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EVALUATION OF GLASS FIBER REINFORCED PLASTIC ELASTIC PROPERTIES USING LAMB WAVES

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Abstract:*A problem extremely important of the composite materials with polymer matrix reinforced with long fibers is represented by the nondestructive local determination of elastic properties, due to the influences of few types of degradations as water absorption. This paper presents an evaluation method of elastic properties of glass-polyester composites, intensively used at naval construction and, lately, at the construction of wind turbine blades. The method is based on the measurement of phase velocity of Lamb waves generated and detected with air-coupled low frequency ultrasound transducers. The obtained results are in very good concordance with those obtained by classical destructive methods.*
Keywords: *glass fiber reinforced plastics, ultrasound modes, Lamb waves, phase velocity*

1. INTRODUCTION

The continuing increase in applications of composite materials promotes interest for monitoring and identification of damages in composite materials. Fiber reinforces plastics composites, which provide high stiffness and strength-to-weight ratios, improve fatigue resistance and damage tolerance capability are susceptible to damage. These damages could have originated from either imperfections in the manufacturing process or those developed during service life such as impact of debris or some flying objects on the structure during service life, voids inside the laminates or accidental impact during manufacturing [1]. Damage like fiber breakage, matrix cracking, desbonding between the fibers and the matrix, delaminations or interlayer cracks and water absorption are typical damages in fiber reinforced plastics composite laminate [2]. These damages can significantly reduce the elastic properties of composites; with ultimately grow to a failure of the structure.
One of the most used fiber reinforced plastics composite is the composite having fiber glass as reinforcement and polyester as matrix. This material is broadly used in naval construction and, relatively recent, at the construction of wind turbine blades from on-shore and off-shore wind farms. In the last case, the turbine blades are transported, most times, on long distances and with different transportations means, increasing the risks of damages during transportation. From this reason, the development of nondestructive techniques for determination of elastic properties of the composite structure in chose point became extremely useful.
A method that might allow the evaluation of principal elastic properties as elastic modulus, shear modulus and Poisson coefficients, shall be the measurement of phase velocity of Lamb waves in the studied composite using air coupled transducer, the coupling liquid might be absorbed by the composite material and leads to other damages.

2. THE THEORY OF THE METHOD

The stress-strain relation on the anisotropic composite material can be represented using Hook's law [3]

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \tag{1}$$

where C_{ijkl} means the stiffness matrix and ε_{kl} is defined as the strain tensor

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) \tag{2}$$

For anisotropic material, the stress-strain relation could be written as

$$\begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{23} \\ \varepsilon_{13} \\ \varepsilon_{12} \end{pmatrix} \tag{3}$$

The linear equation of motion in on elastic material is given as follows

$$\sum_{j=1}^{3} \frac{\partial \sigma_{ij}}{\partial x_j} = \rho \ddot{u}_i \qquad (i = 1,2,3) \tag{4}$$

where ρis the mass density and u_i is the particle displacement vector.
When a plane wave propagates through the free surface medium, the particle displacement vector u_i can be written as

$$\overline{u}_i = u_{i0} \exp\left(j\left(\omega t - k\overline{x}\right)\right) \tag{5}$$

where u_{i0} is the amplitude, ω is the angular frequency and k the wave vector. The x_1 represents the wave propagation and x_3 indicates the plate thickness direction. The displacement u_2 and all derivatives with respect to y vanish.
The Lamb waves traveling through the plate can be obtained subject to the boundary conditions. If the thickness of the composite plate is *2h*, the plate surfaces of the x_3 direction is $z=\pm h$. The surface of the plate is in the stress free condition [4], the following boundary conditions are applied

$$\begin{aligned} \sigma_{33}\big|_{z=\pm h} &= 0 \\ \sigma_{31}\big|_{z=\pm h} &= 0 \end{aligned} \tag{6}$$

Introducing (5) to (6), taking into account that (5) is solution of (4), the dispersion equation for the phase velocity of lamb waves is obtained, with supplementary condition

$$u_3(z) = -u_3(-z) \tag{7}$$

that is corresponding to symmetric modes and

$$u_3(z) = u_3(-z) \tag{8}$$

corresponding to antisymmetric modes.
The dispersion equation established a functional connection between the phase velocity of the lamb waves, distinguished for symmetric and antisymmetric modes and frequency. The coefficients depend by the elements of the elasticity matrix that can be determined by solving the inverse problem.

