3rd International Conference
″Advanced Composite Materials Engineering ″
COMAT 2010
27- 29 October 2010, Brasov, Romania

ULTRASOUND EVALUATION OF ELASTIC PROPERTIES OF CFRP

Raimond Grimberg[1], Ioan Curtu[2], Mariana Domnica Stanciu[2], Adriana Savin[1], Nicoleta Iftimie[1], Rozina Steigmann[1], Paul Doru Barsanescu[3]
[1]National Institute of R&D for Technical Physics, Nondestructive Testing Department, Iasi, Romania,
[2] Transilvania University, Faculty of Mechanical Engineering, Brasov, Romania
[3]Technical University Gh.Asachi, Faculty of Mechanical Engineering, Iasi, Romania

Abstract *This paper proposes the determination of elastic and shear modulus through measurements of longitudinal, transversal and Lamb wave propagation speed. The elastic and shear modulus in thickness direction are determined from the propagation speed of transversal and longitudinal waves generated by the US transducers with central frequency of 5MHz, respectively 4MHz and in-plane modulus are determined from the propagation speed of Lamb waves generated by air-coupled transducers with central frequency of 100 kHz. The data obtained by nondestructive procedures is compared with those by Dynamic Mechanical Analyzer.*
Keywords: *ultrasound, CFRP, elastic properties, Lamb waves, compressional and shear waves, air coupled transducers*

1. INTRODUCTION

Fiber Reinforced Polymer Composites (FRPC) materials continue to be used in a large number if applications ranging from aerospace systems to automotive, industrial and consumer products. The high strength-to-weight ratio, good stiffness properties, inherent corrosion resistance, low electromagnetic reflectance, and the ability to embed sensors and actuators have made fiber reinforced composites an attractive material for primary aircraft structures. In many other cases, FRPC materials are being developed and used to replace metal components, particularly those used in corrosive environments. Matrices used in polymer composites are typically epoxy, polyester pr polyphenylene sulphide (PPS) while examples of reinforcements are carbon, glass or Kevlar [1].
Typical aerospace applications for advanced composites are ultra-high-performance pressure vessels, rocket motor cases and launch tubes. Aeronautical applications include structural components as fuselages, helicopter rotor blades and external fuel tanks for combat aircraft. Commercial applications cover a wide range of uses including bike frames, tennis rackets, fuel containers used to store compressed natural gas for motor vehicles and high –performance tubular products used in the off-shore oil and gas industry [2].
Because of their increasing utilization in structural applications, the nondestructive evaluation (NDE) of FRPC continues to receive considerable attention for research and development. Due to the heterogeneous nature of composites, the form of defects is often very different from those typically found in a metallic material and the fracture mechanisms are more complex.
Composite materials represent acoustically heterogeneous materials in which a variety of defects with different dimensions may be formed. Typical defects of FRPC include fiber breaks, micro cracks, delaminations, foreign objects or contaminants, impact damage and porosity or voids. Fiber/matrix distribution, fiber waviness, and fiber orientation are also important micro structural properties of composites. Many of these defects or microstructural variations cause change in the speed of ultrasound in composite materials, consequently, ultrasonic testing is currently one of the most frequently used methods for NDE of FRPC [3].
The propagation speed of ultrasound in solid materials depends by the elastic properties of these [4]. In the case of composite materials, carbon fiber reinforces plastics (CFRP), it has been observed that the existence of some degradations as water adsorption or delamination due impacts with low energies leads to a significant modification of elastic properties [5], [6]. From here results that, when the problem of global examination of CFRP structure is posed, we could detect both micro cracks, porosity or voids, as well as modifications that some degradations as delaminations, water adsorption, local superheating are brought to CFRP elastic properties.

In this paper we propose the determination of elastic properties of CFRP using ultrasound methods with normal transducers for longitudinal and transversal waves that must be coupled with the examined material by means of classical coupling fluids as well as air-coupled ultrasonic transducers.

2. AIR COUPLED ULTRASOUND TRANSDUCERS

Ultrasound transducers are used for generation and reception of ultrasound wave, their functioning being based on the piezoelectric phenomenon. Due high acoustic impedance of piezoelectric material, reported to the acoustic impedance of the air (the acoustic impedance is defined as the product between the propagation speed of the ultrasound and the medium density [7]), the transmission of ultrasound in air will be in a less degree, the majority of generated ultrasound beam being reflected by the interface piezoelectric material – air. From this reason, for an adequate coupling of the ultrasound transducer with the material, a coupling fluid is used.

