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NUMERICAL AND EXPERIMENTAL ANALYSIS OF FIBER REINFORCED COMPOSITE BEAM

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Abstract. Composite materials have advantages like their lightness and strength that make them attractive for purposes in engineering. This paper describes a thin-walled square composite beam subjected to three-point bending test. Computational and experimental models are studied for this beam using carbon fiber as composite material. It is also explored ways to make it as light as possible, supporting a minimum pre-established load. Using ANSYS® Composite PrepPost it is possible to defined layers, thicknesses and orientations for the studied layered composite structures. Then, structural analysis of the geometric model defined is performed with the aid of ANSYS® Mechanical. Numerical results obtained are compared with experimental models produced in laboratory. The beam is made of carbon fiber and epoxy resin by the application of vacuum bagging process after the hand lay-up lamination and post-curing at high temperature. This work is part of the researches of an undergraduate engineering program that aims to study composites, specially for civil and mechanical engineering, in order to analyze their main features using computational tools and experiments.

Keywords: Composite beam, Carbon Fiber, Finite Element Method, Parametric Optimization.

1 Introduction

A composite is a material made from two or more constituent materials that together can generate improvements in its physical and mechanical properties and performance compared with their individual characteristics [1]. It is made of the matrix, usually a viscous material that hardens to give shape to the composite, protecting and transferring loads to reinforcement, a material that provides strength, stiffness and the ability to carry a load. One of the biggest advantage of modern composite materials is that they are light as well as strong. By choosing an appropriate combination of matrix and reinforcement, a new material can be generated meeting exactly the requirements of a particular application. Also, composites are flexible and can get complex shapes.

Composites have been used for most diverse purposes, such as aircraft construction, automobiles, helmets, structural recovery and other. In civil engineering, concrete is a widely used composite material due to its strength and low cost. However, concrete structures are fairly heavy because of its density. Currently, researches look for lighter materials for structures with similar efficacy and load capacity but lighter, compared to concrete.

Material composites made with polymer matrices and synthetic fibers are the toughest found in the modern market. Among the synthetic fibers, the most used and known is carbon fiber.

Carbon fiber or graphite are constantly used to mention this type of material. This is due to the fact that both materials are made of carbon atoms, but with a slight different in a quantity, the firs with up to 95% and the second with up to 99% [6]. However, only carbon fibers with a high modulus and a three-dimensional graphite structure can in fact be referred to as graphite fiber. This fiber can be obtained by pyrolysis of fiber-shaped organic raw material [1], being it polyacrylonitrile (PAN), petroleum-based pitch or rayon. The fibers produced of PAN-based, which is a form of acrylic fibers, gives the best proprieties by having up to 90% of carbon atoms in their composition, but they are more expensive and doesn't produce fibers with high resistance as those made with petroleum-based pitch, which are commonly used to make graphite fiber. Rayon is rarely used today used today, because of higher cost and lower yield involved in your processes. The fibers undergo chemical and thermal processes after weaving to improve their adhesion to the matrix and their strength and stiffness, respectively.

Matrices can be of three distinct classes: ceramic, metallic and polymer. Focusing on polymer ones, they are made up of polymer chains, having low strength and rigidity, but resulting in extremely resistance and with low density material composites, therefore being the most used. They can be divided into two types: thermoset or thermoplastic. The big difference between both is characteristic behavior when headed, in another words, the thermoplastic are polymers who can be molded more than once, as they have the characteristic of becoming fluid by the action of temperature and then solidifying as the temperature decreases. The thermoset does not have this characteristic for the reason that there are crosslinks between their macromolecular chains. Thermosetting polymers are most used for structural use inasmuch they have same good characteristics as low viscosity, good impregnation of the fiber, and lower temperature and cost of the processing. The final product presents characteristics as high rigidity, high thermal stability, good electrical and thermal isolation, and creep resistance, if compares to the other type [2].

