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ANALYSIS OF THE INFLUENCE OF GEOMETRIC ARRANGEMENT IN ELASTIC MODULUS OF COMPOSITE MATERIALS

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Abstract. *The composite material is that one formed by two or more phases, at a macroscopic level, whose performance becomes higher due to this combination. In this paper will be fabricated so-called laminate structures, formed by a thermoset polymer matrix and reinforced by unidirectional continuous carbon fibers, through the process of hand lay up and vacuum bag. The laminates were made with three different geometric arrangements, being 0º, 45° and 90º the selected angles. For the analysis of the influence of the lamination angle on the longitudinal elastic modulus two experimental techniques were performed: a traction mechanical test and the impulse excitation technique, being possible to compare the results obtained experimentally with the developed analytical method, besides a comparison between the two techniques, to verify if the process of manufacturing and cutting of the samples occurred correctly. From the performed analyzes it was proven the great influence that the orientation of the laminate has on the longitudinal elastic modulus, having a decreasing behavior according to the increase of the lamination angle, in addition, it was observed that the modulus decreases abruptly at low angles and becomes practically constant at high angles.*

Keywords: *composite material; unidirectional continuous fibers laminate; longitudinal elastic modulus; hand lay up*

1. INTRODUCTION

A fiber-reinforced composite is a composite building material that consist of two or more materials, the fibers as the discontinuous phase and the matrix as continuous phase. Due to the concept of combining two or more materials, it is possible to manipulate the constituents to obtain desirable characteristics and to minimize some undesirable (Felipe, 2008).

The percentage of fibers present in a cross section of a composite material is an important aspect when it is desired to improve the mechanical properties of the same, since the volume fraction is totally linked to the improvement of properties such as mechanical strength and modulus of elasticity, the higher this percentage of fiber, the greater its resistance and consequently its rigidity (Giovedi, et al, 2004).

According to Otani e Pereira (2014) the study of the inclusion of a quantity of fibers in a matrix is called micromechanical analysis, and through it is possible to predict the elastic constants of the composite material, by the combination between the reinforcement and the matrix. This analysis can be done through the "Rule-of-Mixtures", which consists of two mathematical expressions dependent on the elastic moduli of the constituents and their volume fractions, which are represented by an upper limit, Eq. (1) and a lower limit, Eq. (2) (Callister, 2007).

$$E_1 = V_f E_f + V_m E_m \tag{1}$$

$$E_2 = \frac{E_f E_m}{V_f E_m + V_m E_f} \tag{2}$$

Where E_1 and E_2 the longitudinal and transverse elastic moduli of the blade, V_f and V_m the fiber and matrix volume fractions, E_f and E_m the fiber and matrix modulus of elasticity, respectively. Eq. (1) and (2) predict that the real modulus of elasticity is between the upper and lower limits as seen in Fig. 1.

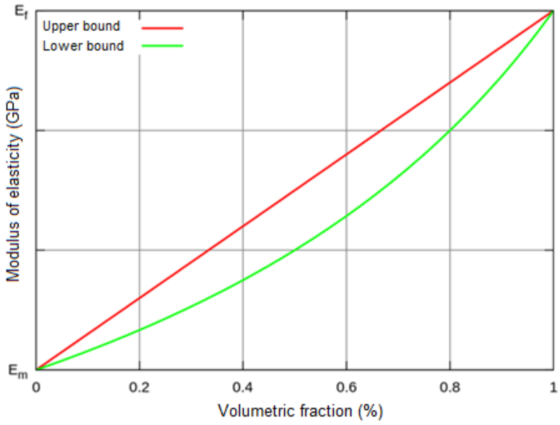

Figure 1: Influence of fiber orientation on the longitudinal elastic modulus of a blade (Callister, 2007)

Due to the non-isotropic characteristic of these materials, that is, properties that can vary in all directions, the mechanical strength is fully linked to the orientation of the reinforcement in the fabrication of the material and the distribution between the two phases (Leitão, 2007).

