ULTRASOUND AND EDDY CURRENT NONDESTRUCTIVE EVALUATION OF CFRP – CORRELATION WITH MECHANICAL PROPERTIES OF THE COMPOSITE

Raimond GRIMBERG[1], Adriana SAVIN[1], Rozina STEIGMANN[1], Ioan CURTU[2]
Paul Doru BARSANESCU[3], Janez GRUM[4]

[1]National Institute of R&D for Technical Physics, Iasi, Romania
[2] Transilvania University, Brasov, Romania
[3] Technical University Gh.Asachi, Iasi, Romania
[4]University of Ljubljana, Slovenia

Abstract: Carbon fiber reinforced plastics (CFRP) composite materials are wide 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 fiber and matrix, but also by the properties of interfaces and interlaminate. The adequate ultrasound techniques allow the determination of the propagation speed of the longitudinal and transversal waves and, also, of Lamb wave, A_0 mode, generated by Hertzian contact.
These methods allow the precise evaluation of the elastic modulus E, shear modulus G on the three principal directions. The data are compared with those obtained by classical destructive tests and with a dynamic mechanical analyzer, being found a good correlation. These procedures allow also the emphasizing of matrix damages due to water absorption.
C-scan ultrasound using phased array allows the emphasizing and characterization of delamination due to low energy impacts as well as of zones with porosities that appear during composite fabrication or due to local overheating.

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 local deteriorate the matrix
- water absorption that can deteriorates the matrix, especially when the matrix is manufactured by epoxy resin

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 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 delamination due to impact with low energy as well as the local heating using ultrasound phased array are presented.

Studied samples

Laminate plates from composite with 1.91mm and 4.2mm thickness having 6 and respectively 12 harness satin weave T300JB type with 285g·m^{-2}, [0^0, 90^0, 45^0]$_S$ layout and fiber volume fraction 50±3% and respectively 30±3% have been taken into study. The matrix is based on diglycidyl ether of bisphenol A, crosslinked with dicyandiamide. The density of composite was ρ=1460kg·m^{-3} and respectively ρ=1520kg·m^{-3}. The samples are presented in Figure 1.

a b

Figure 1. The studied samples: a) studied samples; b) sample for DMA

Samples with dimensions 50x10x1.91mm^3 and respectively 50x10x4.2mm^3 were cropped, and complex elasticity and tanδ along the 0^0 and 90^0 directions were determined using Dynamic Mechanical Analyzer DMA 242C-Netzsch, Germany, 3 points bending fixture.
The samples with thickness 1.91mm are named A and those with thickness 4.2mm are named B.
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 1. Principal mechanical characteristic of the studied samples

Samples	E_{1*} [GPa]	E_{2*} [GPa]	Poisson ratio ν_{12}	Poisson ratio ν_{21}	Poisson ratio ν_{13*}	Shear modulus G_{12}[GPa]	Shear modulus G_{21}[GPa]	Density [kg/m^3]
A	45	44	0.32	0.32	0.03	8.4	8.4	1460
B	16.2	15.1	0.3	0.3	0.03	3.1	3.1	1520

**Note: 1, 2 and 3 represent the direction of principal axis, direction 1 coinciding with direction 0^0.*

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 tanδ ($\tan\delta = \frac{E''}{E'}$) function of temperature for the studied samples. The tests have been made at 1Hz with the heating rate of 2^0C/min.

