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EVALUATION OF THE MECHANICAL CHARACTERISTICS OF CFRP COMPOSITES AND MODELING OF THE DELAMINATION PHENOMENON

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ABSTRACT

In the category of new and advanced materials, carbon fiber reinforced plastic (CFRP) composite materials are used in areas such as structural materials in aeronautics, transport, etc. The bi-phasic structure of CFRP requires knowledge of both fiber and matrix properties. In the conditions where possible delamination's occur during use, these depend both on the properties of the interfaces and of the interlaminate. The appropriate ultrasound (US) techniques allow the determination of the propagation speed of the longitudinal and transverse waves which are used in the evaluation of the elastic modulus E, shear modulus G on the three principal directions. C-scan US using phased array allows the emphasizing and characterization of ones with porosities that appear during composite fabrication or due to local overheating. The results are compared with those obtained by a dynamic mechanical analyzer (DMA), being found a good correlation. These procedures allow also the emphasizing of matrix damages due to high temperature used or establishing maximum temperature for used.

KEYWORDS: CFRP, nondestructive testing, ultrasound, DMA

INTRODUCTION

The weight reduction of the components used in the aeronautical industry as well as that of the motor vehicles aims to reduce energy consumption and recommends composite materials as modular construction elements. The choice and use of composites related to performance and costs [1, 2] it is a direct concern. Increasing the lifespan of vehicles and the impact of vibrations and noises for external insulation as well as shock energy absorption are also problems that concern the car manufacturing industry and not only this one [3]. The applications follow the analysis of the mechanical behavior of these modular components as well as the connections between the composite and metallic structures, aiming to stop the initiation of failure. Carbon fiber reinforced composites (CFRP) are used in most fields and due to their low density, reduced effect of mechanical fatigue phenomena and high strength-to-weight ratio [4, 5]. However, the composites have low impact resistance in the direction normal to the fiber plane, being able to produce fiber delamination/rupture at high energies. The behavior of interlaminar fractures of the composites requires experimental investigation both as reinforcement and matrix. This can be done through non-destructive testing methods based on ultrasound, eddy currents, etc.

Epoxy resin is the most common matrix for CFRP [6], its properties are superior but with the aging process they are susceptible to water absorption [7], due to the polar hydroxyl group inside [8]. Although they are used in a significant amount, they present, like any new material, shortcomings related to performance, processing and costs [9, 10]. There are many researches that analyze the phenomena of delaminations in layered composites, many of them being due to impact, but the stresses inside the materials that appear during their lifetime, permanently monitored, determine the moment when a part, structure or assembly can no longer fulfill its characteristics operation. Sustained stresses of the joint components of composites or in adhesives can be undiagnosed causes that produce crack initiation [11]. The spatial arrangement, as well as the size of the product, can sometimes save the composite structure from failure.

The purpose of the paper is to present the complementary results (using theoretical and experimental methods) obtained in the complex investigation of the elastic properties of composites reinforced with carbon fibers.

MATERIALS AND METHODS

The behavior of CFRP composites under load is useful for understanding how loading affects complex CFRP composite structures, the study being doubled

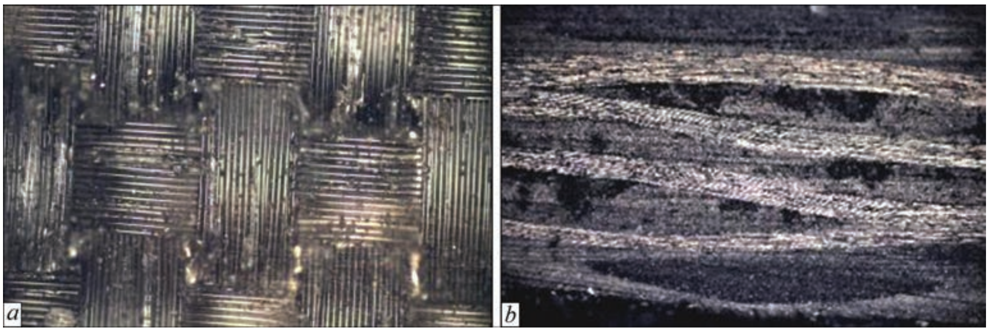

Figure 1. Studied samples: 10× front surface sample (*a*); cross section — optical microscope (*b*)

by analytical modeling to explain the results obtained during the experimental tests [12]. During the tests, large stress concentrators may appear that lead to an unknown mixed loading mode, variable along the sample, which can generate unexpected results.