Among the polymers thermosetting, there are three types of matrices that can be used, such as: Polyester; epoxy; vinyl ester; polyimide [3]. Epoxy is the most widely used polymeric matrix for high performance material composites due to a combination of mechanical proprieties, corrosion resistance, dimensional stability, good adhesion and low cost [1]. It can be subdivided into two categories which vary according to the cure temperature and exposure to moisture [4]. The first involves matrices who is cure up to 120^{o}C and will be exposes to low vary temperature. The second category comprises matrices that have the curing process up to 180^{o}C, which needs a harder or a reaction accelerator. In their formulation there is a principal polymeric chain or a principal epoxy, and in lower quantity there is a second chain. This secondary polymeric chain is added to composite to give viscosity control, improve proprieties in high temperature, reduce moisture absorption or improve resistance [5]. Epon, Epi-rez, D.E.R., Epotuf and Araldite are the trade names given to epoxy polymer matrices [6].

Although composite materials be extremely lightweight, they are expensive and carry to high costs in yours manufacturing process. Therefore, it is indispensable to produce shapes with the same efficiency, but at a lower cost, in other words, with less material waste. Parametric optimization is one way to help achieve this goal.

The concept of optimization is broad and with many possibilities to define, thus being difficult to find. However, in general, optimization is the set of techniques employed to achieve the ultimate goal, which is to maximize or minimize a function, called a metric function, with distinct variables. It is currently possible to program mathematical models that perform this type of methodology, or use software that already has this type of tool, as is the case with ANSYS®.

2 Methodology

The study was based on a thin-walled square composite beam subjected to three-point bending test. Figure 1 details the cross section studied.

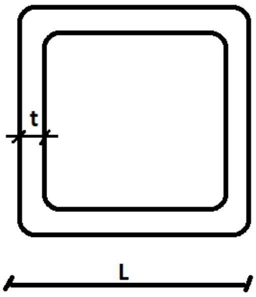


Figure 1. Scheme of beam cross section, with L = 100 mm and t varying with the number of beam layers

2.1 Computational modeling

The modeling of the beam, supports and load cell was performed using the SIEMENS NX10 software, in which all the pieces were modeled and subsequently assembled properly to represent the three-point bending test in study. In Figure 2, it is possible to see the geometry created.

The geometry created with SIEMENS NX10 software was imported into ANSYS® Workbench and served as the basis for the initial model of a beam with 15 layers of bidirectional carbon fabric oriented in 0/90º and epoxy resin, with typical features of the software through the ACP PrepPost tool. After the beam layers were created, the generated solid was imported into the Static Structural module for analysis by the Finite Element Method (FEM), an efficient and widely used technique to obtain the physical behavior of structures. The FEM basically consists of subdividing the domain in elements interconnected by nodes, generating a mesh. This gives the approximate solution of the problem under study.

At this stage the supports both fixed, and the value of the load were imposed. The results analyzed: Von-Mises equivalent stress; total deformation and inverse reserve factor of the structure, which was obtained by Tsai-Wu failure criterion for composite materials.