The modulus of elasticity is also a parameter dependent on the shape and structure with which the material is made, that is, its orientation and arrangement between the constituents. For engineering processes in industries such as aeronautics, automotive or aerospace it is necessary to have reliable values of this type of parameter, due to the required reliability in which equipment of these industries are submitted (Tognana, et. al, 2010). The Figure 2 illustrates the behaviour of the longitudinal elastic modulus with the variation of the lamination angle.

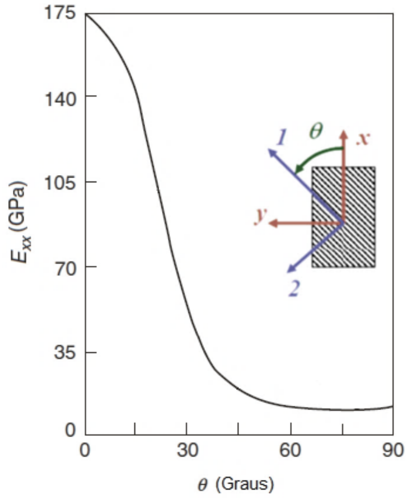

Figure 2: Influence of fiber orientation on the longitudinal elastic modulus of a blade (Jones, 1999)

2. MATERIALS AND METHODS

The laminated sheets comprised of a unidirectional carbon fiber, aligned in one direction only, as the discontinuous phase and resin epoxy as the continuous phase. The manufacturing method used to make the laminates was hand lay-up, where the laminate is manufactured manually on a mold.

The adhesion between the components is done through a process called vacuum bag, where above the laminate is applied a layer of a fabric, called as peel ply to obtain a better finish of the laminate and act as a first absorbent of the resin, then a perforated plastic is introduced which allows the resin to pass through and finally an absorbent foam, to ensure absorption of all of the excess resin. This step also has the function of guaranteeing a ratio between its constituents close to the ideal, being 80% reinforcement and 20% matrix (ABMACO, 2009). The last step is the positioning of the vacuum pump hose above the foam, initiating the vacuum bag process.

The pump remained on for 5 hours, as recommended by the manufacturer, to remove as much of the surplus resin that will be retained in both the peel ply and the absorber foam and ensure a better compaction between the blades, this period is known as geltime, and is the time elapsed after mixing the resin with the hardener and the beginning of resin hardening and varies according to the type of resin used (ABMACO, 2009).

Upon completion of the geltime, the pump was turned off and the mold remained closed for 24 hours prior to opening and removing all layers of plastics, foam and fabric with the absorbed resin, to obey the curing time, resulting in laminates rigid, lightweight and compact. A schematic of the entire process of manual lamination and vacuum bag can be seen in Fig 3.

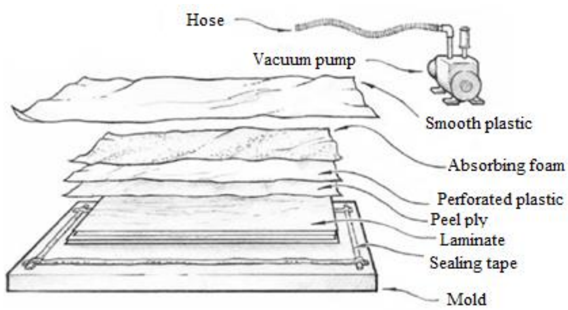

Figure 3: Manual lamination and vacuum bag process (West Systems Epoxy Procucts, 2010)

After the manufacturing process, samples for both tensile test and non-destructive test were obtained, following certain dimensions depending on the test to be performed and the direction of the sample. The samples obtained for each orientation and test can be seen according to Fig. (5), where it is possible to notice the oriented fibers at 0 °, 45 ° and 90 ° respectively.

