DETERMINATION OF CFRP’S MECHANICAL PROPERTIES USING ULTRASOUND METHODS

Raimond GRIMBERG¹, Adriana SAVIN¹, Rozina STEIGMANN¹, Alina BRUMA¹,
Paul Doru BARSANESCU², Daniel Petrica SALAVASTRU²

¹ Nondestructive Testing Department, National Institute of Research and Development for Technical
Physics, 47 D.Mangeron Blvd, Iasi, 700050, Romania; Phone: +40232430680, Fax +40232231132; e-mail: grimberg@phys-iasi.ro, asavin@phys-iasi.ro,
steigmann@phys-iasi.ro, abruma@phys-iasi.ro
² Faculty of Mechanical Engineering, Technical University Gh.Asachi,
67 D.Mangeron Blvd, Iasi, 700050, Romania; e-mail: paulbarsanescu@yahoo.com,
danmmutzi@yahoo.com

Abstract
Carbon fiber reinforced plastics (CFRP) composite materials are widely used as structural materials in aeronautics, transportation etc. The bi-phase nature of the CFRP makes that the possible degradations shall depend not only by the properties of fibers and matrix, but also by the properties of interfaces and interlaminate. Using compressional and shear waves is possible to determine the Young modulus and shear modulus in off plane direction. Using Lamb waves generated by Hertzian contacts is possible to determine the in-plane mechanical properties. The obtained values are in good concordance with the values obtained using a Dynamic Mechanical Analyzer and the electromagnetic tests. Using a phased array transducer is possible to detect and evaluate the delamination created by the low energy impact and porosity.

Keywords: CFRP, ultrasound, Hertzian contact, phased array, delamination

1. Introduction
Fiber reinforced composite materials are currently occupying the centre stage of structural materials especially in aerospace, automotive industries and defense applications. A composite is a material system consisting of two or more phases on a macroscopic scale, whose mechanical performance and properties are design to be superior to those of the constituent materials acting independently. One of the phase is continuous stiffer and stronger and is called reinforcement. Where the less stiff and weaker phase is continuous and is call matrix. The low density, high strength, high stiffness to weight ratio, excellent durability and design flexibility of fiber reinforced composite materials are the primary reason for their extended use [1].

The properties of carbon fiber reinforcement plastics (CFRP) can be controlled by the appropriate selection of the substrate parameters such as fiber orientation, volume fraction, fiber spacing and layer sequence. Carbon fiber reinforcement plastics are obtained selecting carbon fiber as reinforcement and plastic materials as matrix. The major degradations that can appear during the exploitation of CFRP structures are:

- delamination due to impact with high and low energy, eventually accompanied by the breaking of the carbon fibers
- local superheating that can deteriorate the matrix

Supplementary, during the fabrication of CFRP structures, the porosities can appear.
For an optimal design of the CFRP structures, evidently, the mechanical properties of the material must be known. Also, for a judicious exploitation of the structures, nondestructive evaluation (NDE) methods in the basis of which the structural integrity
shall be evaluated must be developed. One of the most used NDE methods for CFRP is the ultrasound method that allows both the evaluation of delamination and the porous zones as well as the principally mechanical parameters (elastic modulus, shear modulus, Poisson ration) [3], [4].

In this paper it is presented an ultrasound method based on the measurements of compression and shear wave’s velocities and determination of the phase velocity of Lamb waves in $A_0$ mode. The obtained data allow the determination of the principal mechanical characteristics, these being compared with those obtained by destructive tests in quasi-static and dynamic regime. Also, the results obtained at the detection and characterization of delaminations, due to impact with low energy as well as the local heating using ultrasound phased array are presented.

2. Studied samples

Laminate plates from composite with 1.91 mm thickness and having as reinforcement 6 layers of biaxial woven $[0^0, 90^0]$ which have been rotated with $45^0$ so that quasi isotropic in plane plate are made. The volume ratio was $0.5\pm0.03$ and the density of composite was $\rho=1460\text{kg/m}^3$. The samples are presented in Figure 1.

![Figure 1. The studied samples](image)

Samples with dimensions 50x10x1.91 mm$^3$ were cropped and complex elasticity and shear modulus along the $0^0$ and $90^0$ directions (corresponding to fibers layout in the first layer) were determined using Dynamic Mechanical Analyzer DMA 242C – Netzsch Germany, 3 points bending fixture.

The complex elasticity modulus was directly determined by the analyzer software. The shear modulus has been determined by calculation, taking into account that the part of the deflection generated by the shear force is the difference between total deflection and the deflection generated by pure bending moment.

Also, quasi-static tensile tests have been effectuated using INSTRON E1000 equipment with special hydraulic fixture for carbon epoxy composites.

The principal mechanical characteristics of the studied samples are presented in table 1.