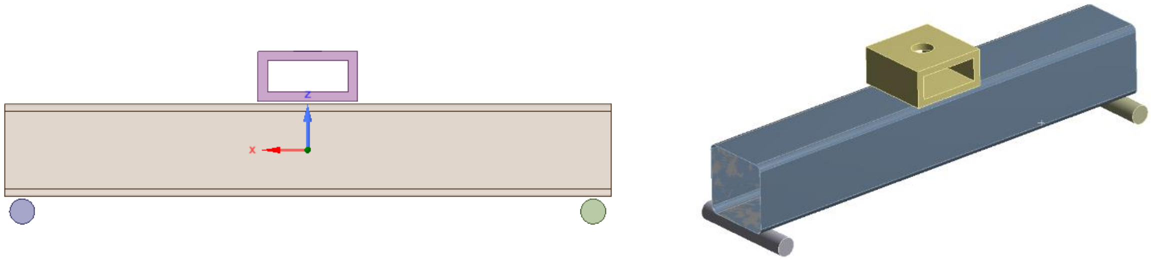


Figure 2. Modeled geometry in front and isometric view

Next, the parametric optimization process was started with the Response Surface Optimization tool. Initially, the problem variables were defined as the number of layers of the beam, ranging from 0 to 15, and the fiber angle in each layer, which can vary from 0º to 90º, with step of 22.5º. Thus, the objective of the merit function was set to minimize the maximum Von-Misses stress. The criterion chosen only for this step, and total deformation, keeping the inverse reverse factor between 0 and 1, denoting that the structure will not suffer fractures.

With the results obtained in the above optimization, another beam was modeled, now with different number of layers and orientation of fibers and placed with the same load and support conditions, in order to verify the maximum stress and deformation sites and analyze their behavior.

Another optimization was performed, but this time removing the objective of minimizing the stress. The same procedure as above was followed for the results found.

Finally, the same models as above were performed, but this time using the material characteristics obtained from laboratory tests in the experimental stage, such as Young's modulus and tensile strength, and not the characteristics provided as standard by ANSYS®.

To evaluate the failure of the model beams, the Tsai-Wu criterion was used, which is the failure criterion chosen for anisotropic materials, such as composite materials. The failure criterion aims to estimate the resistance of materials under certain stress state [7]. For composite materials it is relatively complex to obtain these values as they depend on the direction that the fiber is set. For the same material numerous strength values can be found depending on the direction in which the loads are imposed.

The Tsai-Wu criterion is based on expanding the number of terms of the Hill criterion. The latter is based on the Von-Mises yield stress criterion used for isotropic materials. The criterion is intended to be operationally simple so that it can characterize the material, being easily usable in component design. This criterion does not explain or predict the actual mechanisms of failure. It is one of the most popular criteria because it is computationally easy to implement and requires a relatively simple method to predict the loadability of a structure [8].

2.2 Experimental models

The experimental models were performed using the results obtained by the software. The manufacturing process is completely manual and involves several steps. First, the site was cleaned with suitable product to prevent any impurities from came into contact with the fiber. A high density Styrofoam mold with the estimated dimensions of the part was prepared and coated with plastic to facilitate demolding. Once this step was done, the fiber was cut with the correct dimensions and angle according to the computational analysis and, on a precision scale, the resin was prepared with the catalyst in the right proportion giving the matrix to be used. This process is presented in Fig. 3.

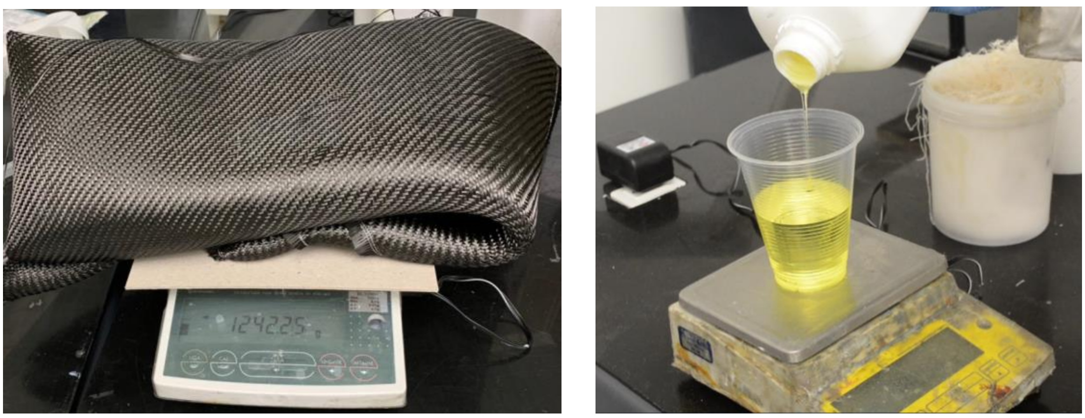


Figure 3. Precision balance used to estimate fiber and resin mass used in beam production

With this initial stage completed, the material began to be laminated, which consisted of applying the matrix to the fiber to impregnate it, and wrapping the mold with the fabric, as shown in Fig. 4, turning it until the number of layers is as previously stipulated.

