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ACCURACY OF MECHANICAL PROPERTIES TESTING USING COMPLEMENTARY METHODS FOR GLASS FIBER REINFORCEMENT POLYMERS

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Abstract: *The mechanical characteristics of glass fiber composite materials are time-dependent and typically show viscoelastic behavior. Since the use of these materials has increased dramatically in recent decades, it is necessary to determine their mechanical properties with the high precision. Used in different domains, from sporting goods to aeronautics, the study of behavior under load is useful for understanding how it affects the design capability under conditions of internal geometric complexity. The paper presents the fabrication concept of a glass fiber reinforced composite plate (GFRP) having stacking sequence $[0^\circ/90^\circ]$ and the results obtained by uniaxial tensile tests on three cutting directions: longitudinal, transverse and 45° respectively, following the validation of the mechanical parameters performance. The elastic characteristics of the composite were determined by sinusoidal cyclic loading testing using the Dynamic Mechanical Analyzer (DMA) three-point bending device. The tensile failure mode is analyzed on the basis of specific stress-strain characteristic curves.*

Key words: *composite materials, tensile test, GFRP, DMA.*

1. INTRODUCTION

Glass fiber reinforced polymer composites (GFRP) are materials used in structural applications [1]. Although the manufacturing costs are slightly higher than traditional materials, these materials have various advantages including good strength to weight ratio, good fatigue properties, low density. GFRP is used in different fields such as, automotive engineering [2], marine structures [3], additive manufacturing industry [4]. Due to the complexity of the structure of these materials, results of numerous studies have shown that there is a close relationship between the size and shape of the fibers, their orientation and distribution and the viscous-elastic behavior of the matrix [4,5,6]. The mechanical and elastic characteristics of GFRP composites depend on the fiber modulus, strength and bonding efficiency of the matrix-fiber interface [7,8,9]. In order to demonstrate their ability to perform challenging loads, composite materials must be subjected to a series of mechanical tests both

static (tensile, compression, shear, bending) and dynamic (fatigue) depending on the type and direction of loading. Other studies, such as [10,11,12,], have mainly addressed the determination of mechanical and elastic properties by destructive and non-destructive testing on RT800 and MAT 600 fabric reinforced polymers. A new test method on an octagon type specimen made of GFRP was used for the three-directional determination of the elastic characteristics. The obtained results demonstrate the orthotropic properties of GFRP [13]. Many experimental and numerical tests have been carried out to study the cracks in the matrix because they are the main cause of affecting the mechanical and elastic properties [14, 15, 16, 17]. The aim of this research is to investigate the mechanical behavior of glass fiber reinforced composite material having a stacking sequence $[0^\circ/90^\circ]$. The study aims to analyze how fiber orientation influences the mechanical properties of the material. In order to obtain a complete characterization, the research combines both destructive methods, such as

tensile tests and dynamic-mechanical analysis (DMA), and non-destructive methods, such as ultrasonic method. This approach allows not only direct assessment of the mechanical performance of the material, but also the correlation of these results with techniques that can be used for monitoring and diagnostics of material integrity in practical applications. Through this approach, the paper provides relevant information for optimizing the use of composite materials in structures subjected to different types of mechanical stresses, thus contributing to the improvement of their design and reliability.

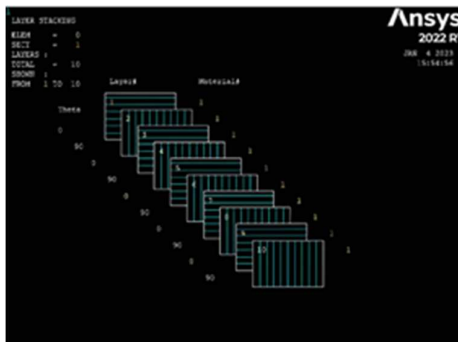
2. MATERIALS AND METHODS

2.1 Materials

A composite plate reinforced with RT 500 fiberglass and EPIKOTE RL 1941 epoxy resin was fabricated by the lay-up method is shown in Figure.1a, to determine the material characteristics. The composite plate is composed of 10 layers having the fiber orientation at $[0^\circ/90^\circ]$ is shown in Figure. 1b. Fifteen specimens were cut from the plate in three different directions (5 transverse (TR), 6 longitudinal (LG) and 4 diagonals at 45°), Fig. 1c. The cross-sectional dimensions of the specimens are $15\text{mm}\times 4\text{mm}$.