2.1. SAMPLES MANUFACTURING

The composite materials proposed for theoretical and experimental analysis are CFRP type made using carbon/epoxy laminates manufactured by autoclave processing technology. Studies on the construction behavior of CFRP composites have demonstrated that the properties depend on the applied technology [13, 14]. In [15] the method of obtaining the laminates used in the tests presented in the paper is presented, CFRP with 8 plies of plain weave fabrics GG200P-PL1/1 (SLG group) with fiber diameter 7 μm Torayca T300 fibers [16] with different ply stacking sequences $[0]_8$ and $[(45/0)2]_s$ and ET445 resin. Made in the form of boards with dimensions 295×205 mm^2, thickness of 2.2 mm and volume ratio $V_f = 0.45$, density of 1.58 kg/dm^3, the realized configuration provides the laminate with a quasi-isotropic structure, having a modulus of elasticity of 0.44 ± 0.03.In the case of the analyzed composite, the polymer matrix ensures the adhesion between the fibers and the matrix and gives it a structure that resists until the fibers break. Plain fabric provides a simple repeating pattern Figure 1.

Besides the working conditions and the degree of loading, the architecture of the composite, the polymer matrix and the structure of the fibers can determine microstructural accumulations in the general damage mechanism.

2.2. FINITE ELEMENT ANALYSIS (FEA)

Finite element analysis allows obtaining detailed information on the distribution of stresses and deformations in the composite, following the optimization of the design and its performance. The 3D graphic model made in SolidWorks was imported into Ansys software version R17.0., Figure 2.

For the simulation, the quadrilateral discretization method was used, the table was uniformized and a function of the size of the elements of 1mm was introduced to ensure accuracy, obtaining a geometry of the section having 22505 nodes and 3936 elements. The sample was considered without discontinuities, from its surface (the one caught between the ends) only a portion was used in the study (Figure 2), the simulation was made for the tensile test. Figure 2, *b* shows the stress state in the tensile specimen. One can observe the stress distribution over its entire cross-section throughout its volume with maximum values at the level of the tabs that continue towards the central area.

2.3. METHODS

The presence of porosity in the composite material was analyzed using the ultrasound (US) method, the elastic waves being produced in CFRP with the Phasor XS equipment coupled with a sensor array with central frequency 5 MHz and a delay line. US attenuation in composites is a measure of the degree of porosity. The analysis of US propagation speeds in composites was obtained using transducers connected to a US PR 5073 Pulser Receiver — Panametrics equipment.

As the composite plates are thin for reflected US analysis, a Plexiglas delay line was applied. The compression waves were excited with a G5KB GE trans-

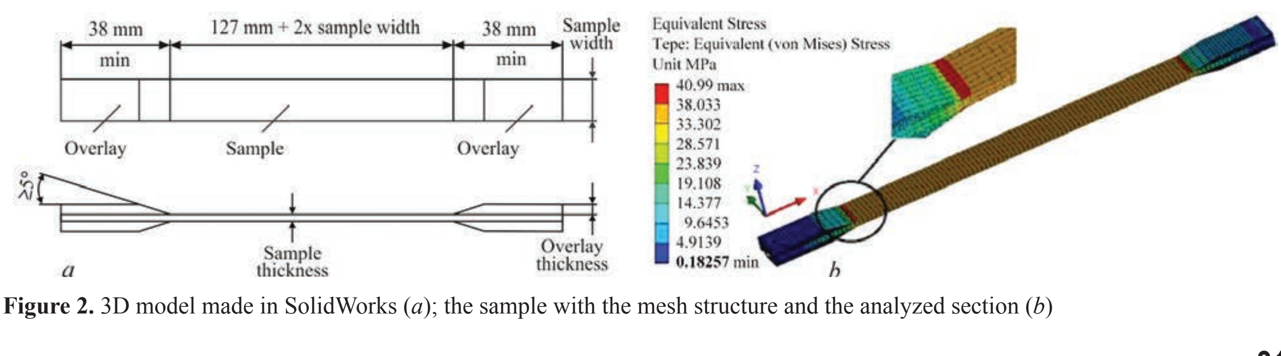

Figure 2. 3D model made in SolidWorks (*a*); the sample with the mesh structure and the analyzed section (*b*)

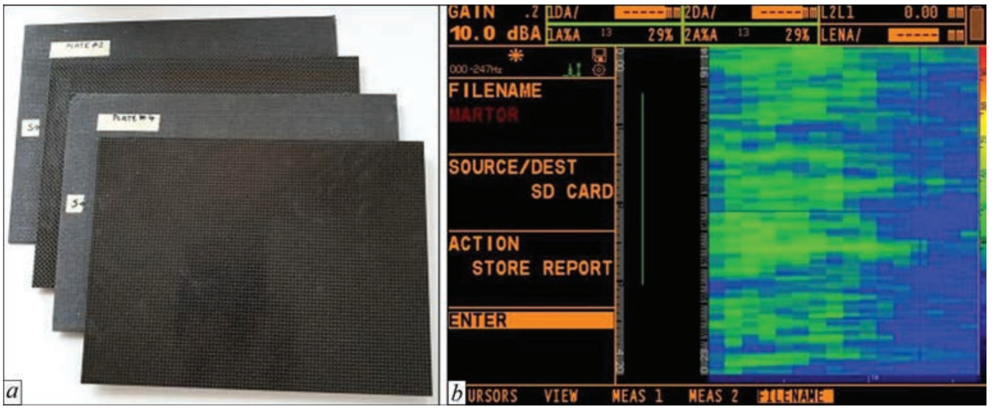

Figure 3. The CFRP specimens (*a*); the propagation C scan modes of US waves (*b*)