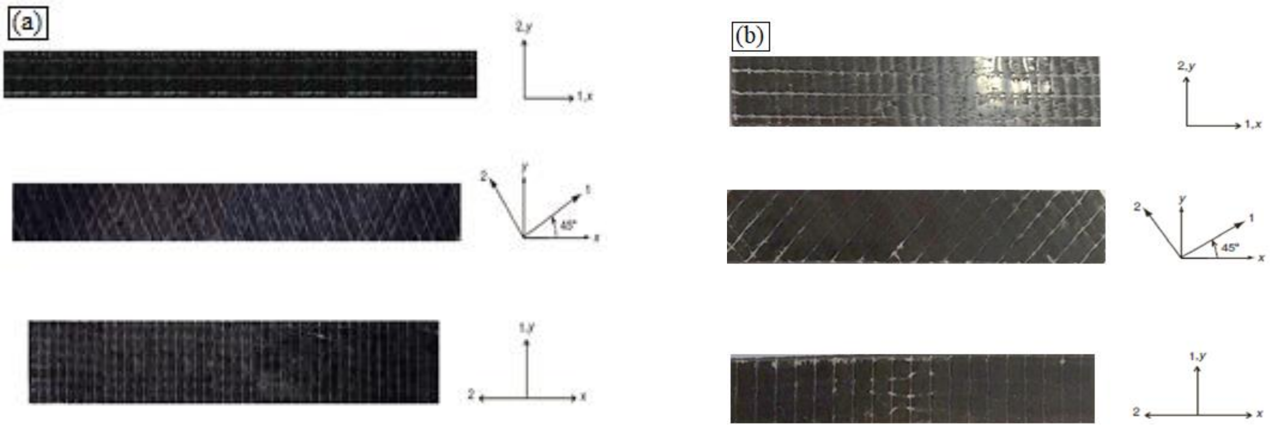

Figure 5: (a)Samples obtained for the traction mechanic test; (b) Samples obtained for the traction mechanic test.

The non-destructive test performed is called as impulse excitation technique, consisting on the determination of the dynamic modulus of elasticity of a material, based on the natural frequency of a sample (ASTM E1876, 2011). The excitation of the frequencies of a sample occurs through a short-term mechanical impulse, which may be automatic or manual, which has its acoustic response obtained by a microphone and processed by the Sonelastic® software, as seen in Fig. (6) .The software performs a scanning on the acoustic response through the computer's audio card, analyzing the transient vibrations through excitation and extracting the frequency spectrum for the characterization of the elastic modulus through a mathematical treatment (ATCP, 2014).

Figure 6: Schematic representation of acoustic tests (ATCP, 2014).

The equipment used for the traction test was a universal testing machine provided by the ITAIPU Binacional Concrete Laboratory, with a maximum capacity of 2000 kN.

Before starting the test, the samples were measured by a digital caliper to obtain the initial area, which was used in the calculation of the modulus of elasticity. Then, the samples were accommodated in the equipment, so that the claws of the equipment were fixed only to the tabs added to the specimen during the preparation, in order to avoid premature rupture. The displacement occurred during the test was obtained by a clip gage attached to the samples. The accommodation of the sample and the clip gage can be visualized according to Fig. (7).

Figure 7: Sample accommodation in the traction test.

3. ANALISYS

3.1 Constitutive relations

The following equations were based on (Mallick, 2008) and (Jones, 1999).

The stress-strain relationship for a particularly orthotropic blade, where $\theta = 0°$ or 90°, can be seen through the local stiffness matrix [Q], according to Eq. (3).

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_2}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} \quad (3)$$

Where ε_{xx} and ε_{yy} are normal strain in x and y direction, E the modulus of elasticity, σ_{xx} and σ_{yy} normal stresses in x and y direction, γ_{xy} shear strain in xy plane, τ_{xy} shear stress in xy plane, G he shear modulus and ν the Poisson coefficient.

For an orthotropic blade, where $\theta \neq 0°$ or 90 °, that is the local axis (1,2,3) do not coincide with the global reference axis (x, y, z), stress and strain must be transferred from the local axis to the global axis, known as global stiffness matrix, $\overline{Q}$, as seen in Eq. (4).