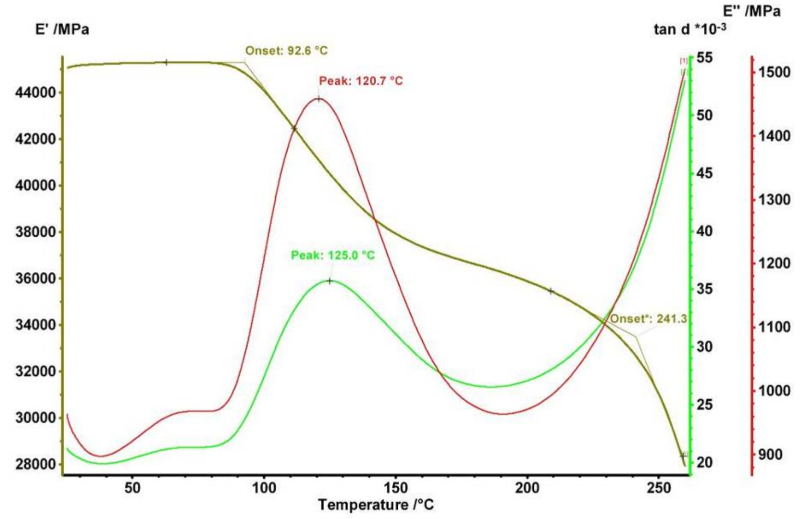


Figure 2. The dependency of storage modulus E', loss modulus E" and tanδ ($\tan\delta = \frac{E''}{E'}$) function of temperature for the studied sample A

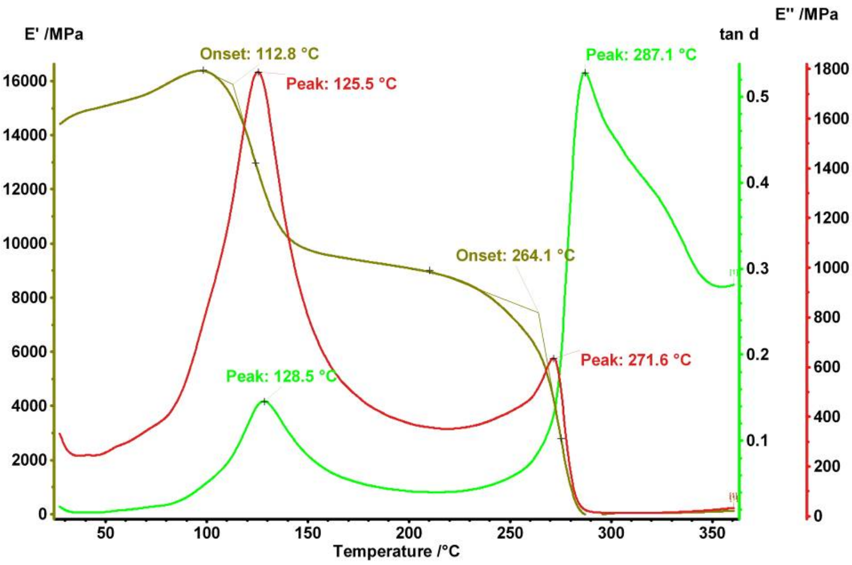


Figure 3. The dependency of storage modulus E', loss modulus E" and tanδ ($\tan\delta = \frac{E''}{E'}$) function of temperature for the studied sample B

From data presented in Figure 2 results that the glass transition starts at onset temperature of 92.6^0C. E" presents a peak at 120.7^0C and maximum of tanδ is reaching at 125.0^0C, for the samples A. From data presented in Figure 3 results that the glass transition starts at onset temperature of 112.8^0C. E" presents a peak at 125.5^0C and maximum of tanδ is reaching at 128.5^0C and 287.1^0C, for the samples B.

The thermal destruction of the matrix material starts at 241.3^0C for the sample A and 264.1^0C for the sample B. According to the effectuated tests, glass transition is reversible until the temperature of the tanδ peak 125 ^{0}C for sample A and respectively 128.5^0C for sample B, namely at the cooling of the sample and at a new test, the measures of E', E" and tanδ have practically the same values as at the initial thermal treatment. For higher temperature, the glass transition is irreversible.

The samples A 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.

The samples B were immersed in water, the samples being taken out after 14, 28 and 42 days.
The water absorbed by the samples was quantitative determined and ultrasound nondestructive testing and respectively destructive testing using DMA have been performed.
In Figure 4, wt% absorbed water function of immersion time is presented.

