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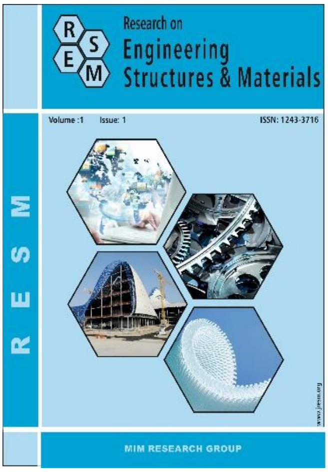

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Research Article

Evaluation of damage anisotropy induced in GFRP composite materials by an innovative ultrasonic experimental approach

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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 theoretical model here employed 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 using 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 allows 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 above cited anisotropic tensorial damage measure.

1. Introduction

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. Here, the possibility of using ultrasonic immersion testing procedures – usually employed for the mechanical characterization of anisotropic materials like composite materials [1-5] – for a quantitative characterization of the damage has been explored. We recall that the use of goniometric devices in ultrasonic immersion tests allows for the determination of all the elastic constants needed for the description of the mechanical response of an anisotropic material; to this aim, velocity measurements of ultrasonic waves propagating along suitable directions are needed [6-10]. The possibility of studying the propagation of ultrasonic waves along any direction into the material also allows to relate the damage to the degree of anisotropy of the response of the material (damage-induced anisotropy). In particular, the anisotropy induced by the damage is related to the variation of the ultrasonic velocities and of the acoustic axes [5]. For composite materials, the evaluation of the damage-induced

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anisotropy, which is 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 [11-12], a damage model for composite materials, developed within the CDM theory (Continuum Damage Mechanics), is proposed; in this model, the damage is directly related through an anisotropic tensorial damage parameter to some quantities which can be directly measured in an ultrasonic immersion test. Indeed, the damage is evaluated starting from the variation of the elastic constants, directly related to the change of the velocity of ultrasonic waves in suitable directions.

In this paper, we show a new experimental 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 above cited damage model for the determination of the parameters of the anisotropic tensorial damage measure. By the latter we characterize the anisotropic damage into the composite independently of the detection of the presence of cracks, interface fiber-matrix debonding phenomena, fiber fractures, interlaminar voids and independently of the fibers reinforcement nature.

The applicative field of the proposed Non-Destructive technique is the quantitative evaluation of the damage in wind turbine blades made of fiber-reinforced composites. Indeed, the increasing use of wind energy creates the need of reliable Non-Destructive Tests (NDT) techniques for assessing the integrity of the structures and for avoiding (catastrophic) failures. The blades are one of the most damageable components of a wind turbine, and several causes of damage may arise both before starting the turbine and during its service life. Before starting the turbine, damage due to incomplete permeation of resin in manufacturing process, to adhesive missing in bonding process, to impacts during transportation and installation is possible. During the service life, the most common causes of damage are: sudden wind gusts, foreign objects impacts, heavy hail-stones impacts, natural disaster such as lightening, typhoons, etc..

The experimental approach here proposed is suitable for laboratory testing, where goniometric immersion tests are performed by the immersion of the specimen in a water tank and by rotating the specimen and/or the probes. Anyway, once defined the procedure and the methodology for interpreting the results, it is possible to incorporate these techniques in devices for in-situ ultrasonic scanning of wind turbine blades during their service life. These devices may consist of a robot for the movement of the probes along the span of the blade, and of a squirter system, which allows the sound to be transmitted through a water column. The availability of an effective NDT technique for quantitatively assessing the damage may allow for the design of longer and lighter blades that would provide higher performance with less conservative margins of safety.

2. Theoretical Model: Wave 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

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

where **a** is the direction of motion, **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 **a** and **n** are linearly dependent, while is transverse if **a** and **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

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

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 [13]; here we prefer to write this condition in the form of the Christoffel equation

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

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

$$\boldsymbol{\Gamma}(\mathbf{n}) = \mathbb{C}^{\mathrm{t}}\left[\mathbf{n} \otimes \mathbf{n}\right]. \tag{4}$$

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

The Christoffel tensor $\boldsymbol{\Gamma}(\mathbf{n})$ is related only the elasticity tensor $\mathbb{C}$ and direction of propagation **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 **n**, while the direction of motion **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 $\mathbb{C}$, are linked to the velocity of wave propagation along certain directions [13]. 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 [13].

