Nondestructive evaluation and characterization of GFRP using non-contact ultrasound and complementary method

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Abstract. This paper presents two methods, non-contact low frequency ultrasound method and fiber Bragg gratings, and their application to nondestructive testing of glass fiber reinforced composites used in wind turbine blades. Theoretical models are used and experimental results are in good concordance with destructive testing results.

1. Introduction
The process of implementing a damage detection and characterization structures has become an economic necessity. The monitoring of large structures has started to be broader applied, sensors based on different physical principles being developed, as well as diagnosis and prognosis methods. Wind turbine blades are one the most damageable components of wind turbine system, are produced from composite type Glass Fiber Reinforced Composites (GFRP) with orthophthalic polyester resins matrix.

GFRP composites is a versatile material that combine lightweight with inherent strength to provide a weather resistant finish, with a variety of surface texture and an unlimited color range available. The mechanical performances of GFRP composites depends on the fiber strength and modulus, the matrix strength and chemical stability, and the effectiveness of interface bonding between the matrix and fiber to enable stress transfer [1, 2]. Glass fiber reinforced polyester (GRP) composites are the most “popular” GFRP.

The matrix is based on cured thermosetting resin. The damages presented in composite materials, which in most cases they are not detectable, include matrix cracking, fibers breaking, and desbonding of fibers from matrix as well as delamination / slides of fibers between two adjacent layers. Most of experimental results have emphasized the failure of polymer composites, other have allowed the development of methods to foreseen the initiation of the damages and their propagation within composite. In the production of sustainable energy, the principally components of wind turbine blades are made by GFRP and carbon fiber reinforced plastics (CFRP). These components are usually subject to random and complex mechanical stresses so they require testing and monitoring.

The paper present the methods developed such as non-contact low frequency ultrasound method, fiber Bragg gratings, applied to testing of composites used for construction of wind turbine blades. For in-plane components, using the value of propagation speed of fundamentals modes of Lamb waves [3],
generated and received by air-coupling ultrasound transducers mechanical properties have been
determined. The results are compared with those obtained from destructive tests as dynamic
Mechanical Analysis using DMA 242C.

2. Studied samples
It has been find that the presence of degradations in GFRP as thermal destruction or delaminations due
to low energy impacts leads to significate modification of elastic properties [4, 5]. GFRP composites
reinforced with 6 sheets of ravings with 250±50gm-2 density and matrix from different types of
unsaturated orthophthalic polyester resins, made by Helios, Slovenia, were taken into study (figure 1).
The characteristics are presented in table 1.

| Table 1. Samples characteristics. |
|-----------------------------------|
| sample | matrix | Fiber volume | Density [Kg/m3] | observation | Production process |
|--------|--------|---------------|-----------------|-------------|--------------------|
| 7201   | COLPOLY| 0.43±0.005    | 1550±20         | Medium reactivity resin | In two steeps |

Figure 1. Studied GRP samples.

3. Experimental set-up

3.1. Air coupled ultrasound transducer
For generation and reception of ultrasound waves, US transducer are used, mostly their
functioning is based on piezo-electric phenomenon. Due to high acoustic impedance of piezo-
electric material reported to air acoustic impedance (acoustic impedance is defined as the
product between the propagation speed of ultrasound and the density of medium) [6], the
transmission of ultrasound through air will be low, the majority of ultrasound beam being
reflected on the interface piezo-electric material – air. For this reason, a coupling fluid is
required in order to obtain adequate coupling between the US transducers and the material to
be examined. In order to use air as coupling, air-coupled transducers are used. The most
performant transducers have piezo-composites as active element [7].

For generation of surface waves, SH0 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–UltranGroup USA. The central frequency of the
transducers is 100kHz, they are focused, having the focal distance of 76 mm. 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 (figure 2).

The incident angle, $\theta$, is chosen so the SH0 modes horizontally polarized shear waves shall
appear, that is $\theta = \arcsin \left( \frac{c_{air}}{c_s} \right)$ where $c_{air}$ is the ultrasound speed in air at the experiment
temperature. The phase velocity of Lamb waves \( c_p = 2\pi fL / \Delta \phi \) where \( \Delta \phi \) is the difference in the phase spectrum of two signals that were collected with a different distance between them of \( L \) and \( f \) is the frequency. Using this method, we can induce in composite skin, the Lamb waves or guided waves. We can detect the delaminations or the desbonding regions inside of composite skin, and we may determine the complete matrix of elasticity. Considering a composite plate with \( 2h \) thickness and a Cartesian coordinate system attached to it, having axis x “1” along the fibers, the axis y “2” perpendicularly on the direction of fibers, axis z “3” perpendicularly on the plate’s plane (figure 3).