ducer with a central frequency of 5 MHz, the shear ones with a MB4Y transducer with a central frequency of 4 MHz, the signals were analyzed on the screen of a Le Croy Wave Runer64Xi digital oscilloscope. The values of the modulus of elasticity and the elastic properties of the composite are determined from the wave propagation speeds,

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

$$C_L = \sqrt{\frac{E}{\rho}\frac{1-\upsilon}{(1+\nu)(1-2\nu)}} \text{ and } C_T = \sqrt{\frac{G}{\rho}}. \quad (1)$$

Knowing that E — elastic modulus; G — the shear modulus; ν — the Poisson coefficient and ρ — the density.

The Dynamic Mechanical Analyzer equipment, DMA 242C — Netzsch Germany, with the 3-point bending device using Protheus software v.4.8.5 was used to determine the main characteristic quantities, elastic modulus along the principally axis (E_x, E_y, E_z). The obtained values were compared with those determined by traction tests by classical procedure using INSTRON E1000 machine with hydraulic fixture.

EXPERIMENTAL RESULTS

The degree of porosity is in linear correlation with the attenuation of US in composites and with the mechanical properties ie shear resistance. The plates thus prepared (&2.1) were scanned with US at a single sweep of the 5 MHz frequency transducer moved with the ENCSTD axial scanner. The procedure applied to the material leads to the analysis of the scan image results shown in Figure 3.

The presence of localized porosity represents a break in the continuity of the environment. It can be observed that in this case the recorded measurements show a material without discontinuities.

Using the US technique to determine the longitudinal and transverse wave propagation speeds in the material, the elasticity modulus E_2 and the shear modulus G_{12} were determined. The average US propagation speed for longitudinal waves was C_l = 2732 and C_t = 1937 m/s for transverse ones.

From the CFRP samples, tested with US to ensure the absence of discontinuities, samples with dimensions of 50×10×2.2 mm^3 were cut for the DMA dynamic mechanical analysis. These samples were analyzed optically, because during the cutting process discontinuities may appear, some lamellas may change their direction

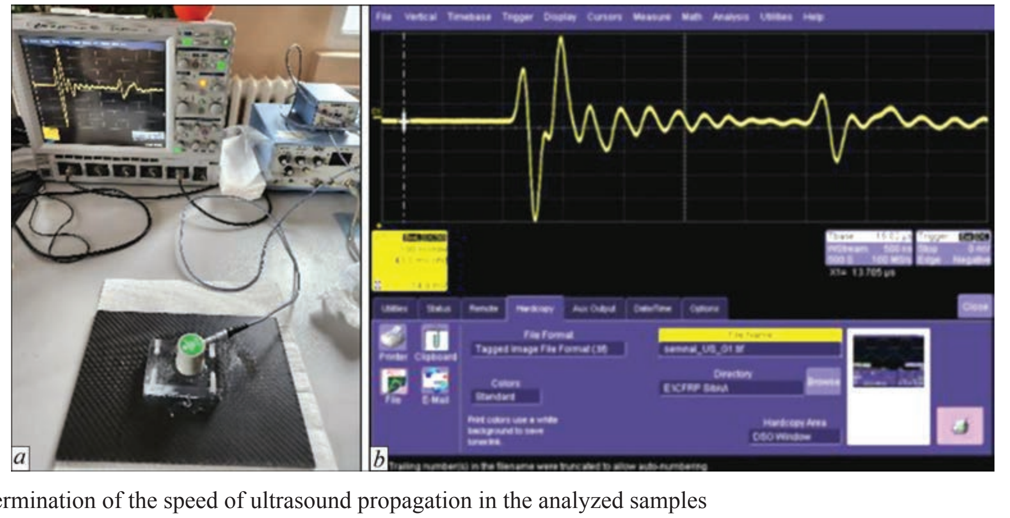

Figure 4. Determination of the speed of ultrasound propagation in the analyzed samples