<table>
<thead>
<tr>
<th>$E_1$ [GPa]</th>
<th>$E_2$ [GPa]</th>
<th>Poisson ratio $\nu_{12}$</th>
<th>Poisson ratio $\nu_{21}$</th>
<th>Poisson ratio $\nu_{13}$</th>
<th>Shear modulus $G_{12}$ [GPa]</th>
<th>Shear modulus $G_{21}$ [GPa]</th>
<th>Density [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>44</td>
<td>0.32</td>
<td>0.32</td>
<td>0.03</td>
<td>8.4</td>
<td>8.4</td>
<td>1460</td>
</tr>
</tbody>
</table>
At dynamical tests, the elastic modulus results as a complex magnitude, $E^* = E' + jE''$ type where $E'$ is the storage modulus and $E''$ is named loss modulus.

In Figure 2 is presented the dependency of storage modulus, loss modulus and $\tan \delta$ $(\tan \delta = \frac{E''}{E'})$ function of temperature for the studied samples. The tests have been made at 1Hz with the heating rate of 2°C/min.

![Graph showing the dependency of storage modulus, loss modulus, and tan δ as a function of temperature.](image)

From data presented in Figure 2 results that the glass transition starts at onset temperature of 92.6°C. $E''$ presents a peak at 120.7°C and maximum of $\tan \delta$ is reaching at 125.0°C.

The thermal destruction of the matrix material starts at 241.3°C. According to the effectuated tests, glass transition is reversible until the temperature of the $\tan \delta$ peak 125 °C, namely at the cooling of the sample and at a new test, the measures of $E'$, $E''$ and $\tan \delta$ have practically the same values as at the initial thermal treatment. For higher temperature, the glass transition is irreversible.

The samples were impacted with 1J, 2.5J and 3J energies using a semispherical impactor with 22.5mm diameter.

The porous zones were manufactured by the producer, SC Compozite SA Brasov, Romania by pumping air during the operation of composite production.

### 3. Experimental set-up

For determination of propagation velocity of compressional and shear waves, a transmission method has been used, the emission transducer being mounted on a delay block made from plexiglass having 20mm width and propagation velocity of the compressional waves of 2700m/s and respectively of the shear waves 1100m/s.
For the generation of compressional waves, A5518 Panametrics transducer with 0.375” diameter and central frequency of 5MHz, has been used. For shear wave’s generation, MB4Y-GE transducer with 9mm diameter and central frequency 4MHz has been used. The transducers were connected at 5073PR Pulse Receiver – Panametrics. The visualization of the signal and the measurement of the time of propagation was made with Le Croy Wave Runner 64Xi digital oscilloscope, with sampling frequency of 10G S/s.

In the conditions of compressional wave’s measurements, the coupling gel ZG-F – GE was used, meanwhile for the shear waves, honey has been used.

The Lamb waves used in the measurements were generated by Hertzian contact with P111-01-P3.1 Introscope transducers with central frequency 100kHz. The transducers were coupled with buffer rods made from AISI 316L with curvature radius of the peak 3mm. The transducers were coupled with the Pulser Receiver 5077PR, the waves shapes and the measurements of propagation time being made with Wave Runner Xi oscilloscope.

For detection and characterization of delaminations and of porous zones of CFRP, an equipment Phasor XS coupled with a phased array with 32 sensors with pitch of 0.5mm and central frequency 5MHz was used. The transducer was placed on a wedge with 36° angle. The linear displacing of the array was made with one axis scanner type ENCSTD.

In Figure 3 are presented the measurements system for Lamb wave generated by hertzian contact (Figure 3a) and the phased array equipment (Figure 3b).

Figure 3. The experimental set-up: a) Equipment with Lamb wave generated by hertzian contact; b) Phasor XS
4. Generation of Lamb waves by Hertzian contact

Two solid bodies in contact under the application of force are deformed elastically and form a flat contact region, the so called Hertzian contact (M, N point in Fig.4) [5]. The Lamb waves are guided elastic waves which can propagate in solid plates. These waves are a combination between compressional (P-wave) waves and shear (S-wave) waves. The main scheme of the system which generates and detects the Lamb waves is presented in Figure 4.

![Diagram of Lamb wave generation and receiving using Hertzian contact](image1)

Figure 4. Generation and receiving of Lamb waves using Hertzian contact

A piezo-electric transducer, having a low central frequency (tens of kilohertz) is coupled with a buffer rod made from a material having the elastic modulus $E_1$ and the Poisson ratio $\nu_1$, which has at one end a semispherical bumped head of radius $R$. If the buffer rod is compressed on the plate (which has the elasticity modulus $E_2$ and Poisson ratio $\nu_2$) with a normal force $F$, the contact radius, $a$, will be given by [5]

$$a = \left[\frac{3}{4\pi} \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)RF\right]^{1/3} \tag{1}$$

The detail of a Hertzian contact is presented in Figure 5.