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} \tag{4}$$

Where the terms can be written according to Eq. (5) to Eq. (10).

$$\overline{Q}_{11} = Q_{11}\cos^4\theta + 2(Q_{12} + 2Q_{66})\ sen^2\theta\cos^2\theta + Q_{22}sen^4\theta \tag{5}$$

$$\overline{Q}_{12} = Q_{12}(sen^4\theta + \cos^4\theta) + (Q_{11} + Q_{22} - 4Q_{66})\ sen^2\theta\cos^2\theta \tag{6}$$

$$\overline{Q}_{22} = Q_{11}sen^4\theta + 2(Q_{12} + 2Q_{66})\ sen^2\theta\cos^2\theta + Q_{22}\cos^4\theta \tag{7}$$

$$\overline{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})\ sen\theta\cos^3\theta + (Q_{12} - Q_{22} + 2Q_{66})\ sen^3\theta\cos\theta \tag{8}$$

$$\overline{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})\ sen^3\theta\cos\theta + (Q_{12} - Q_{22} + 2Q_{66})\ sen\theta\cos^3\theta \tag{9}$$

$$\overline{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\ sen^2\theta\cos^2\theta + Q_{66}(sen^4\theta\cos^4\theta) \tag{10}$$

3.2 Classical Laminate Theory

According to Daniel and Ishai (2006) the classical laminate theory constitutes a relation of force and moment with the deformation and the curvature of a laminate, considering the geometric arrangement and the properties of the laminae. For its use it is necessary to assume some hypotheses, known as Kirchhoff hypotheses.

The implication of these hypotheses in the displacement components of a laminate denominated u, v and w in the directions x, y and z, respectively are demonstrated in the x - z plane, as seen in Fig. (4).

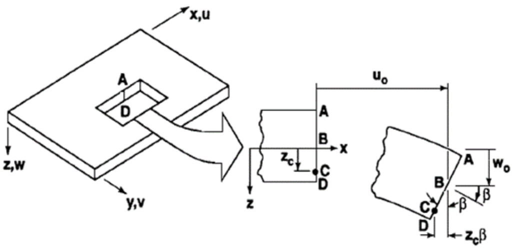

Figure 4: Relation displacement - deformation (Daniel and Ishai, 2006).

Through Fig. 4, Eq. 4 and definition of deformations it is possible to obtain the following relation, Eq. 11, for any lamina k of the laminate.

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix}_k = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \left\{ \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} + z \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \right\}_k \tag{11}$$

Where ε_x^0 and ε_y^0 are the midplane normal strains in the laminate, γ_{xy}^0 midplane shear strain, z the distance of one layer from the midplane, κ_x and κ_y bending curvatures and κ_{xy} twisting curvature of the laminate.

To assess the stress and strain state of each slide, the stress and momentum can be integrated along the thickness of the laminate to provide the forces and the resulting moments, ass seen in Eq. (12) and (13).

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}_k dz \tag{12}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} z\ dz = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}_k z\ dz \tag{13}$$

Where N_x and N_y normal forces, N_{xy} shear force, M_x and M_y bending moments and M_{xy} twisting moment.

Replacing Eq. (11) on Eq. (12) and (13) the following matrices can be defined in a simplified way, according to Eq. (14).

$$\begin{bmatrix} [N] \\ [M] \end{bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{bmatrix} [\varepsilon^0] \\ [\kappa] \end{bmatrix} \tag{14}$$

The matrix elements [A], [B] and [D] can be calculated by Eq. (15), (16) and (17).

$$[A]_{ij} = \sum_{k=1}^{N} \left[\overline{Q}_{ij}\right]_k (h_k - h_{k-1}),\ i, j = 1,2,6 \tag{15}$$

$$[B]_{ij} = \frac{1}{2} \sum_{k=1}^{N} \left[\overline{Q}_{ij}\right]_k (h_k^2 - h_{k-1}^2)\ \ i, j = 1,2,6 \tag{16}$$

$$[D]_{ij} = \frac{1}{3} \sum_{k=1}^{N} \left[\overline{Q}_{ij}\right]_k (h_k^3 - h_{k-1}^3),\ i, j = 1,2,6 \tag{17}$$

In order to determine the deformations (ε^0) and curvatures (κ) of the midplane for stresses and resulting moments, we can invert the matrix that relates the deformations to the forces, see Eq. (14), thus obtaining Eq. (18).

$$\begin{bmatrix} [\varepsilon^0] \\ [\kappa] \end{bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix}^{-1} \begin{bmatrix} [N] \\ [M] \end{bmatrix} = \begin{bmatrix} [a] & [b] \\ [b]^\tau & [d] \end{bmatrix} \begin{bmatrix} [N] \\ [M] \end{bmatrix}, \tag{18}$$

