Determination of mechanical properties of some glass fiber reinforced plastics suitable to Wind Turbine Blade construction

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Abstract. The control of wind turbine’s components is very rigorous, while the tower and gearbox have more possibility for revision and repairing, the rotor blades, once they are deteriorated, the defects can rapidly propagate, producing failure, and the damages can affect large regions around the wind turbine. This paper presents the test results, performed on glass fiber reinforced plastics (GFRP) suitable to construction of wind turbine blades (WTB). The Young modulus, shear modulus, Poisson’s ratio, ultimate stress have been determined using tensile and shear tests. Using Dynamical Mechanical Analysis (DMA), the activation energy for transitions that appear in polyester matrix as well as the complex elastic modulus can be determined, function of temperature.

1. Introduction
Wind energy has more and more gained terrain in the energy industry, being a reliable green source due to no toxic waste and no emission of carbon to the environment, etc [1]. The tendency in reducing wind energy costs is to make a system to monitories and control the components with high risks [2].

Blades are the most critical components in wind turbine systems, so that it is important to have a rigorous materials selections to satisfies the WTB construction requirements [3] as high stiffness, low density, fatigue resistance, in order to obtain optimal performance, reduced gravity forces, resistance to degradation [4], [5].

Glass fibers are reinforced with a polymer matrix in order to produce glass fibers reinforced plastics (GFRP), which has a higher strength-to-weight ratio than steel and aluminum, has scratch resistance, corrosion resistance, insulation, and low susceptibility to moisture. Nowadays, GFRP and CFRP replace wood and steels in the construction of WTB. The mechanical, thermal and chemical properties are improved by combining glass fibers or carbon fibers with matrix materials as polyesters, vinyl esters, epoxies etc [6]. Most glass-reinforced products are made with E-glass (electrical glass), which has good electrical and mechanical properties and high heat resistance. Due to the cost-performance ratio, GFRP is the preferred option for the longer blades needed for offshore turbines and for multi-MegaWatts onshore turbines [7].

Full characterization of the properties of anisotropic and inhomogeneous composite materials, for use in demanding structural applications, requires a wide range of mechanical tests. Determination of
bulk properties requires tension, compression and shear tests [8]. The most common properties reported for fiber-reinforced polymers are those obtained from tensile testing. These properties include modulus of elasticity, Poisson’s ratio, tensile strength, and ultimate tensile strain. Use of the Iosipescu shear test for measurement of shear properties of unidirectional lamina has been studied both analytically and experimentally [9], allowing determination of intralaminar shear strength and shear stiffness of glass-reinforced polyester material for specimens with two different fiber orientations.

This paper presents the test results, performed on GFRP, with two different fiber orientations, suitable to construction of blades for on-shore wind turbines. The Young modulus, shear modulus (Coulomb), Poisson’s ratio, ultimate stress etc., on the reinforcement directions have been determined using tensile and shear tests with INSTRON 8801. Also, using Dynamical Mechanical Analyser - DMA 242C Netzsch, the activation energy for transitions that appear in polyester matrix as well as the complex elastic modulus can be determined, function on temperature.

2. Studied samples
Plates from combination of multilayers glass roving fabricRT800 and nonwoven MAT600 oriented at $\pm 45^\circ$ and $0^\circ/90^\circ$ with Epikote resin MGS LR 385 were taken into study. The specimens are presented in figure 1.

From these GFRPs, special specimens were cropped:
- For tensile tests: the cross section of the $0^\circ/90^\circ$ sample has 13mm×4mm and the cross section of the $\pm 45^\circ$ sample has 26 mm × 4 mm, respecting the ASTM D3039 [10]. The aluminum grip tabs [11] are bonded with Bison – two components epoxy adhesive (figure 2);
- For shear tests, according to ASTM 5379 [12], Iosipescu specimen[13] indicates the shape and the dimensions of the sample;
- For DMA tests, the dimensions are 50x10x4mm. Two specimens from each sample are tested.