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 layers of DISTITRON® Unsaturated Polyester ortho-phthalic DCPD resin reinforced by glass fibers, 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 Fig. 1). The dimensions of the parallelepiped sample are 200 x 100 x 3,4 mm.

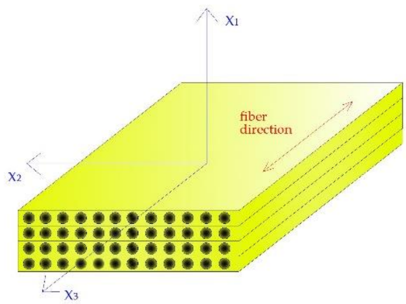

Fig. 1 Unidirectional glass – fiber reinforced composite (GFRP)

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

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

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].

3. A Damage Model for Composite Materials

For quantitatively characterizing the damage, we refer to a damage model suggested by Baste and Audoin in 1991 [11], and developed in the framework of the CDM theory (Continuum Damage Mechanics theory) [14-16]. 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

$$\mathrm{D}_{ii} = 1 - \frac{\tilde{\mathrm{C}}_{ii}}{\mathrm{C}_{ii}},\ i = 1,2,...,6 \tag{6}$$

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

are employed. The above 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.

4. 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" [7], [13]. 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.

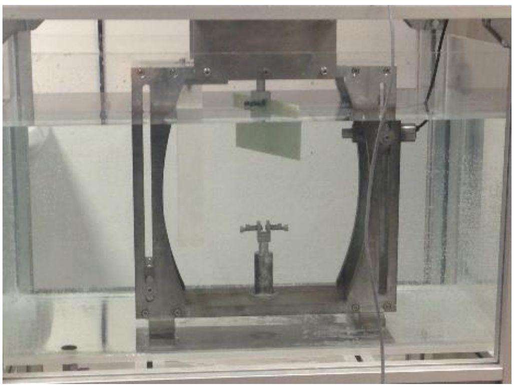

Fig. 2 Ultrasonic immersion device

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 (Fig. 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.

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]:

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

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).

5. 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 behavior of isotropic materials, the plane π_{12} is denominated "isotropic plane". After the first critical angle, we observe after some spurious echoes the propagation of pure shear waves (PS) 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 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. To this aim, since from the measured velocity data we get a redundant system of non-linear equations in the unknown elastic constants, an optimization procedure has been applied in order to minimizing the errors [7].

Table 1 Elastic constants of undamaged composite material (GPa)

C_{11}	C_{33}	C_{44}	C_{66}	C_{13}	C_{12}
17,41	29,93	7,85	7,90	1,45	1,61

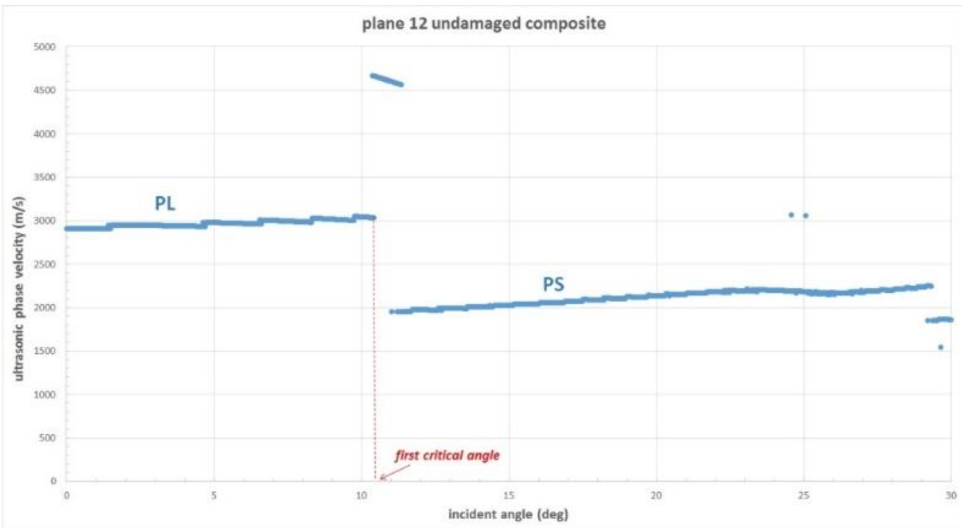

Fig. 3 Ultrasonic phase velocity-incident angle (plane π_{12}, undamaged composite)