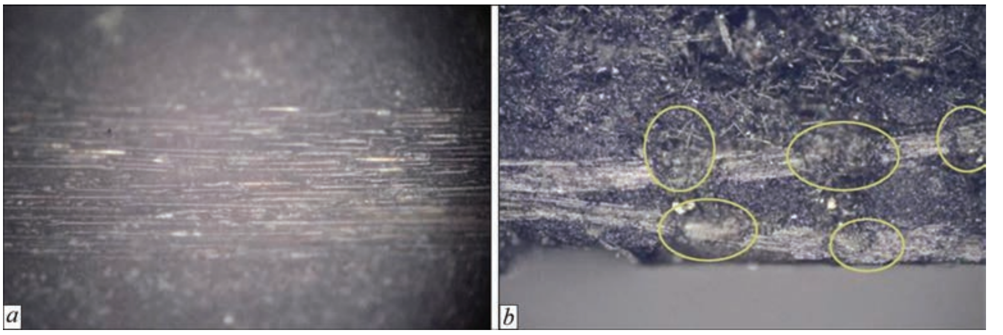

Figure 5. Cross-section microscope images of the DMA tested samples

Table 1. Elastic characteristics of studied samples

E_x, GPa	E_y, GPa	E_z, GPa	ν_{xy}	ν_{yx}	ν_{xz}	G_{xy}, GPa	G_{yx}, GPa	G_{xz}, GPa
42	40	9	0.30	0.3	0.03	8.2	8.4	5.1

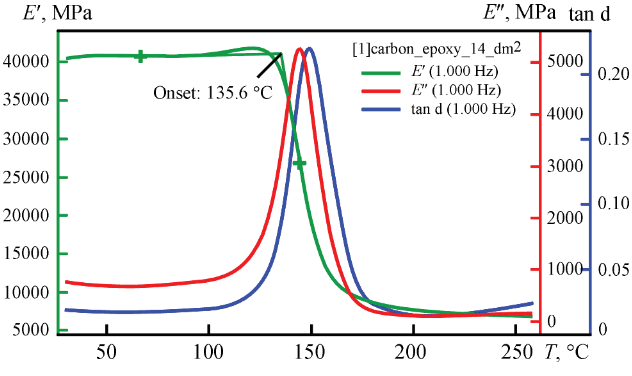

Figure 6. DMA results for sample CFRP

of orientation, some fibers may break, detachments from the lamellas may occur. Samples with this type of defects were removed Figure 5, *b*.

In the DMA analysis, the sample loaded with an oscillating sinusoidal force of 6 N at different preset frequencies provides information on the visco-elastic properties as a function of frequency, temperature and time. The parameters obtained through the tests provide information on vitrification, referred to T_g (glass transition), resulting from the cross-linking reaction. The determinations were made at a single frequency of 1 Hz, temperature range (25–260 °C).

A slight increase in the storage modulus, E', from 40000 to 42000 MPa is observed. After this increase, a maximum of the Young's modulus is reached, followed by a decrease with the same slope of the storage modulus (elasticity modulus), E', so that it remains constant around the value of 180 °C. The mechanisms for changing the elastic and viscoelastic mechanical properties were highlighted: storage modulus (E'), behavior over time to temperature changes of the composite, loss modulus (E''), loss factor (tan δ), temperature glass transition (T_g = 135.6 °C).

The DMA analysis shows the changes in the dynamic modulus of CFRP under the load with temperature as follows: the loss modulus reflects the adhesion of the material; the storage modulus, i.e. the elasticity modulus reflects the rigidity of the material; the ratio between the loss modulus and the storage modulus, i.e. the depreciation of the material $\tan\delta = \dfrac{E''}{E'}$. δ is the phase angle of stress and strain. The ratio of stress (σ) to strain (ε) under dynamic load is defined as the complex Young modulus of the material (E^*) which can be expressed as

$$E^* = \frac{\bar{\sigma}}{\bar{\varepsilon}} = \frac{\sigma_0}{\varepsilon_0} e^{i\delta} = E' + iE''. \quad (2)$$

The main mechanical characteristics of the composite samples, E_x, E_y, E_z, were determined from the DMA graphs. Poisson's ratio ν_{xy} and ν_{yx} were determined by measuring US velocities. The shear modulus were calculated only by US procedure. The results are presented in Table 1.

The data obtained through complementary DMA methods and tensile tests completed with those of US allow a complete characterization of composites with polymer matrix reinforced with carbon fibers.

CONCLUSIONS

Characterization of carbon-epoxy composites can be made using ultrasound method complementary with destructive testing using Dynamical Mechanical Analysis. Using C-scan the regions with porosity due to manufacturing can be easily evaluated. For determination of elastic and shear modulus, Poisson's ratio of the composite materials with reinforcement from carbon fiber woven, the use of combined ultrasound methods is proposed, namely impulse-echo for compressional waves, send-receive method for transversal waves. Numerical analyzes and additional tests are required for different CFRP specimens to avoid discontinuities around the fasteners and to predict the evolution of crack propagation in the failure process.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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