A New Ultrasonic Immersion Technique for the Evaluation of Damage Induced Anisotropy in Composite Materials

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ABSTRACT

We present a theoretical and experimental approach for the characterization of the damage induced anisotropy superimposed to the constitutive anisotropy of fiber-reinforced composite materials.

The proposed theoretical model has been developed in the framework of the Continuum Damage Mechanics theory and allows for determining a tensorial damage measure based on the change of the elastic moduli of the composite material. Moreover, the model is general since it is applicable independently of the fibers reinforcement nature, of the presence of cracks, interlaminar voids and delamination, of the geometry of this cracks, and from of failure mechanisms of the composite materials.

We perform damage experiments by employing an innovative goniometric device designed and built at our laboratory (Laboratorio "M. Salvati"), and aimed at the mechanical characterization of materials. In particular, by rotating the sample into a water tank, we measure the ultrasonic "natural" velocities of the undamaged composite material along suitable propagation directions. This allow us for classifying the degree of symmetry of the material and for determining the elastic constants, also in highly anisotropic materials. Then we measure the ultrasonic velocities of the artificially damaged composite and we determine again the elastic moduli. The comparison between the elastic moduli of the damaged and the undamaged composite allows us for the characterization of the anisotropic tensorial damage measure.

Keywords: *Ultrasonic immersion test; Wave propagation; Damage Mechanics; Composite materials; Anisotropic Damage.*

INTRODUCTION

The ultrasonic tests are usually employed for a qualitative analysis of the damage in materials; for example, the ultrasonic C-Scan technique is widely used for the identification of defect in components starting from the measure of the amplitude of the ultrasonic waves. Recently, alternative test procedures for a quantitative evaluation of the damage in the materials are under research. To this aim, the possibility of using ultrasonic immersion testing procedures – usually employed for the mechanical characterization of anisotropic materials like composite materials [1-5] – has been explored. We recall that immersion ultrasonic techniques with the use of goniometric devices allows for the determination of all the elastic constants characterizing the mechanical response of an anisotropic material starting from the

measurement of the velocity of ultrasonic waves along suitable directions of propagation [6-9]. The possibility of studying the propagation of ultrasonic waves along any direction into the material also allows to relate the damage to the anisotropy of the response of the material (damage-induced anisotropy); to this aim, the variation of the ultrasonic velocities and the acoustic axes [5] must be measured. In the case of the composite materials, the evaluation of the damage-induced anisotropy, superimposed to the constitutive anisotropy of the undamaged material, is very difficult and requires the development of suitable test procedures and the employment of appropriate theoretical models for the interpretation of the experimental results. In [1-4] and [10-11], a damage model developed within the CDM theory (Continuum Damage Mechanics) is proposed; in this model, the determination of the damage is directly related to some quantities measured in ultrasonic immersion test through an anisotropic tensorial damage parameter. In particular, the damage is measured starting from the variation of the elastic constants of an anisotropic material, directly related to the change of the velocity of ultrasonic waves in suitable directions.

In this paper, we show a new approach for evaluation of the damage in composite materials based on the use of an innovative goniometric ultrasonic immersion device designed and built at our laboratory (Laboratorio "M. Salvati"). In particular, we first determine the ultrasonic "natural" velocities of an undamaged glass fiber–reinforced composite material (GFRP), and the related elastic constants; the hypothesis on the initial anisotropy of the material is justified by the arrangement of the reinforcements in the matrix. Then, we performed an impact test for artificially damaging the GFRP composite material, and finally we measured the ultrasonic velocities of the damaged GFRP and we determined the new values of the elastic constants. The experimental data are employed in the damage model for the determination of an anisotropic tensorial damage parameter. By this parameter we characterize the anisotropic damage into the composite material independently of the evaluation of the presence of cracks, interface fibre-matrix debonding phenomena, fiber fractures, interlaminar voids and independently of the fibers reinforcement nature.