3. STUDIED SAMPLES

Samples of GRP plates having as reinforcement 5 and 6 sheets of ravings with 250± 50gm^{-2} density and matrix from different types of unsaturated Orthophthalic polyester resins, made by COLPOLY Slovenia have been taken into study, Figure 1.
The characteristics of studied GRP samples are presented in Table 1.

Table 1: Studied GRP samples.

No	Sample	Matrix	Number of reinf.layers	Fiber volume ratio	Density [kg/m^3]	Observations
1	7201-5l	COLPOLY 7201	5	0.52±0.005	1466±20	medium reactivity resin
2	7201-6l	COLPOLY 7201	6	0.43±0.005	1550±20	medium reactivity resin
3	7524-6l	COLPOLY 7524	6	0.43±0.005	1530±20	Chemical resistance
4	7243-6l	COLPOLY 7243	6	0.57±0.005	1410±20	Preaccelerated thixotropic

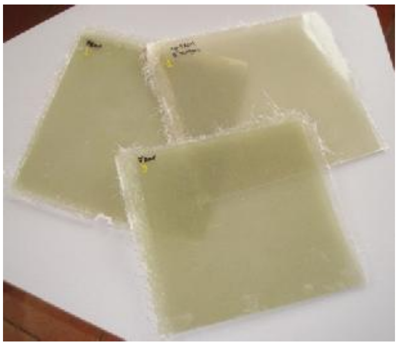
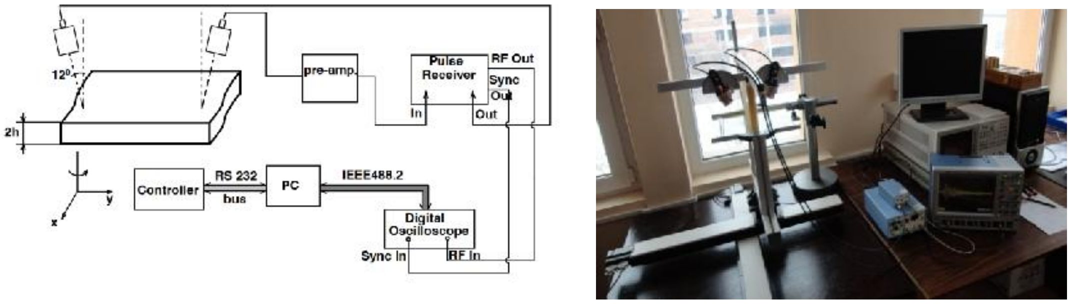


Figure 1: Studied GRP samples

For a better characterization of studied GRP samples, the temperature of glass transition has been determined using Dynamical Mechanical Analyzer, resulting in between 96^0C and 110^0C.

4. EXPERIMENTAL SET-UP

In order to generate the Lamb waves into the composite plate taken into study, as well as for their detection, air coupled transducers, NGC 100D25 type ULTRAN GROUP USA were used, having the central frequency 100Hz. The transducers were coupled at Pulse Receiver –5073PR Panametrics USA. The received signal is sampled and quantized using a digital oscilloscope Wave Runner 64Xi, Le Croy. The data are saved into PC through IEEE488.2 interface. The same PC, through RS 232 serial interface commands the displacing system XY with rotation on Z, Newmark USA. For the correct functioning, a numerical code elaborated in Matlab 2011b assures the command of equipment and the acquisition of data.
The incident angles of the emission and reception transducers, placed in pitch-catch configuration, are equal, at 12^0, assuring that in the composite plate, both longitudinal and transversal waves are generated.
The principle scheme of the experimental set-up is presented in Figure 2a and the equipment in Figure 2b.