![Figure 1. Studied samples. Figure 2. Specimen for tensile tests: a) 0º/90º; b) ±45º.](image)

3. Experimental set-up and principles
Tensile tests. Two electric strain gauges (TER), oriented at $0^\circ$ (TER L) and $90^\circ$ (TER Tr) oriented in respect with the test direction were bonded with Z70 (HBM) adhesive on one face of the sample (figure 2a) for $0^\circ/90^\circ$ layers. The strain gauges are 1-LY11-6/350, made by HBM(Germany), with resistance $R = 350 \, \Omega \pm 0.35\%$, gauge factor $k_g = 2.07 \pm 1\%$, transverse sensibility $K_t = -0.2\%$.

On one face of $\pm 45^\circ$ sample, two electric strain gauges strain gauges were bonded, oriented at $0^\circ$ (longitudinal transducer) and at $90^\circ$ (transversal transducer) oriented in respect with the testing direction (Figure 2b). The strain gauges are EA-13-249LZ-120, made by VISHAY (USA), with $R = 120\, \Omega \pm 0.35\%$, $k_g = 2.095 \pm 0.5\%$ and $K_t = 0.2\%$. In both cases, the cables were connected with Vishay P3 bridge, in quarter bridge connection. Tensile tests were performed using INSTRON 8801 equipment (figure 3) at room temperature, with a 0.5 mm/min deformation speed setting.

Strains and deformations are determined by [14]
\[ \tau_{12} = \frac{\sigma_{xx}}{2}, \quad \sigma_{xx} = \frac{N}{A}; \quad \gamma_{12} = \varepsilon_{xx} - \varepsilon_{yy} \]  

(1)

where \( \tau_{12} \) is share stress; \( \sigma_{xx} \) = normal stress \( N \)=axial effort; \( A \)=transvers section area; \( \gamma_{12} \)=shear strain in the principal strain plane, \( \varepsilon_{xx}, \varepsilon_{yy} \) = strains in the tensile direction and in the transverse direction.

Output signals from Wheatstone bridge (connected at the two transducers TER) are proportional with strains \( \varepsilon_{xx} \) and \( \varepsilon_{yy} \) and are displayed/recorded on P3 bridge.

In plane shear modulus is determined by

\[ G_{12} = \frac{\Delta \tau_{12}}{\Delta \gamma_{12}} \]  

(2)

**Shear tests.** The shear strain between the two notches was measured using a ±45° strain gages rosette made by Micro-Measurements, Inc. (designation N2A-00-C032A-500/SP61). The strain gages rosette was mounted on the sample between the notches (figure 4).

The calculation of specific shear strain is corrected reported to the transverse sensibility of the gauge transducers

\[ \gamma_{1,2} = (e_1 - e_2) = \frac{1 - \nu_0K_T}{1 + K_T} (e_{\text{ct.1}} - e_{\text{ct.2}}) = \frac{1 - \nu_0K_T}{1 + K_T} \gamma_{12,\text{ct}} \]  

(3)

where \( e_1, e_2 \) si \( e_{\text{ct.1}}, e_{\text{ct.2}} \) are corrected extensional strain, and respective effective/read extensional strains (in the case of separate reading of the two strains). The correction factor results from the values indicated by the producer of the transducer.

\[ \frac{1 - \nu_0K_T}{1 + K_T} = \frac{1 - 0.285 - 0.0019}{1 + 0.0019} = 0.997563 \]  

(4)

**Figure 3.** INSTRON 8801 testing machine. **Figure 4.** Shear tests using ±45° strain gauges rosette, in the UTI share fixture [6].

**Dynamical Mechanical Analysis.** In figure 5 is presented the DMA 242C from Netzsch, Germany, with a three-point bending fixture. The software Proteus v.4.8.5, has been used for analysis of data. The complex modulus \( E^* \) is a phase vector that incorporates both capacities \( E = E' + jE' \) where \( j = \sqrt{-1} \). The real part of this equation is called the storage modulus because it quantifies the material’s ability to store energy elastically [15]. In materials with insignificant damping, the storage modulus is equivalent to the Young’s modulus. The imaginary part \( (E') \) of this is called the loss modulus, because it quantifies the material’s ability to dampen out the energy. The dimensionless loss factor \( \tan(\delta) \) is independent of the contact energy, because it is the ratio of the loss to the storage modulus \( \tan(\delta) = E'/E' \). For all the samples, the bulk modulus \( E' \) and \( \tan(\delta) \) were measured function of the temperature in the range 30°C-250°C with heating speed 2°C/min at frequency of 1Hz. In this range, the studied samples do not reach the thermal destruction.
4. Result and discussions