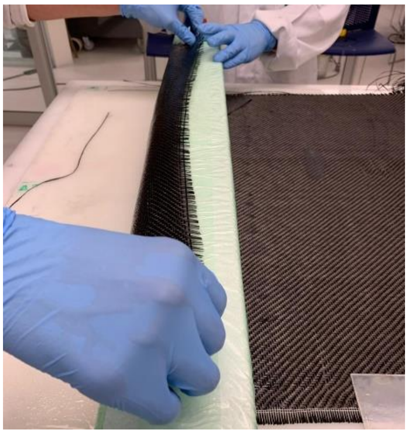


Figure 4. Beam lamination process with resin impregnation in carbon fiber fabric

With the Styrofoam mold already wrapped with all the necessary layers, another fabric is applied over the beam, the peel ply, to aid in the removal of excess resin, thus improving the performance of the composite. The assembly, mold plus fiber, was placed inside the vacuum film, which is a sturdier plastic bag that supports the vacuum, and it was sealed on all sides to ensure that all air was removed from the system through the vacuum pump shown in Fig. 5. Thus, the composite was cured for twelve hours.

Figure 5. Vacuum pump and vacuum mold / fiber assembly

After the stipulated curing time, the vacuum was interrupted and demolding. The initial beam was weighed and final adjustments were made to the piece, such as cutting and sanding of its edges, Fig. 6. Post-cure was performed in an oven at 80ºC for eight hours, according to manufacturer's instructions. At the end of the process, the beam is re-weighed and measurements of its cross section and thicknesses were made.

Figure 6. Final adjustments on beam produced for laboratory testing

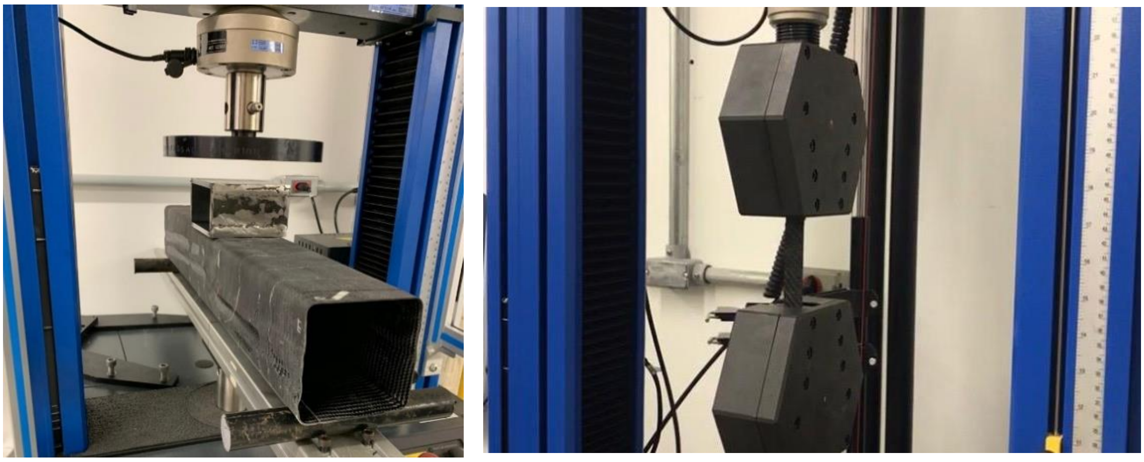
In addiction to the beams, a plate was made of the same material and the same manufacturing process, just with a different molding process. For this plate, a Styrofoam mold was not used, but a polypropylene plate, material that does not react with the matrix, in which one layer of impregnated fiber was placed on another, successively, until reaching the desired number of layers. Their curing and post curing process was carried out in the same way. Like the beam, the plate was cut and adjusted to the desired size and ten proof body of the same size were obtained from it, Fig. 7.