THEORITICAL MODEL: WAAVE PROPAGATION IN ELASTIC MATERIALS

The propagation of ultrasonic waves involved in ultrasonic tests are usually modeled within the theory of linear elastodynamics, i.e., by assuming that ultrasonic waves are small superimposed elastic deformations of the body. Then, the propagation of plane progressive elastic waves may be described by assuming a displacement field of the form

$$\mathbf{u}(\mathbf{x},t) = \mathbf{a}\,\varphi(\mathbf{x}\cdot\mathbf{n} - v\,t), \qquad (1)$$

where $\mathbf{a}$ is the direction of motion, $\mathbf{n}$ is the direction of wave propagation, v is the velocity of propagation and φ is a real valued smooth function. The plane wave is longitudinal if $\mathbf{a}$ and $\mathbf{n}$ are linearly dependent, while is transverse if $\mathbf{a}$ and $\mathbf{n}$ are perpendicular. These waves are called "pure" waves. In absence of body forces, the wave propagation is governed by the displacement equation of the elastodynamics

$$\mathrm{Div}(\mathbb{C}[\nabla\mathbf{u}]) = \rho\ddot{\mathbf{u}} \qquad (2)$$

where $\rho = \rho(\mathbf{x})$ is the mass density, $\mathbb{C} = \mathbb{C}(\mathbf{x})$ is the incremental fourth order elasticity tensor referred to the initial state of the body. A necessary and sufficient condition for the propagation of elastic waves (2) is the classical Fresnel-Hadamard propagation condition [7]; here we prefer to write this condition in the form of the Christoffel equation

$$\left[\boldsymbol{\Gamma}(\mathbf{n}) - \rho v^2\mathbf{I}\right]\mathbf{a} = \mathbf{o} \qquad (3)$$

where $\Gamma(\mathbf{n})$ is the second order Christoffel tensor for the direction $\mathbf{n}$, defined by

$$\Gamma(\mathbf{n}) = \square^{\,t}[\mathbf{n} \otimes \mathbf{n}]. \tag{4}$$

In (4) the subscript "t" denotes the minor transposition of a fourth order tensors.

The Christoffel tensor $\Gamma(\mathbf{n})$ is related only the elasticity tensor $\square$ and direction of propagation $\mathbf{n}$. Indeed, equation (3) shows that the square of the wave velocity v is an eigenvalue of the Christoffel tensor for the given direction of propagation $\mathbf{n}$, while the direction of motion $\mathbf{a}$ is the related eigenvector. It is clear that the symmetries of the material response determine the acoustic properties of the material; moreover, by (3) the elastic constants, i.e., the components of $\square$, are linked to the velocity of wave propagation along certain directions [7]. If the material symmetry is known, it is possible to ultrasonically determine the elastic constants by measuring the velocity of bulk waves propagating along suitable directions, whose choice depends on the symmetry class of the material [10], [16], [18].

In our experiments, we studied the acoustic behavior of a glass fiber–reinforced composite material (GFRP) used for the construction of innovative wind turbine blades. This composite material is made of 4 unidirectional fiber-reinforced layers, and can be modeled as transversely isotropic linearly elastic, with the transverse isotropy axis coincident with the axis of the fibers, and called in what follows x_3-axis (see Figure 1).
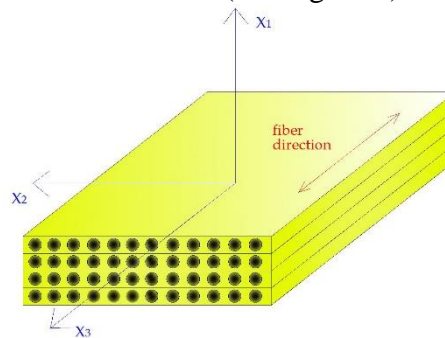

Figure 1 Unidirectional glass – fiber reinforced composite (GFRP)

In a reference system having an axis coincident with x_3-axis, the elasticity tensor $\square$ have the following representation in Voigt notation

$$\square = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}, \tag{5}$$

where $C_{12} = C_{11} - 2C_{66}$.

The mechanical response of the GFRP composite material is then characterized by five independent elastic constants C_{11}, C_{13}, C_{33}, C_{44} and C_{66}.

Once determined the mass density ρ of the material, the velocity data recorded in the ultrasonic goniometric test allow us to determine the above five elastic constants of the GFRP composite material by the inversion of the Christoffel equation [7].