To use the air as coupling fluid, special transducers have been developed, named air-coupled transducers, the most performing transducers use piezo-composites as active element [8]. Piezoelectric rods aligned in parallel along the thickness direction are embedded in a three-dimensional passive polymer matrix (1-3 configuration, Figure 1a). The middle-to-middle distance between two rods must be smaller than half-wave length of the shear wave of the polymer matrix in order that the composite as a whole to vibrate (figure 1b). Both sides of rods are covered with Ni alloy electrodes and galvanization of Au layer. Afterwards, the transducers are focused by forming the composite into a spherical shape.

For a better acoustic impedance matching, a layer of silicon rubber containing air bubbles is deposed on the face of piezo-composite (Figure 1c). The physical realization of the transducer is presented in Figure 1d.

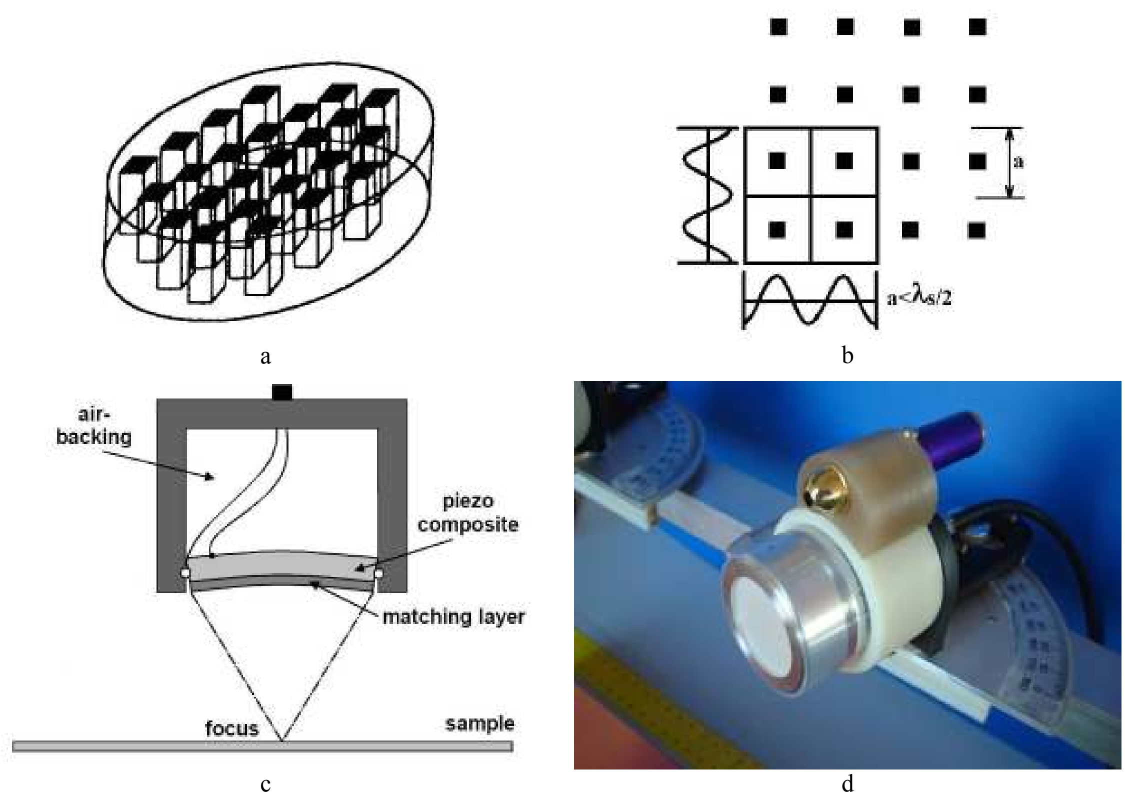


Figure 1: Air-coupled ultrasound transducers: a) 1-3 configuration; b) rods distribution; c) principle scheme; d) physical realization

3. STUDIED SAMPLES

Plates from composite having reinforcement from carbon fibers 5HS type and matrix from polyphenylene sulphide (PPS) – a thermoplastic resin system have been taken into study. The studied samples have 1.91mm thickness containing 12 layers of carbon fibers woven, with quasi-isotropic global distribution (Figure 2a), 0.5±0.03 volume ratio and 1460kg/m^3 density, produced by TenCate Cetex.