The elasticity law for an orthotropic composite was determined by method described in [9]. The elasticity modulus \( E_3 \), the shear modulus \( G_{23} \) and the Poisson’s ratio \( \nu_{23} \) can be determined by measuring the velocity of the longitudinal waves and of transversal waves that propagate along direction “3”. The relationship between these velocities and the elastic parameters are well known

\[
 c_{p3} = \sqrt{\frac{E_3 (1-\nu_{23})}{\rho (1+\nu_{23})(1-\nu_{23})}}; \quad c_{s3} = \sqrt{\frac{G_{23}}{\rho}} \quad \text{in function of Lame coefficients } \chi \text{ and } \mu
\]

\[
 \lambda_3 = \frac{E_3 \nu_{23}}{(1+\nu_{23})(1-\nu_{23})}, \mu = G_{23}. \quad \text{According to [8] and [2] have shown that according to a basic relationship, the phase velocity of fundamental symmetrical mode, } S_0, \text{ is} \quad c_{S0} = \sqrt{\frac{E_s}{\rho (1-\nu_{xy}^2)}}. \quad \text{The phase velocity of fundamental anti-symmetrical mode, } A_0, \text{ can be obtained} \quad c_{A0} = \left( \frac{D_p}{2\rho h} \right)^{1/4} \omega^{1/2}
\]

where \( D_p = \frac{8\mu_1 (\lambda_1 + \mu_1) h^3}{3 (\lambda_1 + 2\mu_1)} \) is the flexural rigidity of the plate.

3.2. Fiber Bragg Gratings (FBG)
Nondestructive evaluation of GFRP included the use of fiber-optic sensors (Fiber Bragg Grating-FBG) for detecting delamination in composite laminates [9] and monitor impact event occurrence [10]. The FBG sensors are made on the basis of optical fiber in integrated structures (figure 4a). The structure is concentric having a central core surrounded by a cladding and a protection sleeve. The refraction index of the core is higher than of the surrounding medium. The light is propagated through the core
that is becoming a “waveguide”. The diameter of the optical fiber of the core is 8-10\(\mu\)m, and the sleeve has 125\(\mu\)m diameter.

![Figure 4. Experimental set-up: a) block diagram; b) equipment.](image)

The Bragg gratings have different wavelength in function of application. The sensors based on FBG act as filter in the propagation of light through the sensor’s core. The sensor reflects the light, in the range of Bragg wavelength, given by

\[
\lambda_B = 2n_{\text{eff}}\Delta
\]

where \(n_{\text{eff}}\) is the effective refraction index in the region of the grating, \(\Delta\) is the periodicity of the grating. The periodicity of the grating is modified by the external forces that can induce mechanical deformations in material, by the temperature variations or impact forces, so \(\lambda_B\) is modified. The method is based on a broadband light source illuminating the optical input line and a reference cell after passing a system coupler [11]. The reflectance cell consists of a double FBG housed in an athermal package and reflects two wavelength peaks (around 1529 and 1571 nm). The reflected spectrum will be analyzed afterwards by a 2 by 2 coupler using an optical spectrum analyzer (figure 4b).

3.3. Dynamical Mechanical Analyzer DMA 242C
A Dynamical Mechanical Analyzer DMA 242C from Netzsch, Germany, with a three-point bending fixture and using the analysis software Proteus v.4.8.5, has been used, figure 5. The measurements were carried out at a frequency of 1 Hz.

![Figure 5. Dynamical Mechanical Analyser DMA 242C a) the equipment; b) three points bending.](image)

The complex modulus \(E^*\) is a phase vector that incorporates both capacities \(E^*=E^\prime+jE^\prime\prime\) where \(j = \sqrt{-1}\). The real part of this equation is called the storage modulus because it quantifies the material’s ability to store energy elastically. In materials with insignificant damping, the storage modulus is equivalent to the Young’s modulus. The imaginary part (\(E^\prime\)) of this is called the loss modulus, because it quantifies the material’s ability to dampen out the energy. The dimensionless loss
factor \( \tan(\delta) \) is independent of the contact energy, because it is the ratio of the loss to the storage modulus \( \tan(\delta) = \frac{E''}{E'} \). For all the samples, the bulk modulus \( E' \) and \( \tan(\delta) (\tan(\delta) = \frac{E''}{E'}) \) were measured function of the temperature in the range 30\(^\circ\)-250\(^\circ\)C. In this range, the studied samples do not reach the thermal destruction. The equipment has been set-up with the parameters: heating speed 2\(^\circ\)/min., amplitude of the down force 6N, the deflection amplitude 30\(\mu\)m. The tests were effectuated at frequencies 1, 3.33, 5, 10, 33.3, 50Hz.

4. Result and discussions

4.1. Low frequency ultrasound using air-coupled US transducer

The presence of delaminations or desbondings as well as the water absorption lead to substantially modification of the elasticity matrix elements and then, they can be detected using low frequency ultrasound by means of air-coupled US transducers. In the figure 6 are presented the experimental dispersion curves traced according to the algorithm described above.

