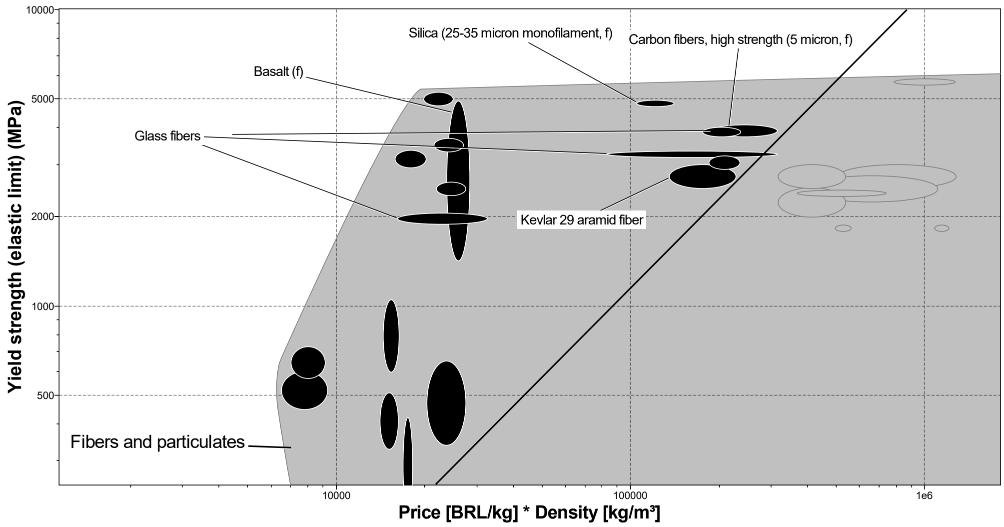


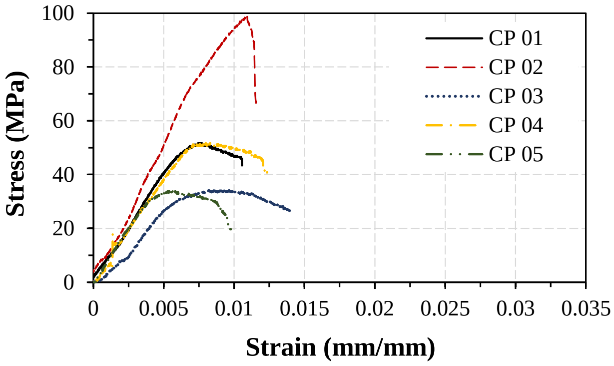
Figure 4: Ashby diagram for the fiber selection.

As illustrated by Fig. 4, Basalt fiber and silica fiber are the materials that best make up the coating of the spar, however, due to limitations to obtaining those materials, carbon fiber (CF) and glass fiber (GF) were the main candidates for coating composition. Moreover, the Kevlar shows to be a suitable candidate. But in order to not considerably increase the number of materials and also tests to be realized, the analyses were made only with carbon fiber and glass fiber.

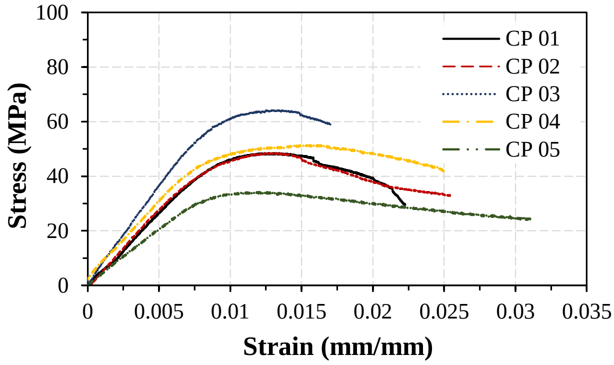
The use of epoxy (REp) and polyester (RPo) resins has increased over the years due to the improvement of mechanical properties and their adherence of the fiber to the core, in addition to being resins of easy access in the market. Therefore, for the selection of the best core-fiber-resin composition, tests were carried out with different coatings, varying the fibers used in the manufacture of the composite.