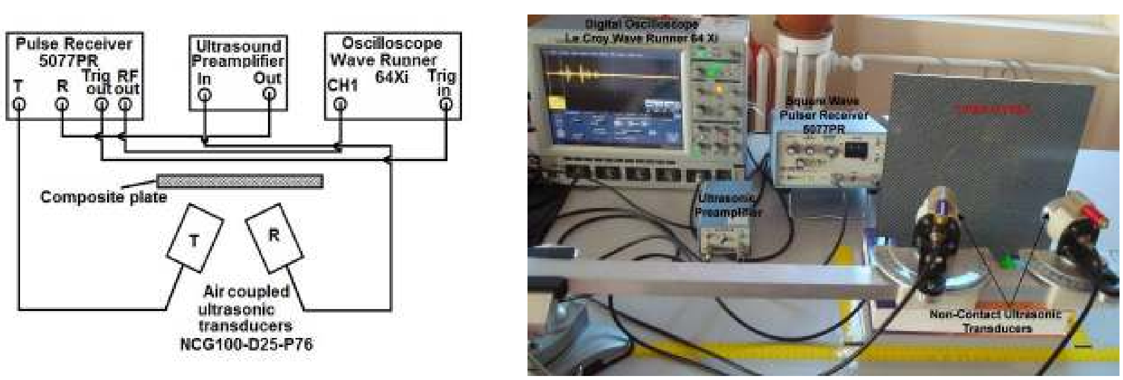
a b

Figure 2: Studied samples: a) photo; b) scheme of 5HS carbon fiber woven

The elastic modulus along the principal directions of the sample were determined using Dynamic Mechanical Analyzer DMA 242C-Netzsch Germany, 3 point bending fixture, on 5 samples. The principal directions are specified by the producer: X axis – direction 1, Y axis – direction 2 (X,Y are axis in the plane of composite) and Z axis - direction 3 is perpendicularly on the composite plane. For determination of elastic modulus E_1 and E_2, the samples were cropped at 50x10x1.191mm^3 and for 3rd direction 50x4x1.91mm^3.

4. EXPERIMENTAL SET-UP

The method impulse –echo was used for determination of compressional waves propagation velocity, with a transducer with 5MHz central frequency, A5518 Panametrics type, mounted on a delay block having 20mm thickness and 2700m/s velocity of compressional waves, using the gel ZG-F – GE as coupling fluid.
The method of transmission was used for determination of shear wave's propagation velocity, using two transducers for shear waves with 4MHz central frequency directly applied on the examined sample and honeybee, a very good non-Newtonian liquid.
The experimental equipment contains a Pulse Receiver 5073PR Pulser Receiver – Panametrics USA, the measurement of the times being made with a digital oscilloscope with memory, LeCroy Wave Runner 64Xi with 10GS/s sampling frequency, allowing a measurement precision of time of ±0.1ns.
For generation of surface waves, SH_0 type (shear waves horizontal, mode 0) as well as Lamb waves, the pitch-catch TR reflection method has been used with a pair of air coupled US transducers, type NCG100-D25-P76 – Ultran Group USA. The central frequency of the transducers is 100kHz, they are focused, having the focal distance of 76mm.
The transducers were coupled to Pulse Receiver 5077PR – Panametrics USA, the signal delivered by the reception transducer being supplementary amplified with 40dB with ultrasonic preamplifier Panametrics USA. The time has been measured with the digital oscilloscope LeCroy Wave Runner 64Xi.
In Figure 3 are presented the basic diagram (a) and the photo (b) of the experimental setup.



a b

Figure 3: Experimental set-up for generation of SH_0 and Lamb waves: a) block diagram; b) photo

5. THE MEASUREMENT PRINCIPLE

Into an homogeneous and isotropic material, the compression wave and shear waves velocities depend on the elastic properties of material [9] according the relation

$$C_P = \sqrt{\frac{E}{\rho}\frac{1-\upsilon}{(1+\upsilon)(1-2\upsilon)}} \qquad \textbf{(1)}$$

$$C_S = \sqrt{\frac{G}{\rho}}$$

where E represents the elastic modulus, G – the shear modulus, υ - the Poisson coefficient and ρ the density.
Applying the compressional waves and respective the shear waves transducers on the surface of the composite plates, the propagation of the US beam will be made along the 3rd principal direction, so that , from the relation (1), E_3, $G_{13}=G_{23}$, and $\upsilon_{13}=\upsilon_{23}$ can be determined [10].
For determination of elastic constants in the pane of composite, the procedures of generation of SH_0 and Lamb waves with air-coupled ultrasonic transducers were used.
The method starts from the observation that allows a critical incidence angle $i_{cr,}$ an incident ultrasound beam, compressive waves type, at the interface air-composite will have a change of mode, in material appearing both compressional as well as shear waves parallel with the interface, according to Figure 4.