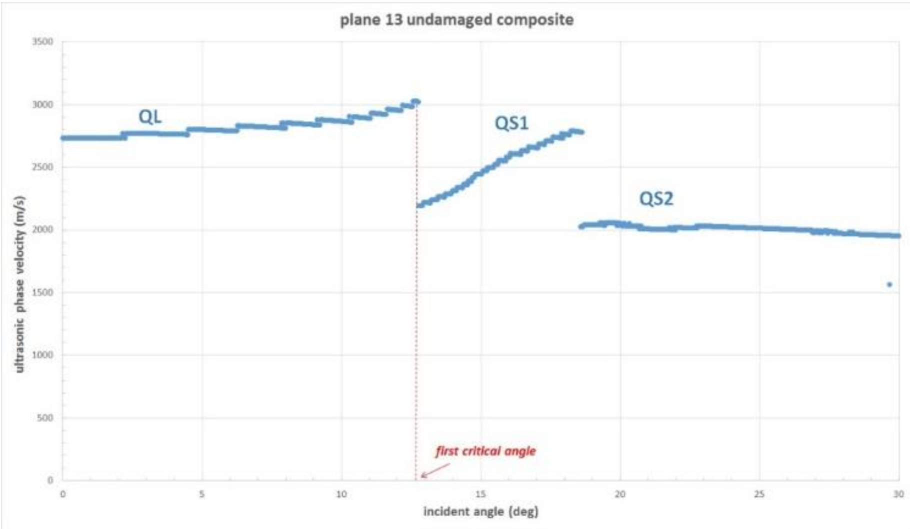

Fig. 4 Ultrasonic phase velocity-incident angle (plane π_{13}, undamaged composite)

In Figure 5 we present the theoretical reconstruction of the slowness surfaces of the undamaged GFRP composite, i.e. the polar plot 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 quite well to the theoretical slowness surfaces of a transversely isotropic material: this confirms the initial constitutive hypothesis on the anisotropy degree.

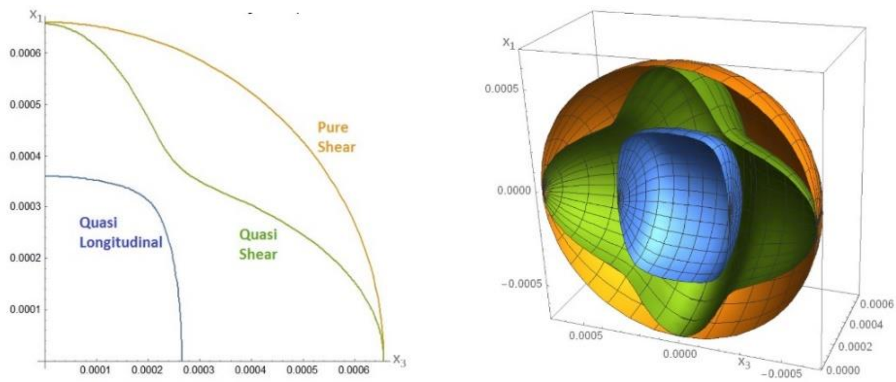

Fig. 5 A plane representation (left) and a tridimensional representation (right) of the slowness surface of undamaged GFRP composite material

6. Ultrasonic 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 Fig. 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, we see again some spurious echoes (now, the recorded signals are less "clean" than in the undamaged case) 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 (see, Tab. 2 where the velocity of pure longitudinal waves propagating at θ =0° and of the first observed pure shear waves are reported).