3.3 Mechanical tests

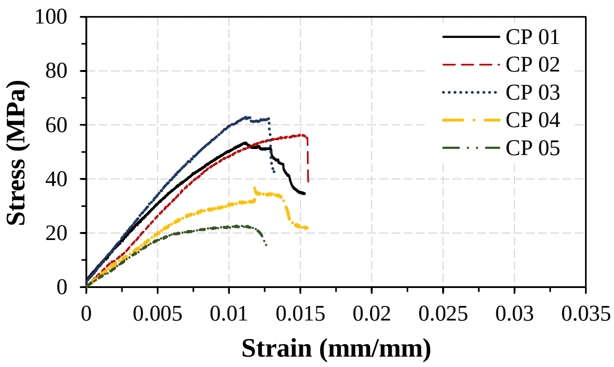
Bending tests, based on the ASTM C393-00 standard, were performed to determine the mechanical properties for each of the selected configurations of composites for the manufacture of the spar. For each configuration, tests were performed with 5 specimens to determine an average value of the properties to compose the performance matrix. The graphs obtained by performing the bending tests for the different compositions of the composite are presented in Fig. 5.



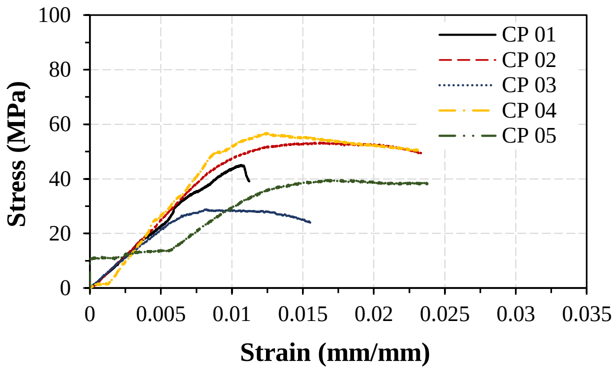
(a) Balsa wood + Carbon fiber + Epoxy resin



(b) Balsa wood + Carbon fiber + Polyester resin



(c) Balsa wood + Glass fiber + Epoxy resin



(d) Balsa wood + Glass fiber + Polyester resin

Figure 5: Influence of (a) Viscosity ratio, N_μ and (b) Capillary number, Ca, on the lost mass fraction m_e.

According to Fig. 5, the specimens of each composite present a variation of the mechanical properties due to the manufacturing process. It was observed some irregularities on the surfaces of the composites during the manufacturing process that justify the variation of the residence of the composites. Moreover, it is possible to see in Fig. 5 that the composites with epoxy resin presents less strain when compared with the composites with polyester resin.

Based on the results of the tests, the eminent properties of each composition of the materials were determined. Table 1 shows the estimate of the mean properties based on the tests performed.

Table 1: Mean mechanical properties obtained by the mechanical tests.

Material	**Density (kg/m³)**	**Bending stress (Mpa)**	**Shear stress (Mpa)**	E **(GPa)**	**Price (BRL/m³)**
BW + REp + CF	385.97	53.92	3.02	4.43	95.80
BW + RPo + CF	396.56	49.25	2.70	2.94	106.20
BW + REp + GF	358.41	46.24	2.51	3.64	32.50
BW + RPo + GF	363.51	44.49	2.30	2.72	36.15

It is possible to see on Tab. 1 that the Young modulus of the composites made with epoxy resin were higher than those made with polyester resin. It was also observed that, although the lower market price of polyester resin compared to epoxy resin, to make the composites with a good surface finish, it was necessary to use larger amounts of polyester resin, resulting in both a higher density and price of the composite compared with the composites made with epoxy resin.

With the design requirements adopted, to maximize the resistance, decrease the deflection of the spar and provide a cheapness, as well as the decrease in the mass of the component, five mechanical properties that best represent such attributes were selected. We can classify such properties as beneficial, when wishes to maximize it, and not beneficial, when wishes to minimize it. The beneficial properties selected were bending resistance, shear stress and Young's modulus (E) to maximize the resistance and decrease the deflection of the spar. The non-beneficial properties evaluated were density and cost to minimize the mass and cost of the component.

3.4 Composite selection

An adaptation of the performance matrix presented by Dehghan-Manshadi *et al.* (2007) was applied to ranking the relevance of all evaluated properties, although it is considered less important when compared to another attribute. This implies that all objectives will also be considered for the selection of materials. Thus, when comparing two distinct properties, the least important receives the value 1 and the most important receives the value 3. When it is considered that properties are equally relevant, the value 2 is assumed for each property. The most important parameters considered for the design of the spar were the density and the bending stress. Therefore, the positive decision of those properties were 2 when compared with each other and 3 when compared with the other evaluated properties.