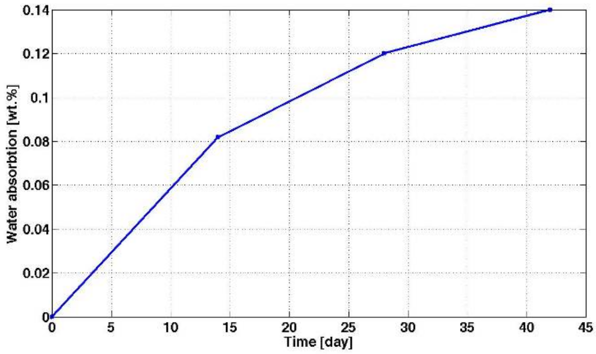


Figure 4. The dependence of absorbed water by immersion time.

In Figures 5 and 6 are presented the modification of E', E" due to water absorption. According to [5], [6] the absorption of water damage the epoxy group leading to plasticization and diminish the thermal and mechanical properties. Examining the figures 5 and 6 it can be observed that once with the increasing of absorbed water weight, the bulk modulus E' drastically decreases.

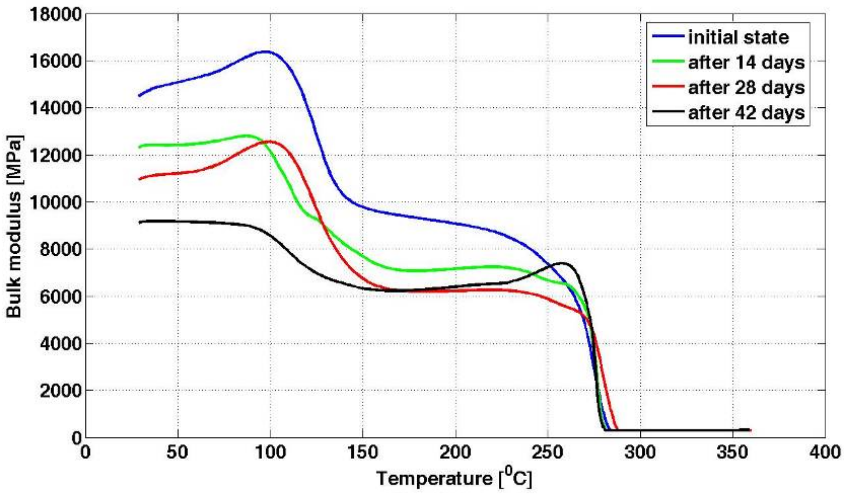


Figure 5. Dependency of bulk modulus by temperature for samples immersed in water during different time period

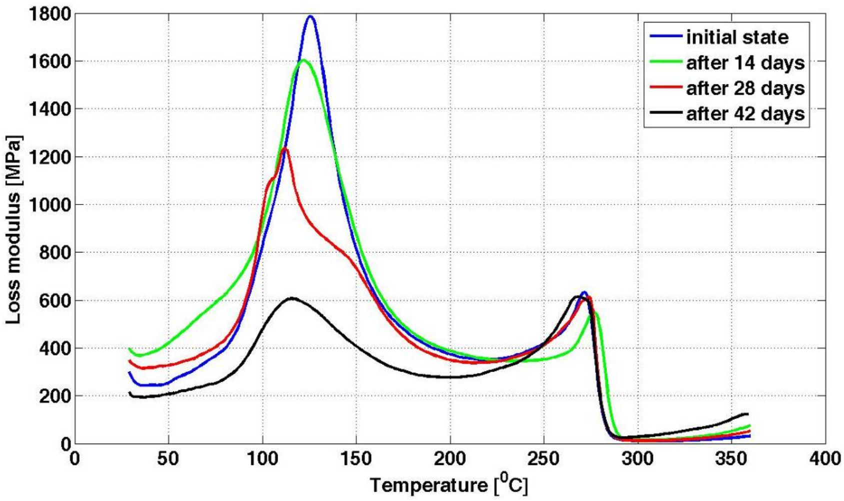


Figure 6. Dependency of loss modulus by temperature for samples immersed in water during different time period

Experimental set-up

For determination of propagation velocity of compression and shear waves, a transmission method has been used, the emission transducer being mounted on a delay block made from Plexiglas having 20mm width and propagation velocity of the compression waves of 2700m/s and respectively of the shear waves 1100m/s.