1. A damage model for composite materials

We refer to a damage model suggested by Baste and Audion in 1991 [10], and developed in the framework of the CDM theory (Continuum Damage Mechanics theory) [12], [13]. This model has a general validity independently of the fibers reinforcement nature of the composite materials and of the geometry, type and distribution of cracks. Here, the following damage parameters represented by the stiffness constants reduction

$$D_{ii} = 1 - \frac{\tilde{C}_{ii}}{C_{ii}}, \ i = 1, 2, ..., 6 \ \text{(diagonal terms)} \tag{6}$$

$$D_{ij} = \frac{C_{ij} - \tilde{C}_{ij}}{C_{ii} + sign\left(C_{ij} - \tilde{C}_{ij}\right)\sqrt{C_{ii}\left(1 - D_{ii}\right)C_{jj}\left(1 - D_{jj}\right)}}, \ i, j = 1, 2, ..., 6, \ i \neq j \tag{7}$$

(off- diagonal terms).   (7)

are employed. The proposed damage model has a phenomenological character, since the tensorial damage parameters (6)-(7) are directly related to quantities measured in ultrasonic immersion test [1-4], i.e., to the phase velocities of ultrasonic waves.

ULTRASONIC IMMERSION SETUP

We have designed and built at Laboratorio "M. Salvati" (Politecnico di Bari) an innovative ultrasonic device for immersion test, specifically designed for the mechanical characterization of anisotropic materials. This device allows for measuring the velocity of ultrasonic waves for any angle of incidence of an ultrasound beam on the sample surface thanks to a goniometric system. In this way, it is possible to determine the velocity of any kind of polarized ultrasonic ("pure waves" and "not pure" waves) waves propagating in the material according to the Snell's law, for any direction of propagation,   in a symmetric plane and in a non-principal plane. This enables for determining all of the elastic constants of a material starting from the measurements of ultrasonic velocities, even for strongly anisotropic materials; to this aim, a so-called "inverse problem" [7] has to be solved. The innovative ultrasonic goniometric device allows to experimentally approach two fundamental problems in the mechanical characterization of the materials: the "classification problem" and the "representation problem" [5], [7]. The first problem consists in the determination of the degree of anisotropy of the material and in the identification of the axes of material symmetry (the so-called "acoustic axes"). The second problem concerns the identification of the elastic moduli by ultrasonic velocity measurements, once known the axis of material symmetry.

The device consists in: an immersion water tank, a frame housing ultrasonic immersion transducers and/or a reflective surface in Plexiglas, and a rotating sample slot operated by a stepper motor (Figure 2). This stepper motor is able to rotate the sample material at very small angular steps (0,036°), and allows for varying the angle of incidence of the ultrasound beam on the sample surface. The device can be configured for two different experimental set-up: through-transmission tests, whit two opposite ultrasonic probes (transmitter and receiver), and back-reflection tests. The rotation of the sample slot is managed by suitable drivers which allows for an accurate control of the rotation angle. In particular, in the reported experimental study we performed back-reflection ultrasonic immersion tests.
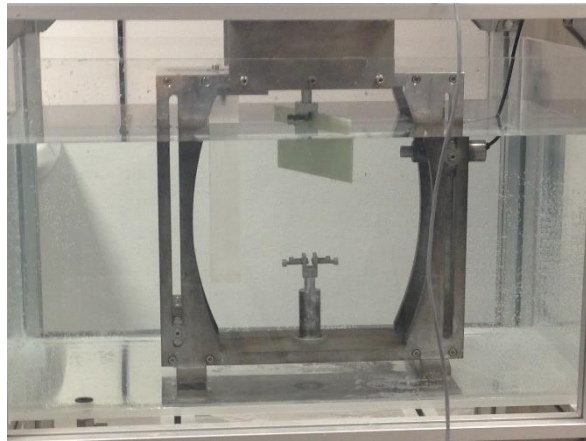
Figure 2 Ultrasonic immersion device

In the experiments below described the ultrasonic signals are generated and received by an unfocused ultrasonic probe with a central frequency of 2,5 MHz. The ultrasonic signals are handled by using an ultrasonic pulser/receiver Olympus 5072PR and an oscilloscope Agilent DSO6014A (100 MHz, 4 channels). A key feature of the experimental setup is a LabVIEW software ad hoc designed, which automatically manages each phase of the experiment, and incorporate various suitable functions for analyzing and processing the ultrasound signals, and, finally, for extracting the required data on the velocity for the mechanical characterization of the material. For each rotation angle of the sample, the managing software measures the time of flight Δt of ultrasonic waves for each possible direction of propagation of the ultrasound beam into the sample by the difference between the time of flight t_2 from the pulser to the receiver with the sample placed in the slot and the time of flight t_1 of ultrasonic waves in the water (without the sample). To this aim, some important signal processing operations were performed through the LabVIEW software for defining the origin of the time scale (auto-correlated reference signal) and for minimizing the noise of the signals (normalized signals). The time of flight (TOF) of the ultrasonic waves into the sample, for each angle of incidence of the ultrasonic beam, is then evaluated by a cross-correlation between the auto-correlated reference signal and the average of the normalized signals acquired for the prescribed angle of incidence. Finally, for the back- reflection technique, the phase velocity v_p of ultrasonic waves travelling into the sample is evaluated as follows [6-7]:

$$v_p = \left[\left(\frac{\Delta t}{2e} \right)^2 - \frac{\Delta t/d}{v_w} \cos\theta + \left(\frac{1}{v_w} \right)^2 \right]^{-1/2} \tag{8}$$

where, for a given angle of incidence θ of the ultrasonic beam, Δt is the time of flight (TOF); d is the thickness of the sample; v_w is the ultrasonic velocity in the water (about 1.473 m/s). At the end of each ultrasonic test, when the entire prearranged rotation angle of the sample has been ultimate, the LabVIEW software displays a graph which shows the measured ultrasonic phase velocity v_p (m/s) versus the angle of incidence of the ultrasound beam θ (deg).

MECHANICAL CHARACTERIZATION OF UNDAMAGED COMPOSITE MATERIALS

We show the results obtained in the ultrasonic immersion test on a GFRP parallelepiped sample before the impact test.

We performed the test by arranging the sample in two different modes: in the first mode, the sample was placed with the axis of rotation parallel to the fiber axis (x_3-axis), so that the

ultrasonic waves propagate in the plane π_{12}. The second mode was obtained by placing the sample in the slot with the axis of rotation orthogonal to the axis of the fibers, and coincident with the x_2-axis; in this case, the propagation of the ultrasonic waves takes place in the plane π_{13}, (a plane containing the fibers).

The GFRP sample was subjected to an overall rotation sufficiently large (about 30°) to obtain the mode conversions needed, according the Snell's law, for generating each kind of ultrasonic polarized waves, whose velocities have to be measured.

Figure 3 shows the graph phase velocity-incident angle obtained as the result of the first mode of test. According to the Snell's law, ultrasonic pure longitudinal (PL) waves propagate into the sample until the first critical angle is reached (approximately 10,37°). In this plane, the velocity of pure longitudinal waves do not depend on the angle of incidence θ. Since this is a typical behaviour of isotropic materials, the plane π_{12} is denominated "isotropic plane". After the first critical angle, we observe first quasi shear waves (QS) and then pure shear waves (PS) propagating into the sample.

Figure 4 shows the graph phase velocity-incident angle obtained as the result of the second mode of test. In this case, we notice the propagation of ultrasonic quasi longitudinal (QL) waves into the sample until the the first critical angle is reached (approximately 12,78°). The velocity of quasi longitudinal waves depends on the angle of incidence θ: then, the plane π_{13} is denominated "anisotropic plane". After the first critical angle, we observe two different quasi shear waves (QS1 and QS2).

Once measured the density of the material (2.055 kg/m^3), we determine by the inversion of the Christoffel equation (3) the elastic constants of the undamaged composite material, collected in Table 1.
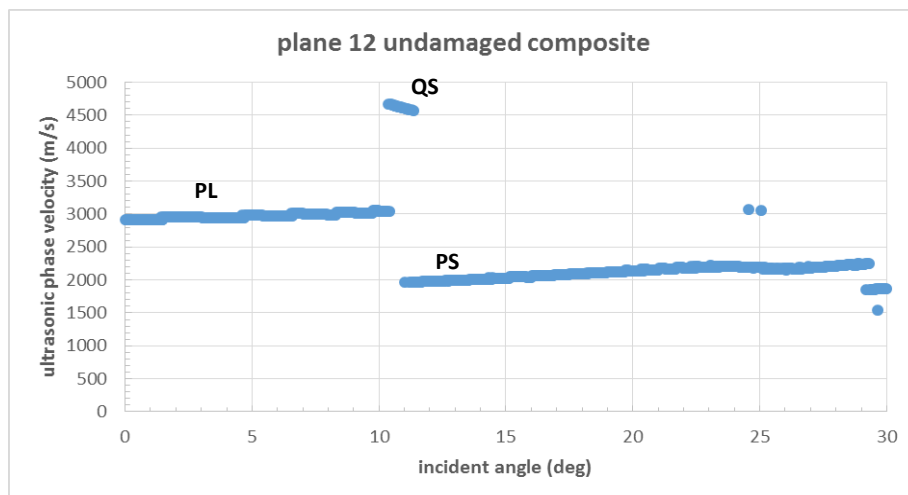