The weighting factor were calculated by dividing the number of positive decisions of each property and the total positive decisions calculated. Five properties were evaluated, totalizing 40 positive factors. Table 2 presents the performance matrix to obtain the α_i weighting factors following the proposed methodology. the subscripts 1 to 5 represents the density, bending stress, shear stress, Young modulus and price, respectively. The terminology $i - j$ represents the comparison between the property i and j.

Table 2: Determination of the relative importance of performance goals.

Goals	**Number of possible decisions**										**Positive**	**Weighting**
	1-2	**1-3**	**1-4**	**1-5**	**2-3**	**2-4**	**2-5**	**3-4**	**3-5**	**4-5**	**decisions**	**factor (α_i)**
[1] Density	2	3	3	3							11	0.275
[2] Bending stress	2				3	3	3				11	0.275
[3] Shear stress		1			1			2	2		6	0.150
[4] E			1			1		2		3	7	0.175
[5] Price				1			1		2	1	5	0.125

As it is possible to note on Tab. 2, the density and bending stress receive the highest weighting factors ($\alpha = 0.275$). The Young modulus (E) receives the weighting factor $\alpha = 0.175$, being the second most important weighting factor and the shear stress and the price receive $\alpha = 0.150$ and $\alpha = 0.125$, respectively. Although price is an important factor to be evaluated in aeronautical projects, the mechanical properties are still preponderant in relation to it. Therefore, price was the least important factor in the analysis.

Then, the values of the properties obtained by the tests of the materials for the candidates were normalized and grouped in a matrix. With the normalized values and weighting factors, the performance index of each composite were calculated, as shown in Tab. 3.

Table 3: Ranking of the selected sandwich composite materials.

Material	**Scaled proportionally value**					$\gamma = \sum_{i=1}^{n} \alpha_i \cdot \beta_i$	**Ranking**
	β_1	β_2	β_3	β_4	β_5		
BW + REp + CF	96.61	100.00	100.00	100.00	33.92	90.81	1º
BW + RPo + CF	90.38	91.34	89.40	66.37	30.60	78.82	4º
BW + REp + GF	100.00	85.76	83.11	82.17	100.00	90.43	2º
BW + RPo + GF	98.60	82.51	76.49	61.40	89.90	83.26	3º

Through the systematic method of digital logic, it was possible to verify behind the data of Tab. 3 that the epoxy resin is preponderantly superior to the polyester resin in terms of increasing the mechanical properties of the material, presenting better results for the candidates for spar coating. Another noticeable aspect during the preparation of the specimens for the tests is a better surface finish and fewer irregularities, due to the greater adhesion of the epoxy resin to the core. In addition, to present higher density and cost, the use of carbon fiber (CF) is more appropriate than glass fiber (GF) for the composition of the composite, according to the methodology adopted.

3.5 Structural test

After selecting the most appropriate materials for the manufacture of the composite, the structural component was manufactured. Seeking an even more efficient means of supporting the applied loads, serving as reinforcement for the laminated material, it filled the internal space of the spar with expanded polypropylene (EPP), density $\rho = 30\ kg/m$. Among the main properties presented by this type of polymer is high-energy absorption, good dimensional stability, resistance to chemical solvents and low humidity absorption.

Considering the highest support load as constant, the structural test was performed by applying loads of 4.7 kg at certain points along the spar section. The assay was carried out to verify the veracity of the methodology applied for the selection of the material and shape of the spar. Figure 6 illustrates the performance of the structural test of the component.

The test was carried out for 60 s and proves the adequate selection of the materials used in the manufacture of the structural component. The product presented a mass of 415g and proved to be adequate for the requirements adopted in the project. The component was used to make the fourth radio-controlled aircraft of the FAM Aerodesign team for the participation in the 20th SAE BRASIL Aerodesign competition.

Figure 6: Structural test of the manufactured spar.

4. CONCLUSION

The present work shows that the selection of materials is an important tool in the optimization of structural components used in the manufacture of radio-controlled aircraft. Ashby's methodology was used for the selection of candidates to compose the core and coating of the composite used in the manufacturing and the systematic method of digital logic was used for the selection of materials that would provide better mechanical properties and lightness to the component. The box shaped spar composed of a balsa wood core, coated with carbon fiber laminated with epoxy resin was the candidate that best meets the design requirements. The applied methodology was validated through structure simulation, verifying the efficiency of the applied methodology.

5. ACKNOWLEDGEMENTS

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