![Diagram of Hertzian contact detail](image2)

Figure 5. Detail of a Hertzian contact
The Lamb waves propagate under two modes, namely symmetric and anti-symmetric, their propagation velocity depending on frequency. On relatively small distances between emission buffer rod and reception buffer rod can be visible both $A_0$ (anti-symmetric) and $S_0$ (symmetric) modes. On bigger propagation distances, the $S_0$ mode is much more dispersive, so it is practically total attenuated, only the $A_0$ mode being then propagated [6], [7].

In Figure 6a, b is presented the propagation of Lamb wave generated by Hertzian contact for two positions of the reception transducer, on the same direction, the emission transducer remaining in the same position. On distance smaller than 23mm (Fig.6a) both $A_0$ and $S_0$ modes are propagated, these being marked on the figure. On distance greater than 29mm, only $A_0$ mode is propagated (fig 6b)

![Figure 6a](image1.png)

![Figure 6b](image2.png)

**Figure 6.** Propagation of Lamb wave in the studied samples

a) emission reception distance=23mm – $A_0$ and $S_0$ modes are visible; b) emission reception distance =29mm, only $A_0$ mode is propagated.
According to [7], the group velocity of $A_0$ mode is given by

$$C_{A_0} = \left( \frac{D}{\rho h} \right)^{1/4} \omega^{1/2}$$ \hspace{1cm} (2)

where $D$ is flexural rigidity of the plate; $h$ – thickness of the plate; $\rho$ - density; $\omega$ - angular frequency of the wave. $D$ can be determined measuring $C_{A_0}$ and knowing $\rho$, $h$, $\omega$. From there, $E$ and $\nu$ for the examined material along the direction of Lamb wave propagation can be also determined.

5. Experimental results

In Figure 7 is presented the distribution of group velocity of $A_0$ mode for different propagation directions. The measurements were made from $10^0$ to $10^0$. Examining the data from Figure 7, it can be shown that the studied samples have quasi-isotropic behavior in the plane of fibers, due to the dispersion mode of the reinforcement.

![Figure 7](image_url)

Figure 7. Angular distribution of the group velocity of $A_0$ mode in studied samples.

Using eq. (2), the angular distribution of the elasticity modulus can be determined also. For the directions $0^0$ and $90^0$, the values of $E_1$ and respectively $E_2$ determined from the propagation velocity of the Lamb waves are 45.2GPa and respectively 43.5GPa, values perfect correlated with those determined by static and dynamic tests (table 1).

The elasticity modulus $E_3$ (on direction perpendicularly on the carbon fibers plane) cannot be determined by static tests or by DMA, but only by measurements of the propagation velocity of the compressional and shear waves. The relationship with material parameters is well known

$$C_p = \sqrt{\frac{E_3}{\rho \left(1-\nu_{13}^2\right) \left(1-2\nu_{13}\right)}}$$

$$C_s = \sqrt{\frac{G_{13}}{\rho}}$$ \hspace{1cm} (3)

For $C_p$ and $C_s$ were obtained

$C_p = 2840 \pm 20$ m/s

$C_s = 1970 \pm 20$ m/s
The values of velocities represent the mean for 100 measurements in different points of the sample, the dispersion being standard calculated.
In these conditions, the material parameters are

\[ E_3 = 11.36 \text{GPa} \]
\[ G_{13} = 5.5 \text{GPa} \]

The detection and evaluation of delaminations were made with C-scan ultrasound using phased array transducer.
In Figure 8 are presented C-scan for the delaminated zones obtained by impacts with 1J, 2.5J and 3J energies.
It can be observed that the delaminated zones are clearly visible even in the case of impacts with small energy. The classical method for detection and characterization of the delaminations is represented by C-scan ultrasound, the sample being immersed and the ultrasound transducer is of high frequency (higher than 10MHz), focused or not. The immersing of the carbon epoxy plate in water and their maintaining the immersing bath a relatively long period can lead to diminishing of the elasticity modulus $E_1$, $E_2$, $E_3$ and after the testing, the material can not be used again. Using phased array transducer and having gel as couplant and taking into account the relatively small period for measurements, the properties of the material are not affected.

In Figure 9 is presented the B-scan of a region with porosities. It can be observed that due to the scattering of the ultrasound waves on porosities, the bottom echo disappear, situation that characterizes the regions with excessive porosity.
6. Conclusions

Using ultrasound examination methods, namely the determination of propagation velocities of compressional and shear waves, the elasticity modulus $E_3$ and shear modulus $G_{13}$ or $G_{23}$ can be determined. Due to profound anisotropic character of the CFRP, these modulus substantially differ by the modulus determined in the plane of carbon fibers. As method for determination of elasticity and shear modulus in the plane of fibers, we propose the use of propagation velocity of Lamb waves, $A_0$ mode, generated by Hertzian contact.

Using C-scan ultrasound with equipment with phased array transducer, the delaminations due impacts with small energies and the zones with excessive porosities due to the composite fabrication process can be detected and characterized.

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References

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