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

	Undamaged composite	Damaged composite
Pure longitudinal waves (PL)	2911	2699
Pure shear waves (PS)	1961	1894

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 π_{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), in the same way described for the undamaged material. These constants are collected in Table 3.

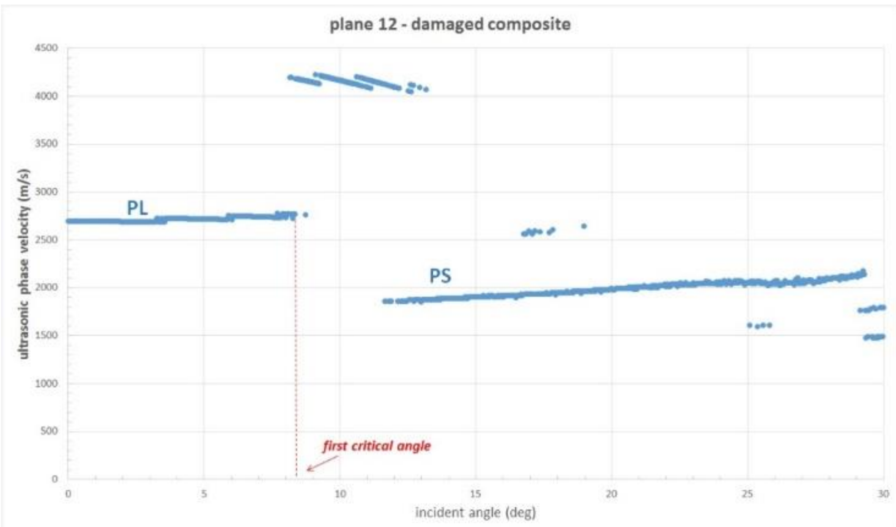

Fig. 6 Ultrasonic phase velocity-incident angle (plane π_{12}, damaged composite)

In Figure 8 we show the slowness surfaces of the damaged GFRP composite. The artificial damage of the composite, due to a low velocity impact, results in a slight but evident modification of the slowness surfaces. In particular, besides the small variations in the shape of the curves, we have an increment of the anisotropy in the direction x_1 (direction of the impact). Indeed, before the impact the velocities of the two shear waves propagating in the direction x_1 were almost the same, and consequently the Quasi Shear slowness surface and the Pure Shear slowness surface were almost tangent in correspondence of the intersection with the x_1 axis. After the damage, the two shear waves propagating in the direction x_1 acquire different velocities, and then the two slowness surfaces intersecting in correspondence of the x_1 axis (see also Fig. 5). This intersection has been clearly highlighted in Fig. 8. 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.

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	7,37	2,01	0,22

By applying the theoretical damage model of Section 3, we determine the components D_{ij} of the damage tensor starting from the ultrasonically determined elastic constants for the undamaged and for the damage composite, respectively. The values of the components of the damage tensor are collected in Tab. 4. We clearly see that in the case under investigation the components of **D** significantly different from zero are those which involve the response in the direction x_1 of the impact load. Indeed, the highest components of **D** are D_{44}=0,3707, related to the shear response in the plane π_{12} and D_{11}=0,1407, related to the extensional behavior in the direction x_1. Remarkable also the value assumed by D_{12} (D_{12}=0,0839), related to the coupling between the extensional behavior in the directions x_1 and x_2, and the value assumed by D_{66} (D_{66}=0,0671), related to the shear response in the plane π_{13}.