a b

Figure 2: Experimental set-up: a) the principle scheme; b) the equipment

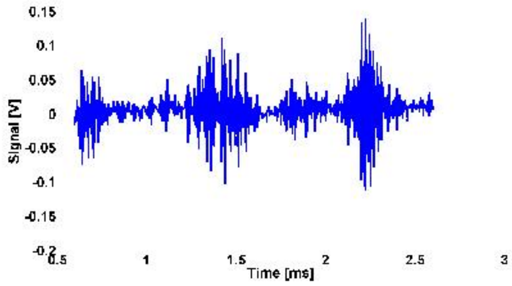
5. EXPERIMENTAL RESULTS

Using the equipment described above, glass-polyester composite plates were investigated. The initial distance between the emission and reception transducer were 80mm, measuring the reception transducer response, which was displaced along 90mm distance in 5mm steps. The received signals are presented in Figures 3 a – e, corresponding to 10mm displacing between the transducers. The existence of more Lamb wave's modes can be observed, but their phase velocity is difficult to be identified and evaluated. The algorithm for determination of the phase velocity is

- The individuals signal vectors are concatenated, the matrix of recordings being obtained, the horizontal dimension representing the time and the vertical is the distance between the emission and reception transducers.
- A 2D FFT is applied to these matrix, the result being filtered by convolution with a 2D Hanning window, the results from Figure 4 being obtained, having frequency, respectively the wave number as coordinates
- For each frequency, the local maxim of 2D Fourier representation are determined, the wave number corresponding to the maximum is obtained, according to relation

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{v_{phase}} \tag{9}$$

the corresponding phase velocity is determined. The algorithm developed in this paper is a generalization of the one presented in [5]. The obtained results are presented in Figure 5 where the lines represent the best fitting of experimental data, the propagation modes of Lamb waves being marked. These results correspond to the composite plate 7543, the same procedures being used to the other plates.



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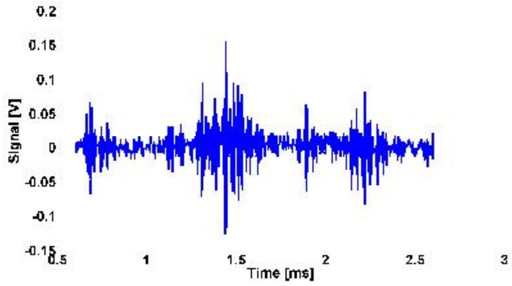

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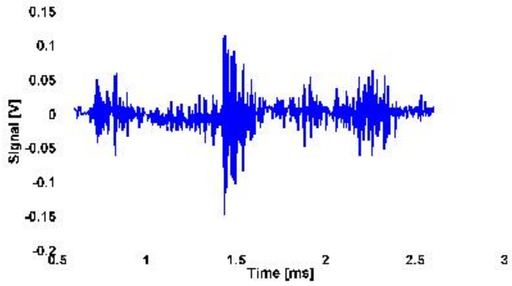

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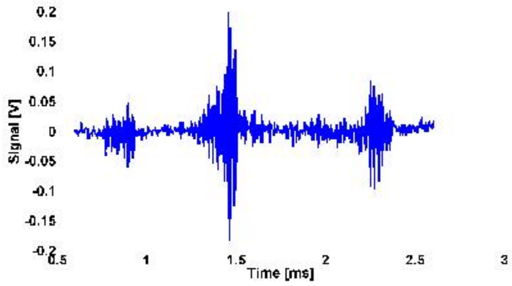

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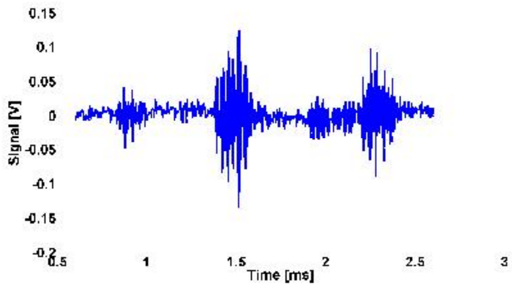