a)



b)

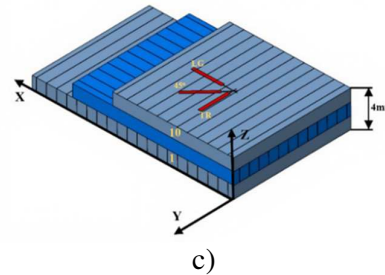


Fig. 1. Lay-up method (a) Lay-up method (b) Stacking sequence of layers composite $[0^\circ/90^\circ]$ (c) Directions for sampling from the GFRP plate.

2.2 Testing using ultrasound method

In order to determine the material characteristics, the specimens were subjected to the tensile test according to ASTM D3039 and for analyzing the mechanical behavior of the composites, the specimens were tested on the universal testing machine type WDW 50, which has a maximum load capacity of 50 kN. The testing speed was 2 mm/min for each specimen until failure.

2.3 Testing using ultrasound method

For detection and evaluation of delamination (glass fibers are not fixed in the epoxy matrix), C-scan US examination is used, using PHASOR XS - General Electric equipment equipped with US sensors array wedged on phase with frequency of 5MHz and a delay line. A US equipment composed of PR 5073 Pulser Receiver - Panametrics set-up on impulse-eco mode was used to determine the longitudinal and transverse wave velocities in the composite.

2.4 Testing using dynamic mechanical analyzer

From the GFRP plate, figure 1b with the fiber orientation at $[0^\circ/90^\circ]$, which was then rotated by 45° obtaining a quasi-isotropic material, specimens with dimensions $50\times 10\times 4\text{mm}$ were cut out according to ASTM D5023. These specimens were tested in sinusoidal cyclic loading with DMA242C - Netzsch Germany, three-point bending test using Protheus v.4.8.5 software.

3. RESULTS

3.1 Mechanical Properties of GFRP under Static Tensile Loading at $[0^\circ/90^\circ]$

Figure 4 shows the superposed characteristic curves for the 6 specimens cut longitudinally from the plate with fiber orientation at $[0^\circ/90^\circ]$.

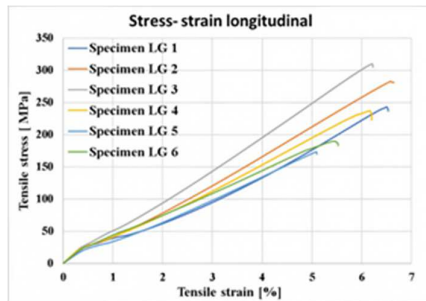


Fig. 2. Characteristic stress-strain curve for longitudinally cut specimens at $[0^\circ/90^\circ]$.

Comparing the 6 curves, it can be observed that the highest breaking stress occurs at specimen 3, with a maximum value of $\sigma_r = 310$ MPa. Analyzing the characteristic curves of the specific stress-strain, strain it is noticed that a bilinear mechanical behavior clearly appears, in which the material starts with a linear elastic portion and after it is preceded by a plastic portion of small length. The failure mode is represented by a decrease in the diagram. The six slopes of the stress-strain curves, show a small deformation energy storage (area under the curve), this aspect being specific to materials with viscous-elastic behavior.

Figure 5 shows the superposed characteristic curves, presenting the differences in tensile behavior for the 5 specimens transversely cut from the plate with fiber orientation at $[0^\circ/90^\circ]$.

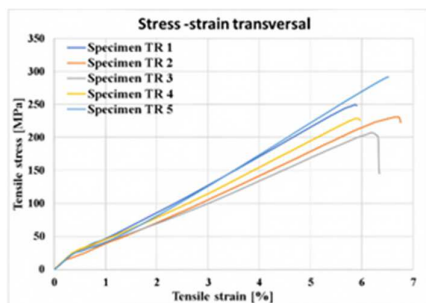


Fig.3. Characteristic stress-strain curve for transversely cut specimens at $[0^\circ/90^\circ]$.