For the generation of compression 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.

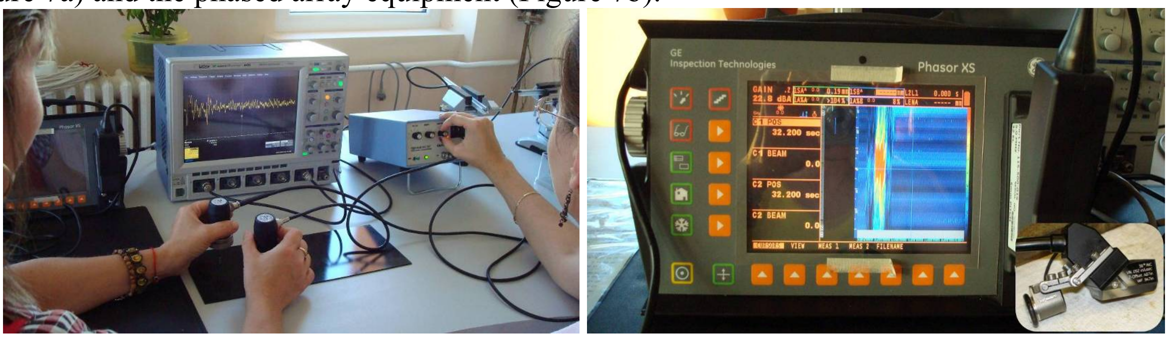
The transducers were connected at 5073PR Pulse Receiver – Panametrics. The visualization of the signal and the measurement of the time of propagation was made with Le Croy Wave Runner 64Xi digital oscilloscope, with sampling frequency of 10G S/s.

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 wave’s 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, 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 36^0 angle. The linear displacing of the array was made with one axis scanner type ENCSTD.

In Figure 7 are presented the measurements system for Lamb wave generated by Hertzian contact (Figure 7a) and the phased array equipment (Figure 7b).



a b

Figure 7. The experimental set-up: a) Equipment with Lamb wave generated by Hertzian contact; b) Phasor XS

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.8) [7]. The Lamb waves are guided elastic waves which can propagate in solid plates. These waves are a combination between compression (P-wave) waves and shear (S-wave) waves.

The scheme of the system which generates and detects the Lamb waves is presented in Figure 8.

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 ν_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 ν_2) with a normal force F, the contact radius, *a*, will be given by [7]

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

The detail of a Hertzian contact is presented in Figure 9.