e

Figure 3: The received signals

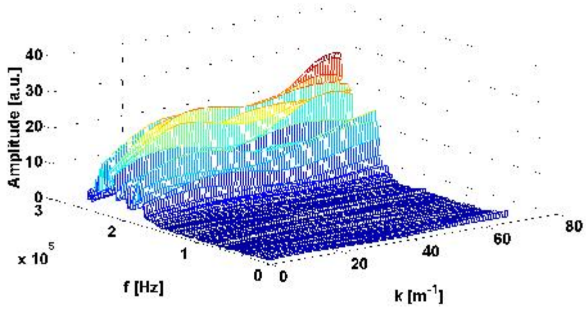

Figure 4: 2D FFT transform

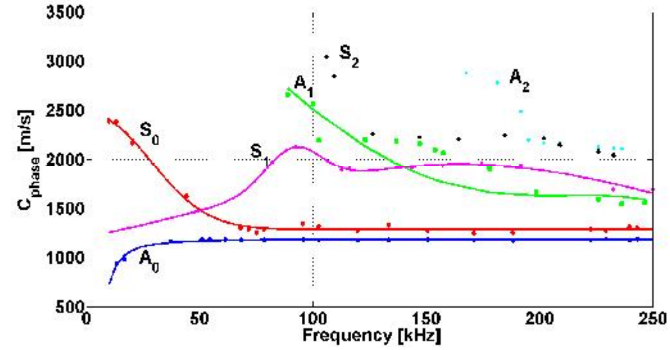

Figure 5: Results of developed algorithm

Through an inversion procedures based on the Newton-Raphson optimization [6], the principal mechanical characteristics of the materials are obtained, being presented in Table 2. In Table 3 are rpesented the mechanical properties of the studied samples obtained by destructive tests with Dynamic Mechanical Analyzer DMA 242C Netzsch Germany and INSTRON E1000 USA.

Table 2. Mechanical properties.

No.	Composite	C_L [ms^{-1}]	C_T [ms^{-1}]	C_{A0} [ms^{-1}]	C_{S0} [ms^{-1}]	E_x=E_y [GPa]	E_z [GPa]	υ_{xy}	υ_{xz}	G_{xy} [GPa]	G_{xz} [GPa]
1	7201-5l	2653	1562	980	2030	5.8	8.8	0.19	0.24	2.4	3.6
2	7201-6l	2261	1550	912	1980	8.9	7.9	0.2	0.19	3.7	3.6
3	7524-6l	2844	1603	1094	2230	10	9.5	0.2	0.27	4.2	3.0
4	7243-6l	2868	1512	1036	2250	8.3	8.4	0.21	0.31	4.2	3.2

Table 3. Mechanical properties determined by destructive tests

No.	Composite	E_x=E_y *	E_z *	υ_{xy} *	υ_{xz} **	G_{xy} ** [GPa]	G_{xz} ** [GPa]	T_g * [^0C]	Activation energy [kJ/mol]
1	7201-5l	6.05	9.1	0.19	0.24	2.44	3.58	96.0	241.5
2	7201-6l	9.1	832	0.2	0.18	3.7	3.6	82.9	149.6
3	7524-6l	10.5	9.65	0.2	0.27	4.2	3.2	110.7	286.2
4	7243-6l	8.4	8.2	0.2	0.31	4.2	3.2	105.7	296.4

* determined by DMA 242C measurements

** determined by INSTRON E1000 measurements

Comparing the data obtained by destructive tests, presented in Table 3 with those obtained by measuring the phase velocity of Lamb waves, a very good correlation can be observed, fact that demonstrates the righteous of the methods developed in this paper.

3. CONCLUSION

The elements of elastic matrix of glass-polyester composites are correlated directly with the phase velocity of different symmetric and antisymmetric modes of Lamb waves. The phase velocities can be determined with an algorithm based on 2D FFT of signals delivered by the transducers that generates and receive the Lamb waves induced in the composite plate, when the distance between emission and reception transducers is modified on equal steps. Determining the elastic matrix elements of composites, the elastic modulus, share modulus and Poisson coefficients are determined for the samples taken into study.

These results are in good concordance with those obtained by classical destructive methods as dynamic mechanical analysis and loading tests.

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