For an assay in which the force is applied in the x-direction, the deformation value at x can be obtained by the following relation, taken from Eq. (18), obtaining the longitudinal modulus of elasticity through Eq. (19).

$$E_x = \frac{M\ b\ 12}{k\ b\ h^3} = \frac{12}{d_{11}\ h^3} \tag{19}$$

4. RESULTS AND DISCUSSIONS

4.1 Analytical elastic moduli

Using the mixing rule, Eq. (1) and (2), it was possible to obtain the local stiffness matrix Eq. (3) for the manually manufactured laminates of epoxy resin and carbon fiber. From the local stiffness matrix and considering the variation of the lamination angle, the $\left[\overline{Q}_{11}\right]$ elements of the global stiffness matrix, Eq. (5), for each orientation were obtained.

Based on the thickness of each blade, and the position of each layer in relation to the midplane, it was possible to perform the sums indicated by Eq. (15) and (17), thus obtaining the elements of the stiffness matrix to the tensile strength extension, matrix [a] and the elements of the flexural stiffness matrix for the non-destructive test, matrix [d].

From the total thickness of the laminate, according to the number of layers used, it was possible to use Eq. (20) and (21) to provide the longitudinal elastic modulus of a laminate. Thus, the analytical longitudinal elastic modules expected for different orientations are described in Tab. 1.

Table 1. Analytical longitudinal elastic modules of the laminate according to fiber angle.

Fiber Angle	E_x
0°	92.64 GPa
45°	31.82 GPa
90°	14.19 GPa

From Table 1 it was possible to obtain a graphic with the behavior of the longitudinal modulus of elasticity with the variation of the lamination angle.

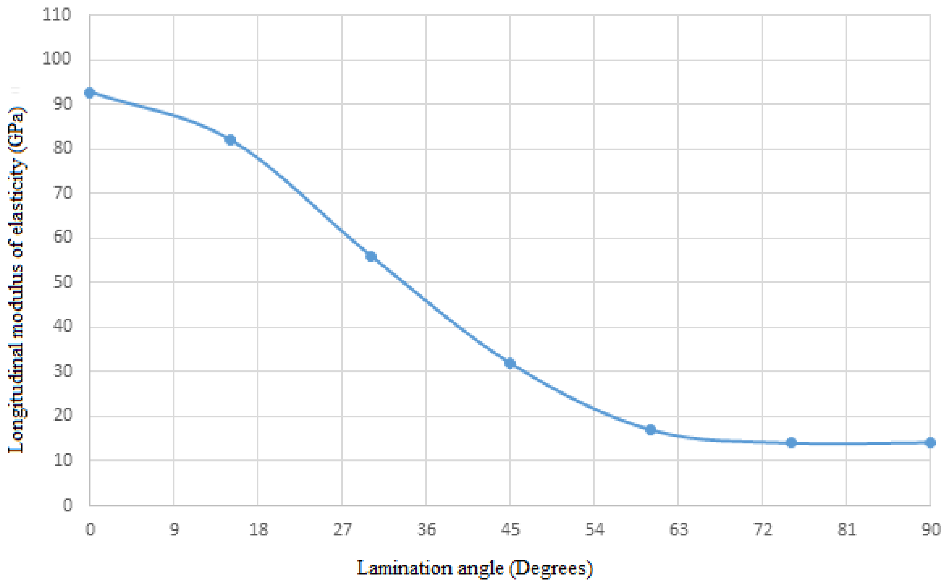

Figure 8: Behavior of the analytical longitudinal modulus of elasticity for different geometric arrangements

4.2 Experimental elastic moduli

The analytical results were compared with the values obtained from the non-destructive test, through the impulse excitation technique using the software Sonelastic® and the traction mechanical test. The results can be seen on Tab. 2 and Fig. (9) and (10), where the errors are represented in percentage.