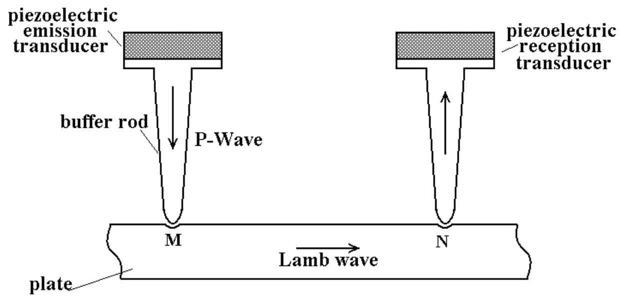


Figure 8. Generation and receiving of Lamb waves using Hertzian contact

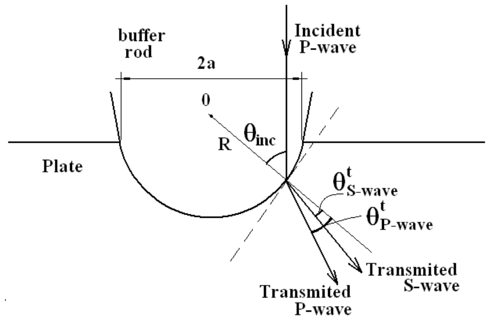
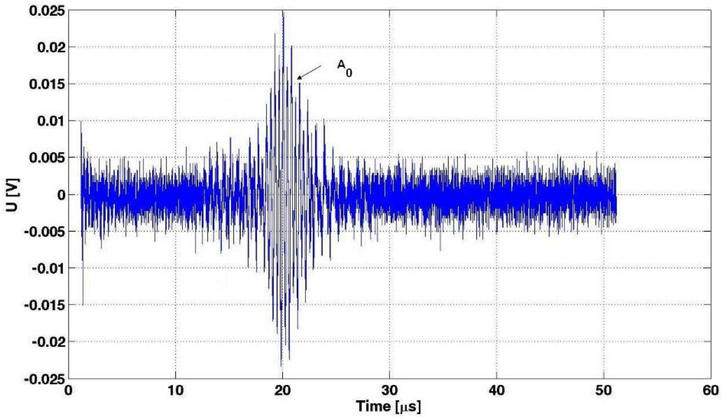


Figure 9. Detail of a Hertzian contact

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 [8], [9].
In Figure 10a, 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 greater than 29mm, only A_0 mode is propagated (fig 10a). On distance smaller than 23mm (Fig.10b) both A_0 and S_0 modes are propagated, these being marked on the figure.



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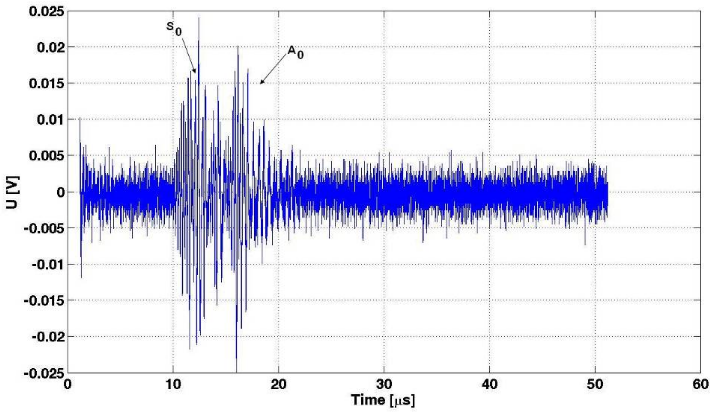


b

Figure 10. Propagation of Lamb wave in the studied samples
a) emission reception distance =29mm, only A_0 mode is propagated; b) emission reception distance=23mm – A_0 and S_0 modes are visible

According to [9], the group velocity of A_0 mode is given by

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

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

Experimental results
In Figure 11 is presented the distribution of group velocity of A_0 mode for different propagation directions for sample A. The measurements were made from 10^0 to 10^0. Examining the data from Figure 11, 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.

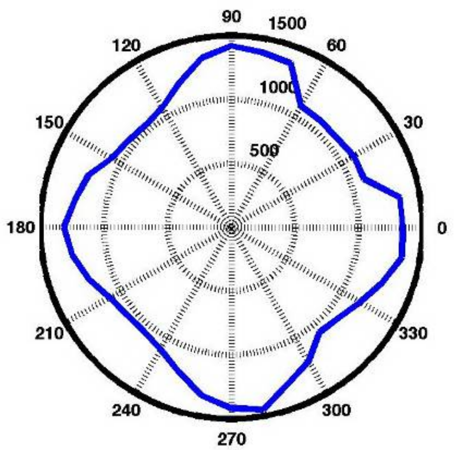


Figure 11. Angular distribution of the group velocity of A_0 mode in studied samples.

