The ultrasonic C-Scan technique for damage evaluation of GFRP composite materials

Anna Castellano, Pilade Foti, Aguinaldo Fraddosio, Salvatore Marzano, Mario Daniele Piccioni

***Abstract*—** We show experimental results obtained by an innovative non-destructive approach for the characterization of the damage of composite materials. The analysis regard an aeronautical rotor made of glass fiber–reinforced composite material, and is developed by applying an ultrasonic immersion C-Scan technique. The experimental data are employed in a damage model developed in the context of the Continuum Damage Mechanics theory. In this model, the evaluation of the damage level depends on a synthetic scalar damage parameter, connected to the quantities directly measured in an ultrasonic test, and related to the specific variation of the acoustical impedance. In particular, from the measurement of the ultrasonic velocity in the undamaged and damaged composite, respectively, we evaluated the damage parameter for an artificially damaged GFRP component.

***Keywords*—** Ultrasonic immersion C-Scan test, Damage, Wave propagation, Anisotropy, Fiber reinforced composite materials.

I. INTRODUCTION

Fiber reinforced composites are very advantageous innovative materials, nowadays used for many engineering applications [1-3]. In general, composite materials are characterized by a synergic union between at least two components, i.e., a strong and rigid fiber reinforcement (made for example of carbon, glass, Kevlar) and a bulk component, usually a resin. Thus, the mechanical response and the strength of the composite strongly depend on the mechanical properties and on the orientation of the fibers. Moreover, the material shows a markedly anisotropic response which somewhat complicates the experimental tests for the mechanical characterization, especially if conventional testing techniques are employed. Many difficulties can be overcome by adopting some non-destructive experimental approaches like, for example, the ultrasonic immersion techniques. In particular, this ultrasonic experimental approach allows for the determination of all the elastic constants characterizing the mechanical response of a composite material starting from the measurement of the velocity of ultrasonic waves along suitable directions of propagation [4-8]. These experimental techniques share a common ground with other non-destructive dynamical experimental approaches, used at the scale of the whole structure, which are capable of accurately characterizing the response of constructions made of highly anisotropic and damageable materials [6-8]. Non-destructive techniques play also an increasingly important role for the detection of defects and damage in composite materials, which may affect the integrity, and therefore the structural safety, of components often having a critical role in aero-spatial, aeronautical, mechanical and civil constructions.

Indeed, in the composite materials the fibers are generally very fragile, and the fracture of the fibers and/or of the resin matrix may involve a fragile and unexpected collapse of the component. This requires a quick and reliable diagnosis of the above phenomena, both during the manufacturing of the component and during its service life.

Typical defects of a composite material, capable of compromising the integrity and thus the safety of structural components may occur [12-13]:

- in manufacturing stage: interlaminar voids, porosity, foreign inclusions, fibers misorientation, resin rich areas, resin starved areas;
- in service life stage: delaminations, fibers fracture, matrix cracks.

The ultrasonic C-Scan technique is currently the main non-destructive method for the diagnosis of defects in composite materials. This technique is based on the analysis of the amplitude of ultrasonic waves; generally, a qualitative approach is adopted by simply identify the defects when a variation of the amplitude is measured. Recent researches attempt to gather quantitative information from ultrasonic C-Scan analysis; for example, in [14] the damage level in composites is related to the variation of the material density of specimens which have experimented different applied loads. Quantitative information on the damage of composite materials

This work has been supported by MIUR-PRIN 2010-2011: “Dinamica, stabilità e controllo di strutture flessibili” and MIUR PON-REC: “MASSIME – Sistemi di sicurezza meccatronici innovativi (cablati e wireless) per applicazioni ferroviarie, aerospaziali e robotiche” research projects.

Anna Castellano, Dipartimento di Meccanica, Matematica e Management, Politecnico di Bari, Bari, Italy (e-mail: anna.castellano@poliba.it).

Pilade Foti, Dipartimento di Scienze dell’Ingegneria Civile e dell’Architettura, Politecnico di Bari, Bari, Italy (phone: 0039-80-5963502; e-mail: pilade.foti@poliba.it).

Aguinaldo Fraddosio, Dipartimento di Scienze dell’Ingegneria Civile e dell’Architettura, Politecnico di Bari, Bari, Italy (phone:0039-80-5963738; e-mail: aguinaldo.fraddosio@poliba.it).

Salvatore Marzano, Dipartimento di Scienze dell’Ingegneria Civile e dell’Architettura, Politecnico di Bari, Bari, Italy (phone:0039-80-5963737; e-mail: salvatore.marzano@poliba.it).