Figure 7. Tensile test plate and specimens

2.2.1 Destructive tests

The beams produced were subjected to the three-point bending test according to standard D 790 - 97. This test consists of supporting the specimen on two supports located at the ends of the workpiece without any links, with load applied though a load cell positioned in the middle of the beam, as shown in Fig. 8 (a).

The blade-shaped proof body were subjected to tensile tests according to ASTM D3039 in order to obtain the characteristics of the fabricated material, such as Young's modulus and tensile strength, Fig. 8 (b). The proof bodies were produced with 25 cm length, 15 cm width and 1 mm thickness. This information is presented in Fig. 9 [9].



(a) (b)

Figure 8. Representation of destructive tests, being (a) flexion and (b) traction

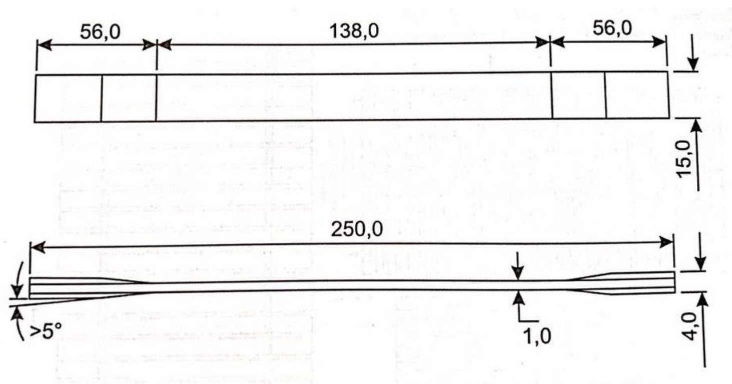


Figure 9. Proof bodies dimensions [9]

3 Results and discussion

3.1 Computational analysis

The method for beam evaluation was the FEM using ANSYS® software, generating a mesh with 32231 elements and 18693 nodes. First, the ACP module was used for layering and defining fiber's orientation for solid generation. Then, in Static Structural, the boundary conditions of the problem were applied for FEM resolution were applied. A 40,000 N load was applied to the underside of the load cell, and the beam simply remained supported on two cylinders. Initially, a 15-layer beam with 0 / 90^{o} fiber orientation was modeled, with the results shown in Fig. 10 and Table 1.