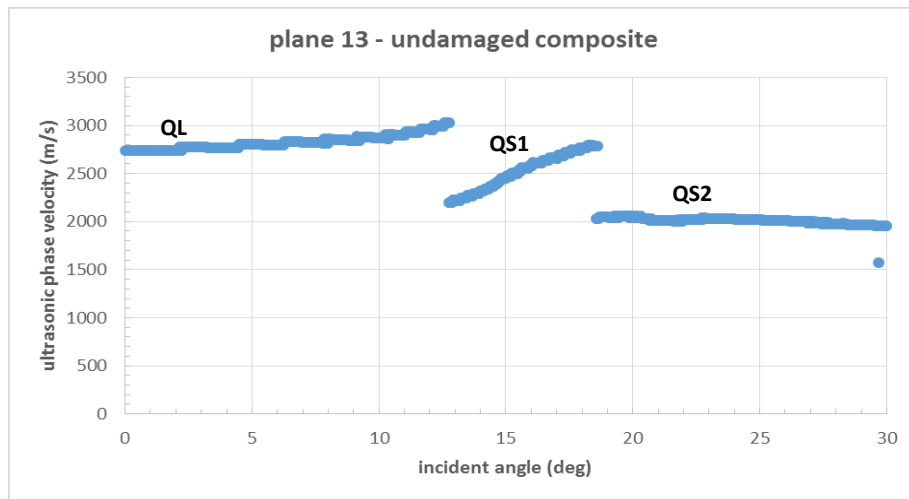Figure 3 Ultrasonic phase velocity-incident angle (plane 12, undamaged composite)

Figure 4 Ultrasonic phase velocity-incident angle (plane 13, undamaged composite)

Table 11 Elastic constants of undamaged composite material (GPa)

C_{11}	C_{33}	C_{44}	C_{66}	C_{13}	C_{12}
15,81	29,03	4,77	4,72	1,00	6,37

In Figure 5 we present the slowness surface of the undamaged GFRP composite, i.e. the polar plot that representing the inverse of the phase velocity (slowness) of each kind of ultrasonic waves as a function of the angle of propagation. The slowness surfaces obtained by the experimental data correspond to the theoretical slowness surfaces of a transversely isotropic material. This confirms the initial constitutive hypothesis on the anisotropy degree, used for the mechanical characterization of the GFRP composite material.
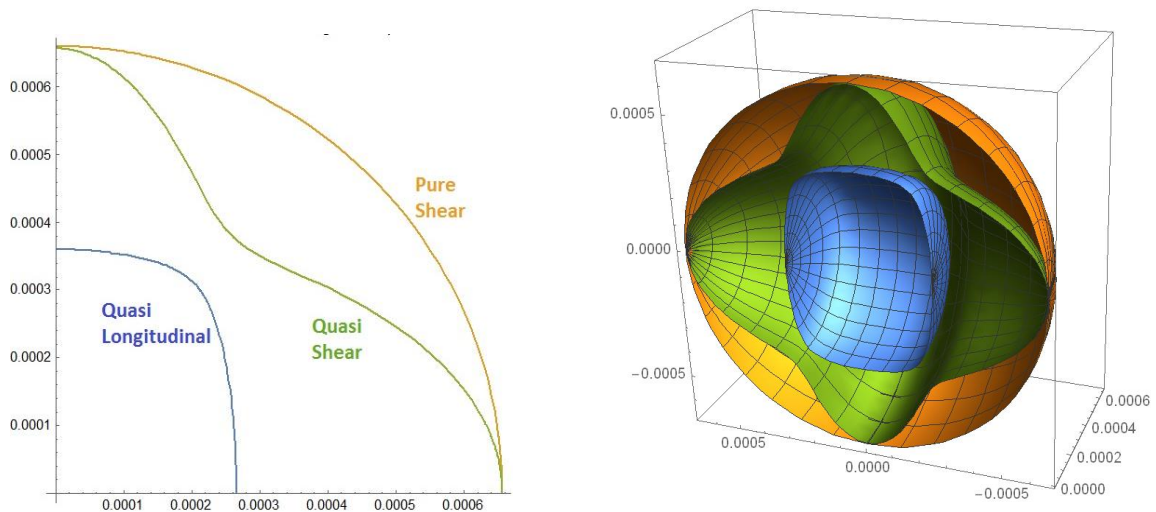

Figure 5 A plane representation (left) and a tridimensional representation (right) of the slowness surface of undamaged GFRP composite material

8. the evaluation of damage induceD anisotropy

We show ultrasonic experimental results for GFRP samples damaged by an impact test. In particular, we have first applied an impulsive load of 140 kN (acting in the direction x_1, see Figure 1), and then we have repeated the ultrasonic immersion goniometric tests arranging the damaged sample in the same two different modes described in Section 7.