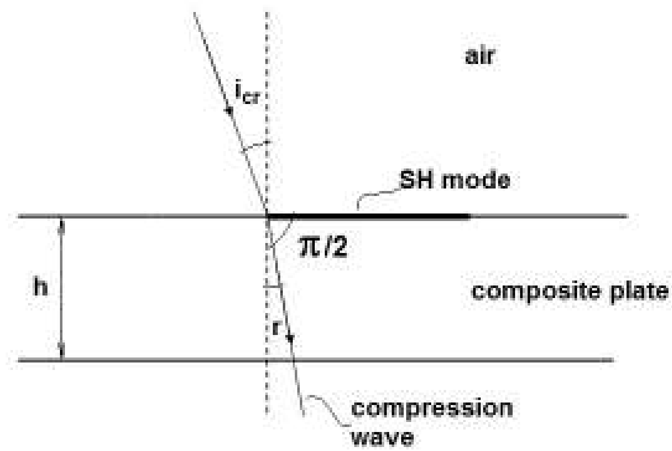


Figure 4: SH waves generation

The dispersion equation for SH is given by the relation [9]

$$\left(\frac{\omega^2}{c_S^2}-k_m^2\right)^{1/2} h = \frac{m\pi}{2}, \qquad m-0,2,4,... \qquad \textbf{(2)}$$

where k_m is the wave's number of SH modes, c_S having the significance from above, with the observation that in this case it is referred to the propagation velocity of the shear waves along a direction in the composite's plane.

$$c_n = \frac{\omega}{\left[\frac{\omega^2}{c_s^2}-\left(\frac{m\pi}{2h}\right)^2\right]^{1/2}} \qquad \textbf{(3)}$$

For SH_0 mode, m=0, so that (3) become

$$c_0 = c_s \qquad \textbf{(4)}$$

From the measurement of SH_0 mode propagation velocity, c_0, the propagation velocity of shear waves in the composite's plane can be determined along any direction.
In Figure 5 are presented the signals delivered by the reception transducer (Fig.1d) when the incidence angle is equal to critical angle, determined with Snell's law

$$\frac{c_{air}}{c_s} = \frac{\sin i_{cr}}{1} \qquad \textbf{(5)}$$

c_{air}=340m/s
c_s=1970m/s.

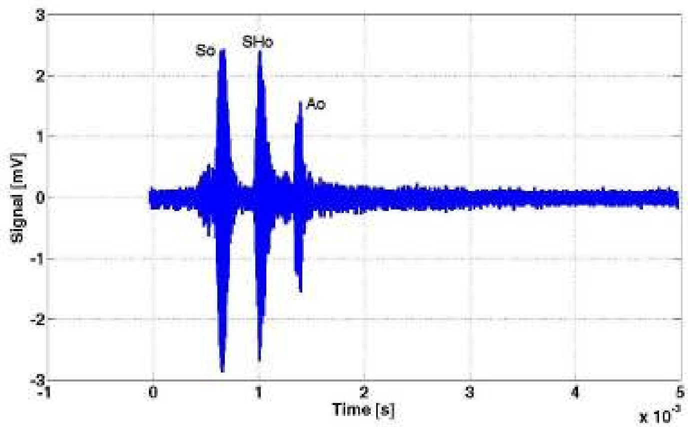


Figure 5: The propagation modes of US waves in studied composite plate for incident critical angle determined according to (5)

The Lamb waves are elastic waves guided between the faces of the composite plate, symmetric and anti-symmetric modes might appear, propagating into plate with different velocities.
The dispersion equations for Lamb waves are named Rayleigh-Lamb, at their mathematical form are

$$\tan\left(\frac{pq}{ph}\right) = -\frac{4k^2pq}{\left|q^2-k^2\right|^2} \quad \text{for symmetrical modes}$$
$$\tan\left(\frac{qh}{ph}\right) = -\frac{\left|q^2-k^2\right|^2}{4k^2pq} \quad \text{for anti-symmetrical modes} \tag{6}$$

where

$$p^2 = \left(\frac{\omega}{C_s}\right)^2 - k^2; \quad q^2 = \left(\frac{\omega}{C_p}\right)^2 - k^2; \quad k = \frac{\omega}{c_{phase}}$$

C_{phase} being the phase velocity of Lamb waves.
The group velocity of Lamb wave is defined

$$c_{group} = \frac{d\omega}{dk} = c_{phase}^2\left[c_{phase} - \omega\frac{dc_{phase}}{d\omega}\right]^{-1} \tag{7}$$

relation available both for symmetrical as well as anti-symmetrical modes.
For relative small thickness of the plate and at relative low frequency, the velocity of the symmetric mode 0 (S_0) is constant so that

$\frac{dc_{phase}S_0}{d\omega} \approx 0$ and $c_{group}S_0 \approx c_{phase}S_0$. In the same experimental conditions, also $c_{group}A_0 \approx c_{phase}A_0$, where A_0 represents 0 order anti-symmetric mode.