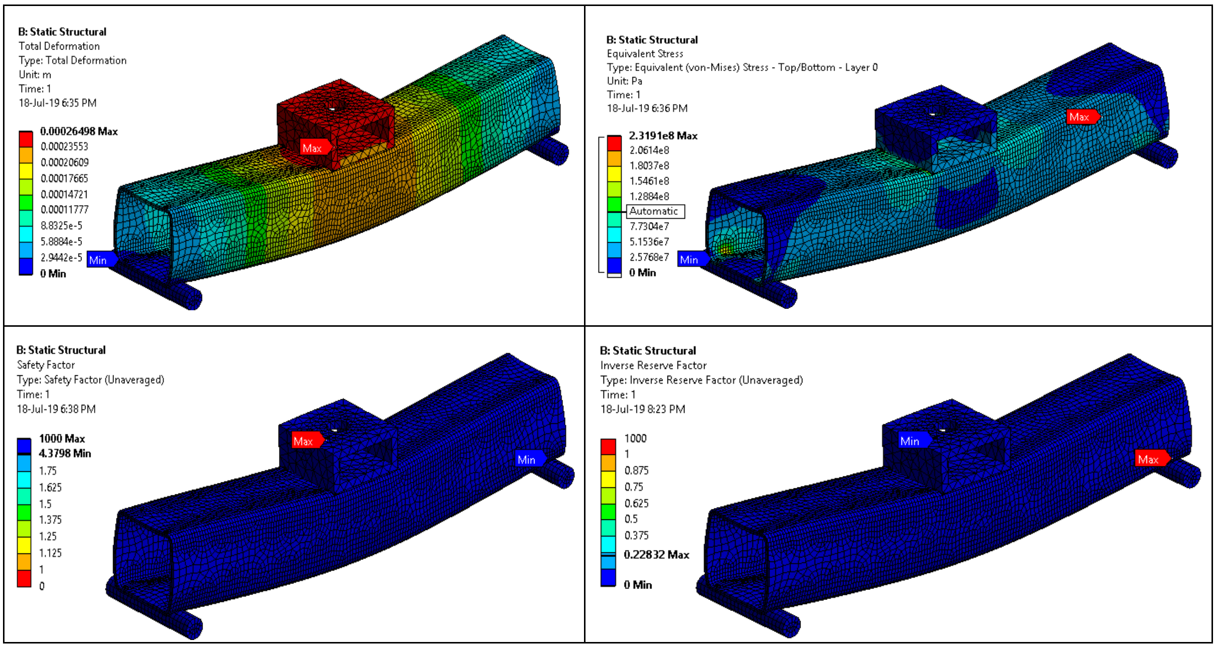


Figure 10. Results obtained in computational analysis

Table 1. Numerical Results of the 15 layers beam

Total Deformation Maximum [mm]	0,265
Equivalent Von-Mises Stress Maximum [MPa]	231,91
Inverse Reserve Factor Minimum	0,228
Safety Factor Minimum	4,38

The results indicate that with the applied load, the structure has few high stress points and high overall safety coefficient. These points show that the presented piece supports the efforts imposed without fail. With this model, parametric optimization was performed. The set objective was minimize total deformation, equivalent Von-Mises stress and safety factor, with the latter also imposing values greater than one, ensuring the stability of the structure. It was established that the number of layers would vary from 1 to 15, at the step of 1, and that the fiber angle would be varied from 0 to 90°, at the step of 22.5°.

This done, the software calculated and presented for the 75 different cases previously mentioned the best 5 candidates that fit the defined objectives. These candidates are shown in Table 2.

Table 2. Candidate Points calculated in the Parametric Optimization

	Candidate Point				
	1	2	3	4	5
Ply Angle	45.203	40.433	54.833	34.673	34.403
Number of Layers	4	4	4	4	4
Safety Factor	2.215	2.215	2.215	2.215	2.215
Total Deformation Maximum [mm]	0.253	0.253	0.253	0.253	0.253
Equivalent Stress Maximum [MPa]	219.03	219.03	219.03	219.03	219.03

The first candidate point was chosen as it provided the most plausible fiber orientation angle. Due to practicality in the laboratory regarding beam lamination, this angle was considered as 45°.

Another modeling was performed, but with the number of layers and fiber angle according to the chosen candidate point. The results are presented in Table 3 below.

Table 3. Numerical Results of the 4 layers beam

Ply Angle	45
Number of Layers	4
Total Deformation [mm]	0.253
Equivalent Von-Mises Stress [MPa]	218.94
Inverse Reserve Factor	0.445
Safety Factor	2.25

Another parametric optimization was performed, only removing the objective of minimizing the equivalent Von-Mises stress. Using the same criteria for choosing the best candidate, the one with the number of layers equal to 8 and fiber orientation of 0 / 90^o was chosen. In Table 4, it is possible to analyze the values found with the modeling of this beam.

Table 4. Numerical Results of the 8 layers beam

Ply Angle	0/90^o
Number of Layers	8
Total Deformation Maximum [mm]	0.241
Equivalent Von-Mises Stress Maximum [MPa]	221.6
Inverse Reserve Factor Minimum	0.283
Safety Factor Minimum	3.53

From the results of the tensile tests shown in Table 5, the Young's Modulus and ANSYS® material tensile strength values were replaced by experimentally obtained values.