Mario Daniele Piccioni, Dipartimento di Scienze dell’Ingegneria Civile e dell’Architettura, Politecnico di Bari, Bari, Italy (phone:0039-80-5963773; e-mail: md.piccioni@poliba.it).

can also be obtained by the application of another non-destructive technique like the thermographic test [15].
However, this promising applications are yet affected by some experimental difficulties; moreover, the interpretation of the experimental data for the analysis of the damage level and for the identification of defects is complicated because composites are anisotropic and inhomogeneous materials. Finally, a crucial issue of the experimental procedures is to perform suitable and complex processing operations of ultrasonic signals in order to reduce measurement errors.

In this paper, we present an experimental study on the characterization of the damage of glass fiber–reinforced composite materials. We apply an innovative non-destructive approach based on an ultrasonic immersion technique. A new damage model developed in the context of the Continuum Damage Mechanics theory directly connects the experimental data to a synthetic scalar damage parameter, related to the specific variation of the acoustical impedance.

In particular, in Section II we first introduce the damage model and show the relation between the damage parameters and the quantities experimentally evaluated in an ultrasonic C-scan immersion test. Then, in Section III we present the experimental setup, the mechanical characterization of the material (glass fiber–reinforced composite) by means of an ultrasonic goniometric immersion technique and finally the ultrasonic C-scan results representative of the state of the undamaged specimen. In Section IV we show the experimental procedure for generating an artificial damage in the specimen, which is an aeronautical rotor. This artificial damage is representative of a possible damage induced by the service life loads on the rotor. Finally, we employ the above cited damage model for the damage characterization of the rotor; to this aim, we employ ultrasonic C-scan velocity data obtained on the damaged specimen.

II. A innovative non-destructive experimental approach for the damage characterization of composite materials

A. The ultrasonic immersion C-Scan tests

In the ultrasonic immersion C-Scan technique a sample or a component is immersed in a tank filled with water. The water guarantees a uniform acoustic coupling for the ultrasonic waves, propagating from the probe into the material of the specimen. Whereas it is possible to use both the through-transmission and the pulse-echo methods, generally the latter is preferred. In the pulse-echo method, an ultrasonic immersion longitudinal probe, acting as transmitter and receiver, is attached to an automatic manipulator which allows for independently moving the probe along three axes (henceforth named X, Y, Z). In particular, for planar specimens, once fixed the distance Z between the probe and the sample to be analyzed (according to the focus length of the ultrasound probe), the manipulator moves the probe along a prearranged paths in the XY plane. For each step of the path an ultrasonic pulse is emitted towards the specimen, and then the reflections of this pulse are recorded in the time scale (A-Scan presentation). The time of flight (TOF) of the ultrasonic waves in the water without the sample is assumed as a reference measurement. Then, by a correlation between the ultrasonic signals measured without the sample and each ultrasonic signal measured throughout the sample, the velocity of ultrasonic longitudinal waves into the material is determined for each step of the scanning path. This way, it is possible to construct a map in a color or grayscale (C-Scan presentation) of the ultrasonic longitudinal velocity into the sample. Generally, if an (homogeneous) sample is free of defects or undamaged the ultrasonic velocity in different points is almost the same. Notice that if the accuracy of the ultrasonic scan is very high, it is possible to distinguish the ultrasonic time of flight in the resin matrix and in the layers containing the fibers. Moreover, if the sample is damaged or contains defects, a difference of the velocity of ultrasonic waves is detected and a variation of the amplitude and an attenuation of the signal may be determined by a frequency analysis of the acquired signals. Of course, starting from the above described measurements it is possible to perform a C-Scan representation of the peak amplitude of the signals.

B. A new damage model for composite materials

Usually, the damage models for composites correlate the damage level to the variation of suitable material parameters like, for example, the elastic constants. Here we propose an innovative damage model developed within the CDM theory (Continuum Damage Mechanics) [16-19], in which the determination of the damage is directly related to quantities measured in ultrasonic C-Scan test. In particular, in our model the damage parameter D is defined by:

$$\mathrm{D} := 1 - \frac{\tilde{\mathrm{Z}}\tilde{\mathrm{V}}}{\mathrm{Z}\mathrm{V}}, \tag{1}$$

where
- Z and V are the acoustic impedance and the velocity of ultrasonic waves in the composite material in absence of damage,
- $\tilde{\mathrm{Z}}$ and $\tilde{\mathrm{V}}$ are the acoustic impedance and the velocity of ultrasonic waves in the damaged composite material.

Since the acoustic impedance of a material is defined as the product of the density and the velocity of ultrasonic waves, (1) takes the form

$$\mathrm{D} := 1 - \frac{\tilde{\rho}\tilde{\mathrm{V}}^2}{\rho \mathrm{V}^2}, \tag{2}$$

where
- $\tilde{\rho}$ is the density for the undamaged composite material,
- ρ is the density for the damaged composite material.