**Tensile tests.** The Young modulus is determined as the slope of approximation line of the plot in normal stress $\sigma$/longitudinal strain $\varepsilon_L$ coordinates, through the points determined recording the value of the forces calculated by Instron machine and the longitudinal deformations recorded from TER L (figure 6). From the plot, the points at very low forces (influenced by the initial processes of gripping) and at very high forces, over which records in bridge were stopped, have been eliminated due to distortions in deformations recording. The Poisson ratio has been determined from the curve $\varepsilon_T/\varepsilon_L$ using the data recorded by the P3 bridge from the transducers TER L and TER Tr (figure 7).

**Figure 6.** Tensile characteristic in initial/linear zone between 60MPa and 160MPa for $0^\circ/90^\circ$ specimen at tensile test.

**Figure 7.** Transverse strain (compression) characteristic in initial/linear zone between $0^\circ$ and $5000^\circ$ for $0^\circ/90^\circ$ specimen at tensile test.

Thus, elastic modulus (Young modulus) and Poisson ratio were determined as $E=36.233$ GPa and respective $\nu=0.1615$.

The average ultimate tensile stress is $\sigma_3=399.4$ MPa.

**Shear tests.** In plane shear modulus is determined as the slope of diagram shear stress/shear strain (figure 8). Thus $G=7.82$ GPa for the $0^\circ/90^\circ$ specimen (figure 8a) and $G=3.05$ GPa and $\tau_r=93.5$ MPa for the specimen $\pm45^\circ$ (figure 8b).

The average ultimate shear stress were determined as $\tau_{rf,90}=86$ MPa.

**Dynamic Mechanical Analysis.** The experimental data are presented in figure 9. It can be observed that the glass transition starts at $67.1^\circ$C which represent the onset on the real component $E'$ of complex elastic modulus. $E''$, the imaginary component of the elastic modulus presents a peak at $72.6^\circ$C, the maximum of $\tan\delta$ is reached at $79.2^\circ$C. The thermal destruction of the matrix starts at $124.3^\circ$C. The glass transition is reversible until $65.5^\circ$C (figure 10), meaning the cooling of the specimen, at a new test, $E'$, $E''$ and $\tan\delta$ have the same behavior as at the initial thermal treatment. For
higher temperatures, the glass transition becomes irreversible. The mechanical properties of the studied samples determined at DMA are presented in Table 1, representing the mean value for 10 specimens measurements cropped from different samples.

**Figure 8.** Determination of in plane shear modulus G: a) 0°/90° specimen in pure share test; b) ±45° specimen in tension test.

**Figure 9.** DMA test of GFRP sample: a) 0°/90°; b) ±45°.

**Figure 10.** Temperature of glass transition for 4 samples.

| Table 1. Mechanical properties determined by DMA |
|-----------------------------------------------|
| Composite GFRP |  E  |  Tg  |  E_A  |
|                | [GPa] | [°C] | [kJ/mol] |
| Layers +45°/-45° | 8.565 | 64.8 | 271.328 |
| Layers 0°/90°    | 14.345 | 67.0 | 274.495 |
5. Conclusions

GFRP samples made from combination of glass roving fabric RT800 and nonwoven MAT600 oriented at ±45°, 0°/90° with matrix of Epikote resin MGS LR 385 were tested in order to determine their principal elastic properties. Tensile and shear test were effectuated using INSTRON 8801 machine for determination of modulus of elasticity, Poisson’s ratio, tensile strength, and ultimate tensile strain. Dynamic mechanical analysis at frequencies 1 Hz, 3.33 Hz, 5 Hz, 10 Hz, 33.3 Hz, 50Hz and increasing temperature with 2°C/min was effectuated to determine elastic properties, activation energy and glass transition temperature. Gravitational loads, inertia forces, loads due to pitch acceleration, as well as torsional loadings influence the stability and reliability of WTB. The obtained results show that this GFRP can be used successfully in the construction of wind turbine blades where stiffness and lightweight represent critical characteristics, imposed by the design requirements. Knowing that the blades are most damageable component of the turbine, the mechanical and physical properties of the materials determine its performance and the lifetime.

6. References

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