Table 2. Longitudinal elastic modulus of the laminates obtained through non-destructive and destructive test

Lamination Angle	E_x -destructive test (GPa)	E_x non-destructive test (GPa)
0°	109.62± 7.08	87.20 ± 3.33
45°	12.14 ± 1.46	14.41 ± 1.36
90°	7.6 ± 0.74	8.16 ± 1.00

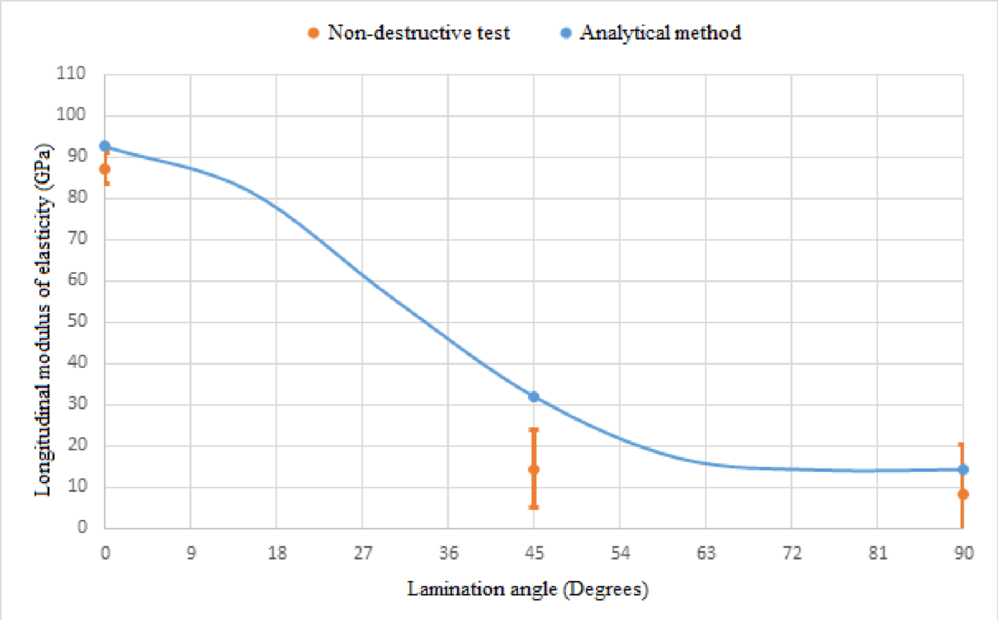

Figure 9: Comparison between the results obtained by the non-destructive test and the analytical behaviour.

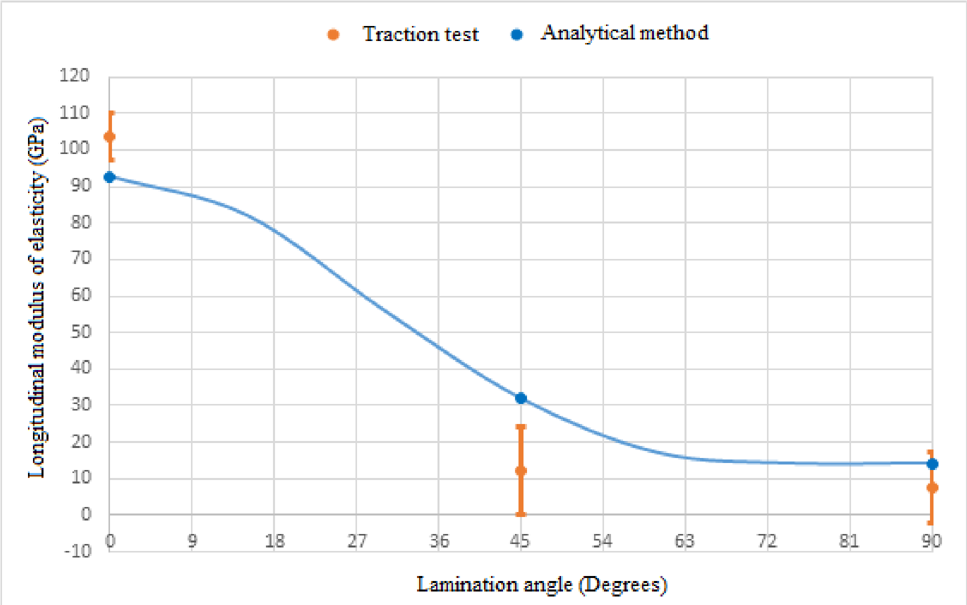

Figure 10: Comparison between the results obtained by the traction mechanical test and the analytical behaviour.