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

$$C_P = \sqrt{\frac{E_3}{\rho} \frac{1-\nu_{13}}{(1+\nu_{13})(1-2\nu_{13})}}$$
$$C_S = \sqrt{\frac{G_{13}}{\rho}} \qquad (3)$$

For C_p and C_S were obtained

C_p=2840±20m/s
C_S=1970±20m/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

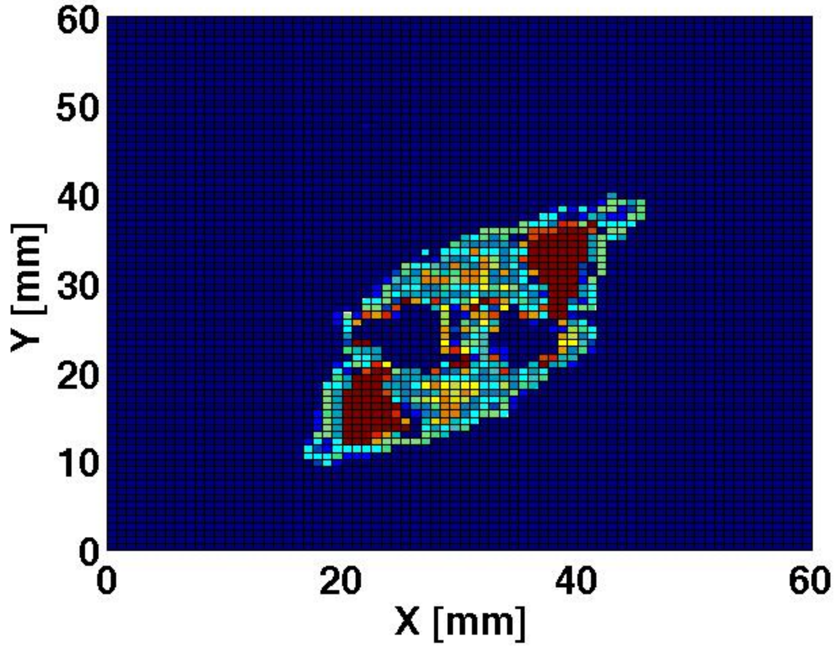
E_3=11.36GPa
G_{13}=5.5GPa

Similarly results have been obtained for samples B.

For samples B which were immersed in water for different time period, the ultrasound measurements demonstrate that the water drastically diminish the elastic moduli E_1, E_2, and $E_{3+.}$

The detection and evaluation of delaminations were made with C-scan ultrasound using phased array transducer.

In Figure 12 are presented C-scan for the delaminated zones obtained by impacts with 1J, 2.5J and 3J energies for the samples A.



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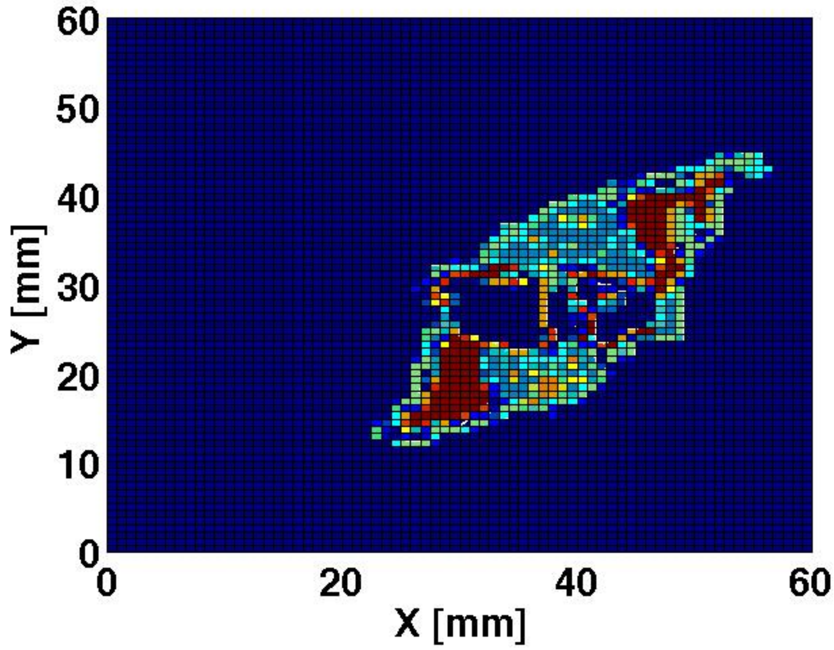