In Figure 6 we show the graph phase velocity-incident angle for the first testing mode of the damaged composite. Now, ultrasonic pure longitudinal (PL) waves propagate into the sample until a first critical angle is reached (approximately 8,37°). Similarly to what observed for the undamaged composite (see Fig. 4), the velocity of pure longitudinal waves not depend on the angle of incidence. After the first critical angle, quasi shear waves (QS) and, then, pure shear waves (PS) propagate into the sample. For the damaged material, we observe a reduction of the values of the phase velocities of ultrasonic waves (Tab. 2).
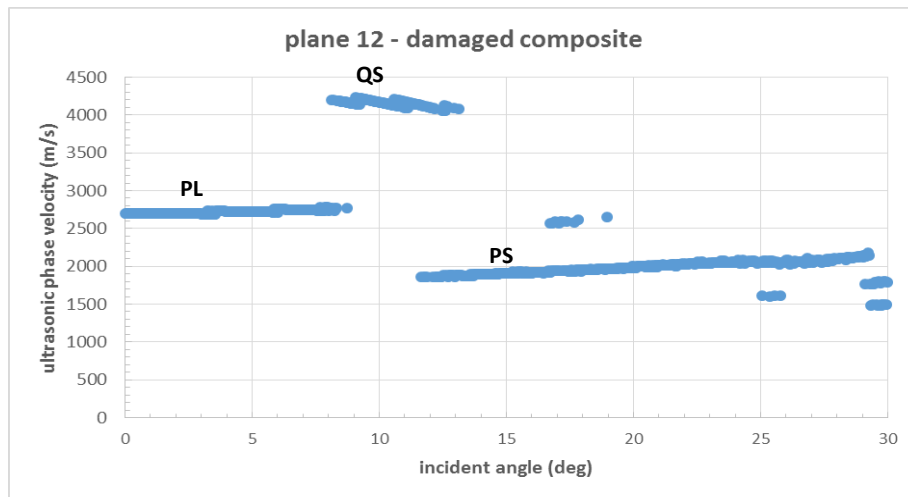

Figure 6 Ultrasonic phase velocity-incident angle (plane 12, damaged composite)

Table 2 Velocities of ultrasonic waves (m/s) for undamaged and damaged composite

	Undamaged composite	Damaged composite
Pure longitudinal waves (PL)	2910,79	2698,51
Quasi shear wave (QS)	4673,05	4201,02
Pure shear waves (PS)	1960,9	1863,79

In Figure 7 we show the graph phase velocity-incident angle obtained as the result of the second mode of test. Ultrasonic quasi longitudinal (QL) waves propagate into the sample until the first critical angle is reached (approximately 6,948°). After the first critical angle, a first kind of quasi shear waves QS1 is observed. Then, the analysis of experimental data in the plane 13 becomes more difficult. We think that the impact test has caused damage in the matrix-fibers interface, and this induces oscillations in the velocities of QS2 quasi shear waves.

Finally we determine the elastic constants of the damaged composite material by the inversion of the Christoffel equation (3). These constants are collected in Table 3.

In Figure 8 we show the slowness surfaces of the damaged GFRP composite. The artificial damage of the composite as the result of the impact test has slightly modified the slowness surface. In particular, now we observe an intersection between the surface related to quasi shear waves and the surface related to pure shear waves, differently to what happens for the slowness surfaces of the undamaged composite (see Figure 5). The representation of the experimental results through slowness surfaces allows to assess the damage induced anisotropy superimposed to the constitutive anisotropy of the examined GFRP composite material.