By the proposed experiments we can determine, with sufficient precision, the propagation group velocity of A_0 and S_0 modes, so that, solving the equations system (6), the propagation velocity of compressional waves in the composite plane can be determined. Knowing the propagation velocities of compressional and shear waves in the composite plane, the elastic and shear modulus as well as Poisson coefficients can be determined.

6. RESULTS

The values of elastic modulus E_1, E_2, E_3 were determined using Dynamic mechanical Analyzer (DMA) with 3 points bending fixture as well as through ultrasound methods described above.
In Table 1 are presented the average of 5 measurements in the case of DMA using and 50 measurements for US procedures.

Table 1: The elastic modulus along principal directions measured on CFRP studied samples

Determination procedure	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]
DMA	45.2 ± 0.7	44.3 ± 0.7	11.1 ± 0.3

US	45.8 ± 0.8	44.8 ± 0.9	11.4 ± 0.5

The shear modulus were determined only with ultrasound procedures previous described, the results being presented in Table 2.

Table 2: The shear modulus measured on CFRP studied samples by ultrasound procedures

G_{12} [GPa]	G_{21} [GPa]	$G_{13} = G_{23}$ [GPa]
8.4 ± 0.2	8.4 ± 0.2	5.5 ± 0.1

Poisson's ratio have been determined also by ultrasound methods, the values obtained are presented in Table 3, as average of 50 measurements.

Table 3: Poisson's ratio determined by ultrasound procedures

υ_{12}	υ_{21}	$\upsilon_{13} = \upsilon_{23}$
0.32	0.32	0.03

Data from table 1 show that the values of elastic modulus determined through the two procedures are closely enough, having, in addition, relative similarly dispersions. This fact shows that, using complex nondestructive procedures of US, described above, the elastic constants of composite materials reinforced with carbon fibers woven and matrix from PPS can be determined with good accuracy.

7. CONCLUSION

For determination of elastic and shear modulus, Poisson's ratio of the composite materials with reinforcement from carbon fiber woven, the using of combined ultrasound methods are proposed, namely impulse-echo for compressional waves, send-receive method for transversal waves as well as guided waves and surface waves using air-coupled US transducers with relatively low frequency. The obtained results are in good concordance with those obtained by destructive testing using Dynamic Mechanical Analysis.

ACKNOWLEDGEMENT

This paper was partially supported by the Romanian Ministry of Education, Research, Youth and Sports under National Plan II Program – Contract 71-016/2008 MODIS, Nucleus Program –Contract PN 09430104

REFERENCES

[1] A.K.Kaw, Mechanics of Composite Materials, 2nd ed., Taylor and Francis, NY, 2006

[2] P.Morgan, Carbon fibers and their composites, Taylor &Francis, NY, 2005

[3] P.J.Shull, Nondestructive Evaluation – Theory, Techniques and Applications, Marcel Dekker, NY, 2002

[4] L.W.Schmerr, jr, Fundamentals of Ultrasonic Nondestructive Evaluation, A modeling approach, Plenum Press, NYLondon, 1998

[5] R. Grimberg, A. Savin, R. Steigmann, I. Curtu,P.D. Barsanescu, J. Grum, Ultrasound and eddy current nondestructive evaluation of CFRP – Correlation with mechanical properties of the composite, ECNDT 2010 – the 10th European Conference on NDT, 7-11 June, 2010, Moscow, Rusia

[6] R.Grimberg, A.Savin, R.Steigmann, A. Bruma, P.Barsanescu, Ultrasound and eddy current data fusion for evaluation of carbon epoxy composite delaminations', INSIGHT, vol. 51, iss.1, (2009), pp.25-32.

[7] J.Krautkramer, H.Krautkramer, Ultrasonic Testing of Materials, 4th ed., Springer-Verlag, Berlin, 1990

[8] R.E.Newnham, Composite piezoelectric transducers, Mater.Eng.2, (1980), pp.93-106

[9] J.L.Rose, Ultrasonic waves in solid media, Cambridge University Press, Cambridge, 1999

[10] R.Grimberg, A. Savin, R.Steigmann, A.Bruma, P.Barsanescu, D.Salavastru, Determination of CFRP's mechanical properties using ultrasound methods, Proceeding of the 5th International Workshop NDT in Progress, Meeting of NDT experts, October 12 – 14, 2009, Prague, Czech Republic, pp.65-74