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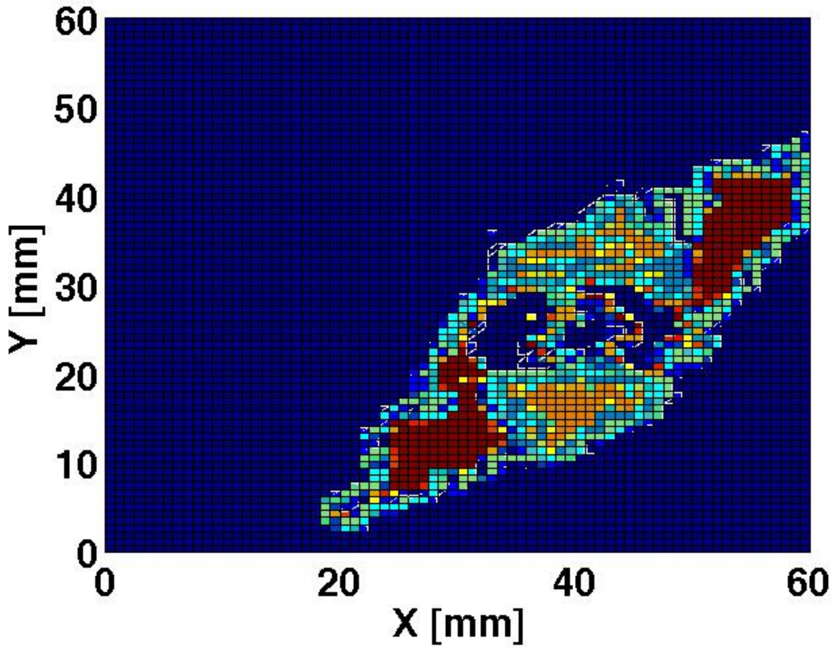

c

Figure 12. C-scan of delaminated zone for samples A

a) impact energy of 1J; b) impact energy of 2.5J; c) impact energy of 3J

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 13 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.

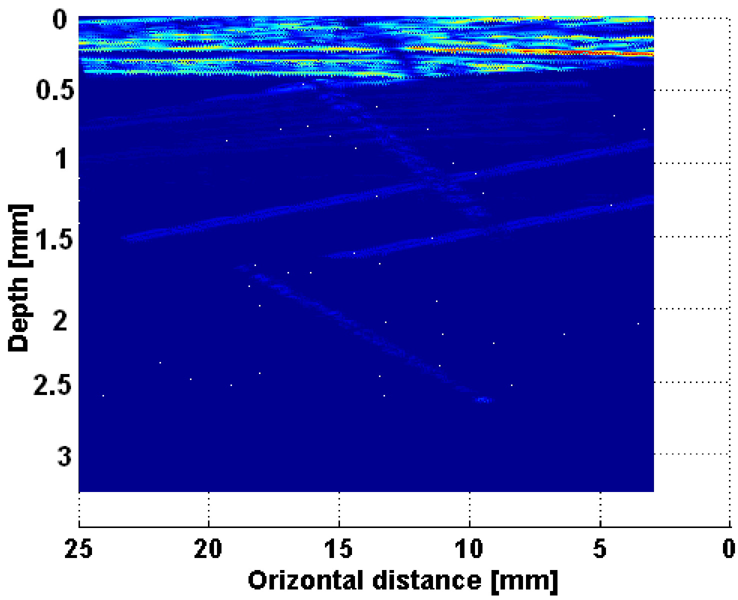

Figure 13. B-scan of a region with porosity for samples A

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.

The measurement for propagation speed of longitudinal, transversal and Lamb waves, A_0 mode, allow the emphasizing of local modification of mechanical parameters due to water absorption.

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.

Acknowledgement

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