A comparison of the 5 curves shows that the highest breaking stress occurs at specimen 5, with a maximum value of $\sigma_r = 290$ MPa. The same bilinear mechanical behavior is also found in the case of transversely cut specimens. The

failure mode is represented by a decrease in the plot, more evident in specimen 3. The five slopes of the stress-strain curves show a small deformation energy storage (area under the curve), this aspect being specific to materials with viscous-elastic behavior.

The superposed stress-strain curves in Figure 6 show the differences in tensile shear strength behavior for the 4 specimens cut at 45° from the plate with fiber orientation at $[0^\circ/90^\circ]$.

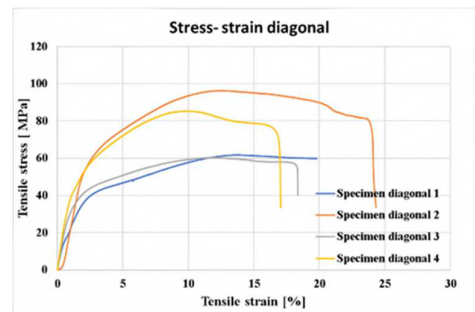


Fig. 4. Characteristic stress-strain curve for 45° cut specimen at $[0^\circ/90^\circ]$.

In the case of specimens cut at 45° , the laminates are no loaded in the direction of load application, and the strength characteristics of the resin become important in the structural analysis of the layered composite material. With comparison to the specimens loaded in the longitudinal and transverse direction, a deviation from linearity of the specific strain stress-strain curves and much lower values of the fracture toughness are observed. Analyzing the four curves, it can be seen that the maximum value is observed at the specimen 2 of $\sigma_r = 96$ MPa. By analyzing the shape of the specific stress-strain curves, it was found that they exhibit a high deformation energy storage, this aspect demonstrating an elasto-plastic behavior and is due to the fact that the stress occurs in a direction along which there are no reinforcing fibers

3.2 Ultrasound and DMA

Figure 7 presents the values obtained were longitudinal waves $C_L = 2342$ m/s and transversal $C_T = 1450$ m/s.

The values of the modulus of elasticity and elastic properties of the composite are determined from the wave propagation velocities and were compared with those obtained by the DMA method.



Fig. 5. Sample wave propagation for a) longitudinal waves; b) transversal waves.

The values of the modulus of elasticity and the elastic properties of the composite are determined from the wave propagation velocities:

$$C_T = \sqrt{\frac{E}{\rho} \frac{1}{2(1+\nu)}}; C_L = \sqrt{\frac{E}{\rho} \frac{1-\nu}{(1+\nu)(1-2\nu)}} \quad (1)$$

The wave propagation velocity in the material is dependent on the material density ρ and its elastic constants, namely the elastic modulus E and the Poisson's ratio ν .

The value of the elastic modulus is a function of the fiber volume V_f , the Poisson's ratio is dependent on the matrix and fiber volume. Using the expressions for the longitudinal and transverse wave propagation velocity in equation (1), the Poisson's ratios were determined and then the Young's modulus and the Coulomb's modulus (as specified below the table).

The main mechanical properties of the samples studied are presented in Table 1, and represent the average of the measurements of 4 samples of the same plate.

Table 1

Principal mechanical characteristics of the samples

| No | Composite | C_L^{**} [ms ⁻¹] | C_T^{**} [ms ⁻¹] |
|----|-------------|-----------------------------------|-----------------------------------|
| 1 | GFRP [0/90] | 2342 | 1450 |
| 2 | GFRP [0/90] | 2342 | 1450 |
| No | Composite | $E_x=E_y^{**}$ [GPa] | E_z^* [GPa] |
| 1 | GFRP [0/90] | 18,38 | 20 |
| 2 | GFRP [0/90] | 18,38 | 13 |
| No | Composite | ν_{xy}^{**} | T_g^* [°C] |
| 1 | GFRP [0/90] | 0,19 | 52,2 |
| 2 | GFRP [0/90] | 0,19 | 46,6 |
| No | Composite | G_{xy}^{**} [GPa] | $\tan \delta^*$ |
| 1 | GFRP [0/90] | 7,73 | 0,40 |
| 2 | GFRP [0/90] | 7,73 | 0,50 |

* determined by DMA 242C measurements

** determined by calculation

The viscoelastic properties of the specimens, the complex modulus of elasticity E^* (Young) and G^* (Coulomb); the loss modulus E'' , which represents the viscoelastic component of the material; the loss factor, $\tan \delta$, as a function of temperature were determined in the temperature range (20°C-190°C). In this temperature range the material does not reach thermal destruction. Figure 8 shows the behavior of the above sizes with respect to the stress direction for the 1Hz frequency.