Table 5. Results obtained from experimental tensile test

Modulus of elasticity [MPa]	Tensile strength [MPa]
13595	322.93
10621	347.50
11065	304.50
12739	318.06
12260	350.05
21634	352.81
12229	312.60
17876	333.15
17164	321.34
11619	281.27

With the characteristics of the material used imposed, the models were recalculated for the three situations shown above and the results are presented in Table 6, below.

Table 6. Numerical Results from computational analyzing

Ply Angle	0/90^o	0/90^o	45^o
Number of Layers	15	8	4
Total Deformation Maximum [mm]	0.267	0.254	0.264

Equivalent Von-Mises Stress Maximum [MPa]	232.22	228.74	226.15
Inverse Reserve Factor Minimum	0.161	0.195	0.335
Safety Factor Minimum	6.19	5.12	2.98

Finally, the failure criterion was checked. The Tsai-Wu criterion was imposed for the above beams and the results are presented in Table 7.

Table 7. Tsai-Wu failure criterion values for each beam

Number of layers	Tsai-Wu failure criterion
15	0.123
8	0.203
4	0.335

3.2 Experimental analysis

Three beams were produced, with fiber orientation and number of layers as shown above, and tested to resemble the maximum of the computational model. The hand lay-up manufacturing process was used to elaborate them, explaining the matrix on the fiber with spatulas made of non-reactive material. The cure was done using a vacuum bag in which the beam remained for twelve hours, in order to eliminate the voids or bubbles of the bodies and increase their strength. Once ready, adjustments were made in their lengths and edges to maintain the same characteristics of the computational model and to improve imperfections, respectively. Then, the pieces were left in an oven for eight hours at 80ºC for post curing and after that period were taken for testing.

The beams were produced and tested to closely match the computational model. The three-point bending tests were performed with gradual and continuous application of the load until the parts reached their exhaustion and, consequently, fracture. The values of the breaking loads are shown in Table 8. The breaking of the beams was by shear, in which the bidirectional material is less resistant.

Table 8. Maximum load supported by the beams

Number of layers	Break load [N]
15	40011
8	13532
4	4888

4 Conclusions

As mentioned before, in the early decades there was a demand for materials that had excellent performance, such as concrete, but with reduced mass. The composites made with the base of carbon fiber present these features, generating the most resistant leaves when compared to conventional structures. In order to achieve these properties, different software are used for modeling parts that are more efficient.

In view of the modeling performed, the software generates models with perfect fiber homogeneity, void volume and ideal fiber and matrix ratio, resulting in very high strength parts. The hand lay-up process used in manufacturing causes errors throughout its execution, such as bubble formation, heterogeneous layers, fiber misalignment, excess matrix or fiber. Such errors decrease the final strength of the part, thus worsening its performance. The appearance of bubbles is the main cause of the drop in the resistance of parts. This is due to the appearance of cracks that are generated by the empty spaces unable to resist the imposed loads. When these cracks move, they generate fractures, and subsequently rupture.

When observing the computational models, it is possible to notice that, with the decrease of the layers, the inverse reserve factor increases, indicating that the pieces are closer to the ruin. On the other hand, it is not observed that they come to break with the imposed load. Looking further into the inverse reserve factor values, it can be seen that the 15 and 8 layer beams are oversized, since their values of this factor are extremely high, resulting in a high cost in their manufacture.

However, with the experimental models, only one of the bodies supports the same load imposed on the software without breaking, this is explained by the errors involved in the process. It is further noted that all the beams broke by shear forces, which if properly contained, by adopting, for example, the orientation of the fibers that assimilated such forces, the bodies could resist the bending force imposed.

Future works to continue this one will analyze the rule of mixtures, aiming to know the volume fractions of the beams manufactured, as well as to establish the void volume and the density of the material. It will also be done the study of topological optimization of beams in order to minimize mass and volume.

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