By applying the theoretical damage model of Section 3, we determine the components D_{ij} of the damage tensor. In the case under investigation, only three components are significantly different from zero: the component in the direction of the impact load $D_{11} = 0.053764$, and the components $D_{44} = -0.035639$ and $D_{66} = -0.061441$.
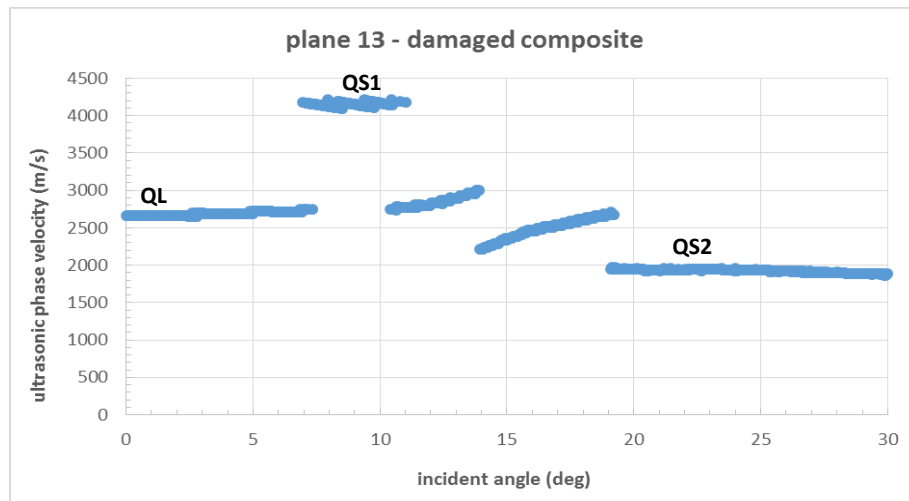
Figure 7 Ultrasonic phase velocity-incident angle (plane 13, damaged composite)

Table 3 Elastic constants of damaged composite material (GPa)

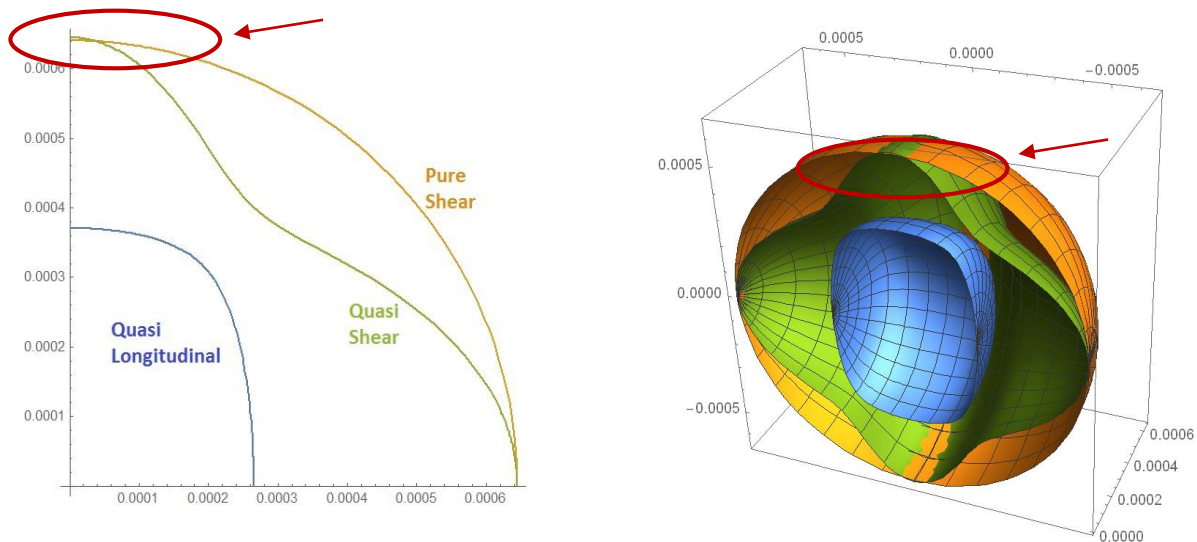| C_{11}	C_{33}	C_{44}	C_{66}	C_{13}	C_{12}
14,96	29,13	4,94	5,01	2,01	4,94

Figure 8 A plane representation (left) and a tridimensional representation (right) of the slowness surface of damaged GFRP composite material

CONCLUSIONS

We propose a new experimental and theoretical approach to study the damage induced anisotropy superimposed to the constitutive anisotropy of an GFRP composite materials. The experimental results obtained by an innovative immersion ultrasonic device are employed for quantifying the damage induced by an impact test as the change of the elastic constants. This change can be also used for characterize the damage by applying a model developed in the framework of the CDM theory.

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