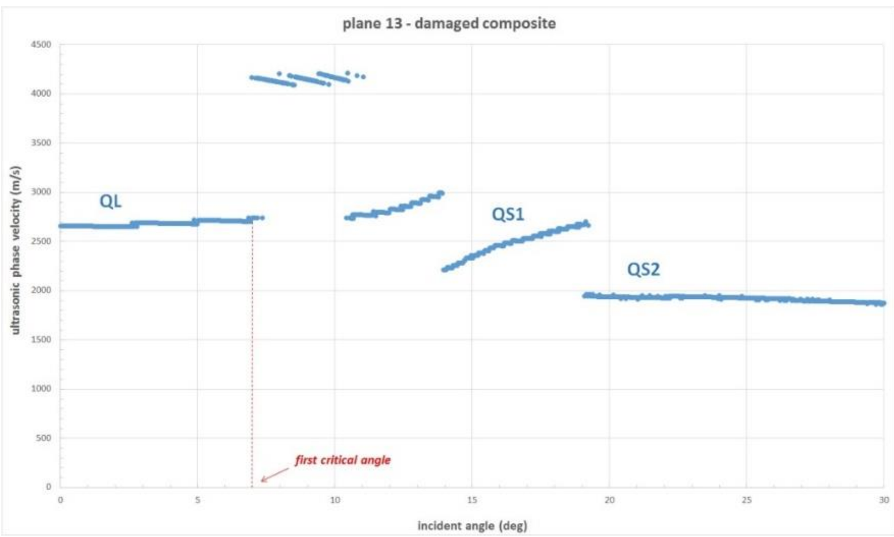

Fig. 7 Ultrasonic phase velocity-incident angle (plane π_{13}, damaged composite)

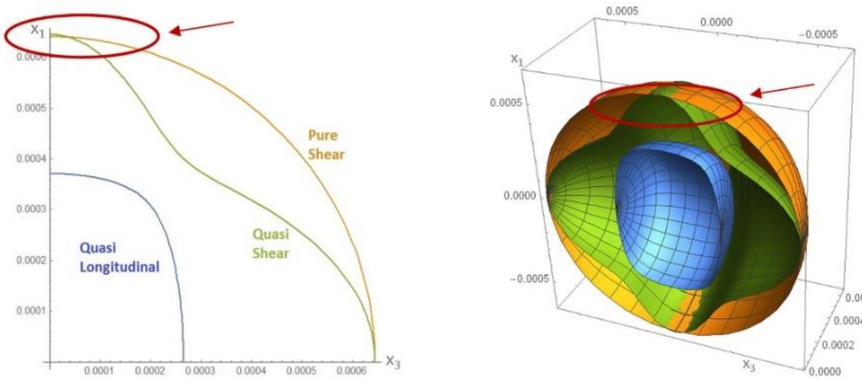

Fig. 8 A plane representation (left) and a tridimensional representation (right) of the slowness surface of damaged GFRP composite material

Table 4 Components of the tensorial damage measure **D**

D_{11}=D_{22}	D_{33}	D_{12}	D_{13}=D_{23}	D_{44}=D_{55}	D_{66}
0,1407	0,0267	0,0839	0,0288	0,3707	0,0671

7. Conclusions

Ultrasonic test may be very effective for quantitative non-destructive evaluations of materials, since the properties of the propagation of ultrasonic waves are directly and strictly related to the mechanical properties of the material. In this vein, here we propose a new experimental approach for studying the damage in composites contextualized in a suitable theoretical framework. In particular, we ultrasonically characterized the damage by analyzing the damage induced anisotropy superimposed to the constitutive anisotropy of an GFRP composite materials.

The proposed experimental approach is based on the use of an innovative immersion ultrasonic goniometric device, capable of characterizing the propagation of ultrasonic waves along different directions into the sample. A crucial aspect for the accuracy of the measurements is represented by the analysis and the processing procedures of the acquired ultrasound signals.

The obtained experimental results are employed for determining the damage induced by an impact test, related both to the change of the elastic constants and to the variation of the anisotropic features of the mechanical response of the damaged material. This variation can be usefully represented by using slowness curves and slowness surfaces, i.e., polar plots of the inverse of the velocity in function of the angle of the propagation direction. Indeed, slowness curves and slowness surfaces are very revealing about the features of the anisotropy degree of the material, and the variation of the anisotropy due to the damage is clearly identifiable by studying the variation of the slowness curves and the slowness surfaces.

Finally, for quantitatively characterizing the damage, we employ a model developed in the framework of the Continuum Damage Mechanics theory. This model is based on a tensorial damage measure, whose components are related to the relative changes of the elastic moduli caused by the damage. We see that in the case under investigation the components significantly different from zero are related to the response in the direction of the impact load: this confirms the effectiveness of the proposed approach.