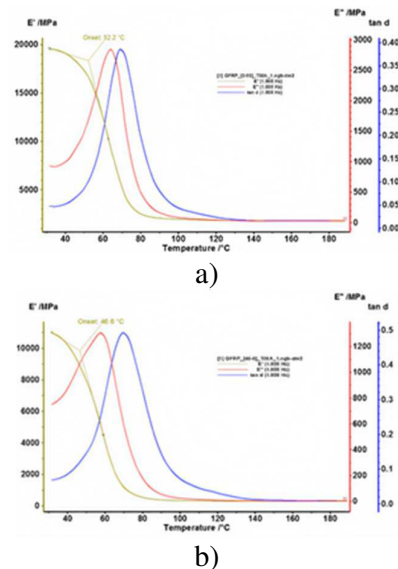


Fig. 6. DMA results for sample.

The set parameters were for frequencies 1, 3.33, 5, 10, 33.3, 50Hz, heating rate of 2°C/min. The parameters obtained from the tests provide information about the vitrification, concerning the T_g (glass transition), resulting from the crosslinking reaction. Additionally, it is observed that temperature has a significant role in the adhesion activity of the resin to the reinforcing fibers. The stress is found to be equally distributed in both directions.

4. CONCLUSION

Tensile tests on the three cutting directions demonstrate an orthotropic behavior of the material, due to the different tensile stresses occurring in different directions in the GFRP plate. The results obtained from tensile tests of specimens cut at 45° of the plate [0°/90°] yielded lower tensile strength values than those obtained in the other two directions. On the other hand, the elongation and deformation of the specimens cut at 45° were much higher than the other two directions. These results emphasize the importance of the arrangement of fibers with respect to the main direction of mechanical stress. Fiber orientation determines not only the tensile strength, but also the overall behavior of the material under load, including its mode of deformation and its ability to dissipate mechanical energy. Thus, in structural applications where high tensile strength is required, the arrangement of the fibers should be optimized so that they are oriented in the main direction of mechanical stress. Furthermore, the mechanical properties of GFRP materials are closely correlated with the propagation velocities of elastic waves within the composite structure.

Analysis based on measurements of ultrasonic wave propagation velocities provides relevant information about the homogeneity and integrity of the material, thus allowing a non-destructive evaluation of the material. The comparison of the results obtained by this method with those provided by destructive tests, dynamic-mechanical analysis (DMA) and tensile tests, showed a good correlation between these methods. This confirms that wave propagation-based measurements can be a

reliable technique for characterizing the mechanical properties of composite materials and for monitoring the integrity of composite materials in structural applications. The presented studies and the obtained values will have use in future studies on the simulation of composite structures of wind turbine blades.

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Precizia testării proprietăților mecanice folosind metode complementare pentru GFRP

Caracteristicile mecanice ale materialelor compozite din fibră de sticlă sunt dependente de timp și prezintă de obicei un comportament vâscoelastic. Deoarece utilizarea acestor materiale a crescut dramatic în ultimele decenii, este necesar să se determine proprietățile lor mecanice cu o precizie ridicată. Utilizate în diferite domenii, de la articole sportive la aeronautică, studiul comportamentului sub sarcină este util pentru înțelegerea modului în care aceasta afectează capacitatea de proiectare în condiții de complexitate geometrică internă. Lucrarea prezintă conceptul de fabricație a unei plăci compozite armate cu fibră de sticlă (GFRP) cu secvență de stivuire $[0^\circ/90^\circ]$ și rezultatele obținute prin teste de tracțiune uniaxială pe trei direcții de tăiere: longitudinală, transversală și respectiv 45° , în urma validării performanței parametrilor mecanici. Caracteristicile elastice ale compozitului au fost determinate prin teste de încărcare ciclică sinusoidală utilizând dispozitivul de încovoiere în trei puncte Dynamic Mechanical Analyzer (DMA). Modul de cedare la tracțiune este analizat pe baza curbelor caracteristice tensiune-deformare specifice.

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