![Figure 6. The dispersion curves for different modes of Lamb waves generated in sample 7201-61.](image)

In table 2 are presented the propagation velocities and elastic properties of the studied samples.

| \( C_L \) [ms\(^{-1}\)] | \( C_T \) [ms\(^{-1}\)] | \( C_{A0} \) [ms\(^{-1}\)] | \( C_{S0} \) [ms\(^{-1}\)] | \( E_x = E_y \) [GPa] | \( E_z \) [GPa] | \( \nu_{xy} \) | \( \nu_{xz} \) | \( G_{xy} \) [GPa] | \( G_{xz} \) [GPa] |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 7201-61        | 2261           | 1510           | 912            | 1980           | 8.9            | 7.9            | 0.2            | 0.19           | 3.7            | 3.6            |

Knowing the experimental dispersion curves, meaning the way in which the phase velocity varies for different modes of Lamb wave function on frequencies, as well as the theoretical curves obtained from the characteristic equation of dispersion, the determination of elastic properties is made by inversion using an optimization method. For this problem we have used the simplex procedure [12], the function to be minimized being quadratic, positive form

\[
F(\hat{P}) = \sum_{k=1}^{m} \left( \nu_{ph} - \nu_{ph} \left( \hat{P} \right)_k \right)^2
\]

where \( P \) represents the elastic constant of the composite plates taken into study (elasticity modulus, shear modulus, Poisson ratio), \( \hat{P} \) is the best estimated vector solution plus an error vector \( \Delta P \): \( \hat{P} = P + \Delta P \). Applying the same inversion procedure for all the samples studied with Lamb waves generated and received by air-coupled US transducers, the elasticity modulus, the shear modulus were obtained and are presented in table 3, together with the results obtained by destructive testing mentioned above, for comparison. Thus, analysis of data from table 3 shows that the elastic constants determined by inversion by measuring the phase velocity of different modes of Lamb waves generated and received with air-coupled US transducers are very closely by those determined by classical destructive testing, framing into the prescribed error vector.
During data processing, the rheological models for the analyzed specimens have been determined based upon the variation curves pressure to deformation. Each specimen was exposed to the same interior pressure regime of 0-800 bars with the interior pressure variation of 100 bars (in the interval 0-500 bars), and 50 bars, respectively (in the interval 500-800 bars). Figure 7 shows the variation curves of the deformations with respect to the interior pressure.

**Table 3.** Elasticity and shear moduli obtained by inversion and ones determined by classical destructive procedures.

| sample | Ex₁ = Ex₂ [GPa] | Ex₃ [GPa] | Ex₃ [GPa] | Gx₁ x₂ [GPa] | Gx₁ x₂ [GPa] | Gx₁ x₃ [GPa] | Gx₁ x₃ [GPa] |
|--------|-----------------|----------|----------|-------------|-------------|-------------|-------------|
| 7201-6L | 9.1             | 8.2      | 8.2±0.5  | 3.7         | 3.7±0.25    | 3.6         | 3.6±0.25    |

The italic notation represents the best estimation obtained by inversion.

4.2. Fiber Bragg Grating sensor

The FBG sensor single DTG S-01 used for monitoring composite materials type GFRP [13] have center wavelength in 1535 nm with strain sensitivity 7.8x10⁻⁷ µε⁻¹ and temperature sensitivity 6.5x10⁻⁶K⁻¹. During the experiments, the temperature has been maintained constant at 19±1°C. The experimental test setup was performed according to [14] upon sufficient drying, a progressively loading/unloaded forces G 0; 112; 236 N were applied.

Physically, stress concentration around the damage in the composite laminates can be directly observed from row sensor signal.

![Figure 7. Spectral response of FBG sensor function of loading for composite materials: a) without delamination; b) with delamination](image)

In the mentioned interval the relative variation of Bragg wavelength Δλ/λ is linear, which will permit the correlation of the deformation states which appear in the material. According to \( \lambda_\mu = 2n_\text{eff} \Delta \); the external factors, as elongation, compression and temperature will produce variations, and in consequence, the wavelength of the light reflected by the grating is \( \frac{\Delta \lambda}{\lambda} = C_\varepsilon \varepsilon + C_T T \) where \( C_\varepsilon \) and \( C_T \) are material constant determined from calibration procedure.

5. Conclusions

The use air-coupled US transducers allow the generation and reception of Lamb waves generated in GFRP plates if the incidence and reception angles exceed the first critical angle. Low frequency ultrasound using air-coupled US transducers in pitch-catch configuration can generate Lamb waves in GFRP composite structures. Using ultrasound methods we can determine entire elasticity matrix of GFRP composite structures. We can detect the delamination or desbonding presence. Somme
modification of matrix/presence of voids dramatically diminishes the mechanical properties of GFRP. As a design recommendation for wind turbine blades, we must suppose that: the existence of regions with excessive moisture/voids content with surface about 4.5cm$^2$ which reduce the elasticity modulus, the shear modulus and also the ultimate tensile stress; the existence of small delaminations/desbondings with surface about 200mm$^2$ that leads to diminishing of the elasticity modulus, the shear modulus and also the ultimate tensile stress.

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