The behaviour of the elastic modulus obtained in both tests followed the analytical method, decreasing according to the increase of the lamination angle, evidencing the low influence that the resin presents for geometric arrangements close to 90 °. The discrepancies found among the results may have been due to external conditions that influenced the manual manufacturing process and the aggressive cutting process in some arrangements that occurred in opposite directions of the fiber, which may have had a high influence on the obtained result.

Based on the elastic modulus obtained by the two tests, a comparison between them can be observed according to Fig. (11).

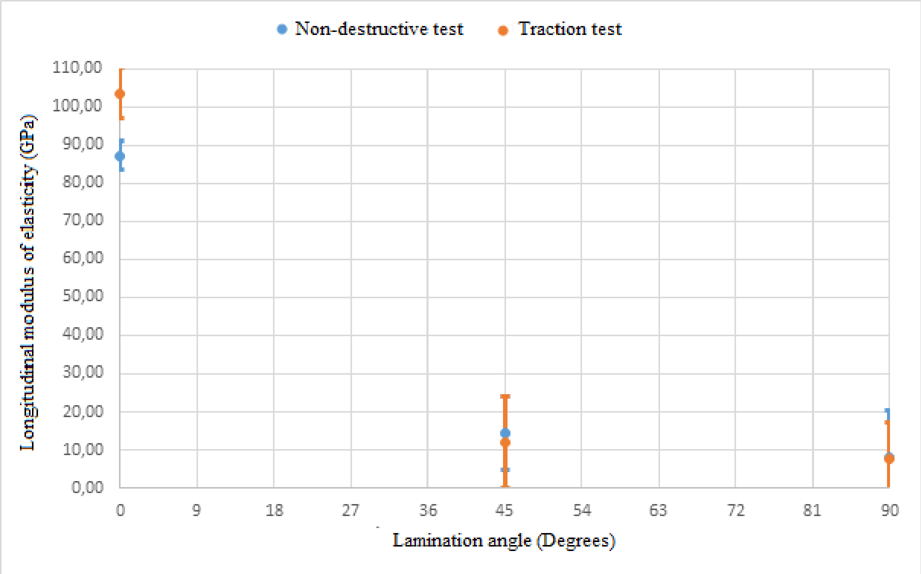

Figure 11: Comparison between the longitudinal elastic modules of the laminate obtained by the tensile test and non-destructive test

The elastic modulus obtained between the two tests were similar and coincided in the 45 ° and 90° samples. In the samples of 0° it is possible that the difference between the results occurred due to the different conditions, such as temperature and humidity, in which the laminates were made, and the vacuum bag process that was performed with different vacuum pumps.

5. CONCLUSIONS

The objective of the paper was to manually make laminates formed by a thermoset polymer resin and continuous unidirectional carbon fiber, with three different geometric arrangements of 0 °, 45 ° and 90 ° for the characterization of the longitudinal modulus of elasticity, both experimentally and analytically.

The experimental results, in general, were not so similar in relation to the analytical result, it is possible that this difference is justified by the manual manufacturing process itself, besides the cutting of the 45 ° and 90 ° laminates which were more complex because they did not coincide with the direction of the fiber, causing an excess of effort during the cut, this effort may have caused an internal damage, locally delaminating the sample. Another consequence of the cutting process is its non-uniformity along the length of the sample, which can cause a tensile concentrator, which will cause a premature failure of the material.

Therefore, the strong influence of the lamination angle on the longitudinal elastic modulus of a laminate is noted, this shows us how much an arbitrarily oriented layer can influence the performance of a mechanical equipment, being a carbon fiber laminate and epoxy resin, despite the high cost value of fiber, proved a good alternative for areas such as automobile and aeronautics, due to desired properties such as high rigidity allied to low structural weight.

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