References

[1] Baste S., Audoin, B. Ultrasonic evaluation of stiffness tensor changes and associated anisotropic damage in a ceramics matrix composite. Journal of Applied Mechanics, 1994; 61: 309-16. https://doi.org/10.1115/1.2901446

[2] Baste S., Aristegui C. Induced anisotropy and crack systems orientations of a ceramic matrix composite under off-principal axis loading. Mechanics of Materials, 1998; 29: 19-41. https://doi.org/10.1016/S0167-6636(98)00003-9

[3] Margueres Ph., Meraghni F., Benzeggagh M.L. Comparison of stiffness measurements and damage investigation techniques for a fatigued and post-impact fatigued GFRP composite obtained by RTM process. Composites Part A: Applied Science & Manufacturing, 2000; 31: 151-163. https://doi.org/10.1016/S1359-835X(99)00061-5

[4] Margueres Ph., Meraghni F. Damage induced anisotropy and stiffness reduction evalution in composite materials using ultrasonic wave transmission. Composites Part A: Applied Science & Manufacturing, 2013; 45: 134-144. https://doi.org/10.1016/j.compositesa.2012.09.007

[5] Castellano A., Foti P., Fraddosio A., Galietti U., Marzano S., Piccioni M.D. Characterization of material damage by ultrasonic immersion test. Procedia Engineering, 2015; 109: 395-402. https://doi.org/10.1016/j.proeng.2015.06.248

[6] Balasubramaniam K., Whitney S.C. ultrasonic through - transmission characterization of thick fibre-reinforced composites. NDT & E International, 1996; 29: 225-236. https://doi.org/10.1016/S0963-8695(96)00014-X

[7] Castellano A., Foti P., Fraddosio A., Marzano S. Piccioni M.D. mechanical characterization of CFRP composites by ultrasonic immersion tests: experimental and numerical approaches. Composites Part B: Engineering, 2014; 66: 299-310. https://doi.org/10.1016/j.compositesb.2014.04.024

[8] Castellano A., Foti P., Fraddosio A., Marzano S. Piccioni M.D. mechanical characterization of apricena marble by ultrasonic immersion tests. Key Engineering Materials, 2014; 628: 109-116. https://doi.org/10.4028/www.scientific.net/KEM.628.109

[9] Castellano A., Foti P., Fraddosio A., Marzano S., Piccioni M.D. Ultrasonic immersion tests for mechanical characterization of multilayered anisotropic materials. EESMS 2014, 2014 IEEE Workshop in Environmental, Energy and Structural Monitoring Systems Proceedings, Naples, Italy, September 17-18, 2014, DOI: 10.1109/EESMS.2014.6923266. https://doi.org/10.1109/EESMS.2014.6923266

[10] Castellano A., Foti P., Fraddosio A., Marzano S., Paparella F., Piccioni M.D. Monitoring applied and residual stress in materials and structures by non-destructive acoustoelastic techniques. EESMS 2016, 2016 IEEE Workshop in Environmental, Energy and Structural Monitoring Systems Proceedings, Bari, Italy, June 13-14, 2016. https://doi.org/10.1109/EESMS.2016.7504830

[11] Baste S., Audoin B. On internal variables in anisotropic damage. European Journal of Mechanics, A/Solids, 1991; 10 (6): 587-606.

[12] Bohm K., Gude M., Hufenbach W. A phenomenologically based damage model for textile composites with crimped reinforcement. Composites Science and Technology, 2012; 70: 81–8. https://doi.org/10.1016/j.compscitech.2009.09.008
[13] Gurtin M. The Linear Theory of Elasticity. Encyclopedia of Physics. V S. Flügge Ed. Springer – Verlag, Berlin Heidelberg, 1973.
[14] Krajcinovic D. Continuum damage mechanics. Appl. Mech. Rev., 1984; 37: 1-6.
[15] Lemaitre J. A Course on Damage Mechanics. Springer – Verlag, New York, 1992. https://doi.org/10.1007/978-3-662-02761-5