If we assume that the density does not vary as a result of the damage, we can express the damage parameter D only as a function of the square of velocities of the ultrasonic waves:

$$D := 1 - \frac{\tilde{V}^2}{V^2}, \qquad (3)$$

In particular, D = 0 if the composite material is not damaged, while 0 < D < 1 if the composite material is damaged.

Notice that our choice of the damage parameter, directly linked to the measure of the ultrasonic velocity, allows overcoming some difficulties related to the application of damage models, which usually require the determination of the elastic constants, which is complex especially when the material is anisotropic [20-21], as in the case of the composites.

Notice that the acoustic impedance is related to the amount of transmitted and reflected energy when an ultrasonic beam reach orthogonally the interface between the water and the composite specimen.

III. The ultrasonic immersion test

We apply the proposed model for the characterization of the damage for a specimen of an aeronautical GFRP composite. To this aim, we perform two C-Scan tests on a restricted area of the specimen by measuring the TOF, and hence the velocity of ultrasonic waves: first, we analyze the undamaged specimen, and then we analyze the same specimen after artificially damaged by a mechanical test machine. The observed variation of the velocity of ultrasonic waves allows to determining for each point of the examined area the value of the damage parameter D in (3).

The experiments were carried out by Laboratorio Ufficiale Prove Materiali "M. Salvati", equipped with advanced facilities for non-destructive testing.

A. The aeronautical GFRP composite component

The analyzed sample is a component of an aeronautical rotor, and in particular is the support disk of 14 permanent magnets (NdFeB) of an electric generator operated by a gas turbine and aimed at supplying the power of the electric services on an aircraft (Fig.1).

This disk is made of a glass fiber–reinforced composite material (LFR4) having a family of unidirectional glass fiber sheets arranged in a cross-ply laminate (0°/90°). Consequently, it is reasonable to assume that the elastic response of the composite is orthotropic, and then characterized by 9 independent elastic constants. By applying a goniometric ultrasonic immersion test procedure like those described in [6], and once measured the density of the material (2.055 kg/m^3), we determine the "technical" elastic constants of the material, collected in Table 1. In this table, we assume a reference system with two axes in the plane of the fibers (x,y) and the other axis (z) along the thickness of the laminate.

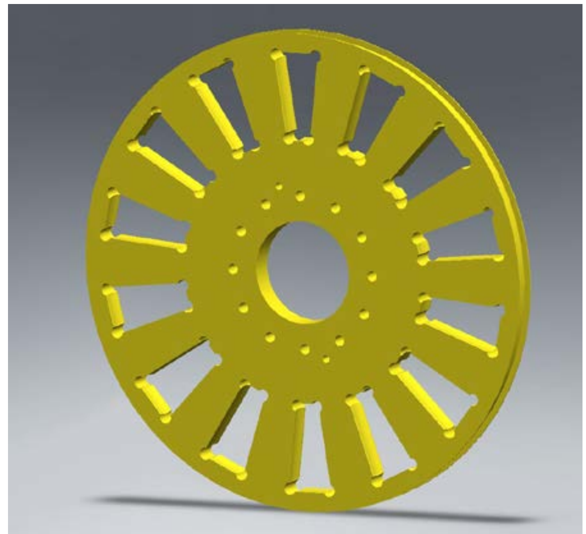

Fig. 1 The disk of the rotor made of GFRP composite material.

Elastic moduli evaluated by goniometric ultrasonic immersion tests		
Young modulus [MPa]	***Poisson's ratio***	***Shear modulus [MPa]***
E_x = 30.800	ν_{zy} = 0,11	G_{yz} = 13.873
E_y = 29.400	ν_{xz} = 0,13	G_{xz} = 13.008
E_z = 22.052	ν_{xy} = 0,13	G_{xy} = 12.998

Table 1. Elastic moduli of the GFRP composite material.

B. The ultrasonic immersion C-Scan test

The ultrasonic immersion C-Scan test was performed by using a 1 MHz longitudinal unfocused transducer, having the diameter of 12,7 mm. This probe was handled by a mechanical manipulator, capable for independently moving the probe along three directions (X, Y and Z) (Fig. 2). For generating and receiving the ultrasonic waves, an Olympus ultrasonic pulser/receiver 5072PR was employed, and an oscilloscope Agilent DS06014A (100 MHz, 4 channels) was used for monitoring the ultrasonic signals. Each stage of the experiment was managed by suitable and expressly written software in LabVIEW. This software is aimed at the management of the manipulator, i.e., at the control of the movement of the probe according to a predetermined path. Moreover, this software is aimed at controlling the oscilloscope by a workstation and at acquiring the ultrasonic impulses for each step; finally, through this software it is possible to reprocessing the experimental data and to generating A-Scan, B-Scan and C-Scan presentations of the ultrasonic results.

The LabVIEW software incorporates various suitable functions for analyzing and processing the ultrasound signals, and for extracting the required velocity and the amplitude data for frequency analysis.

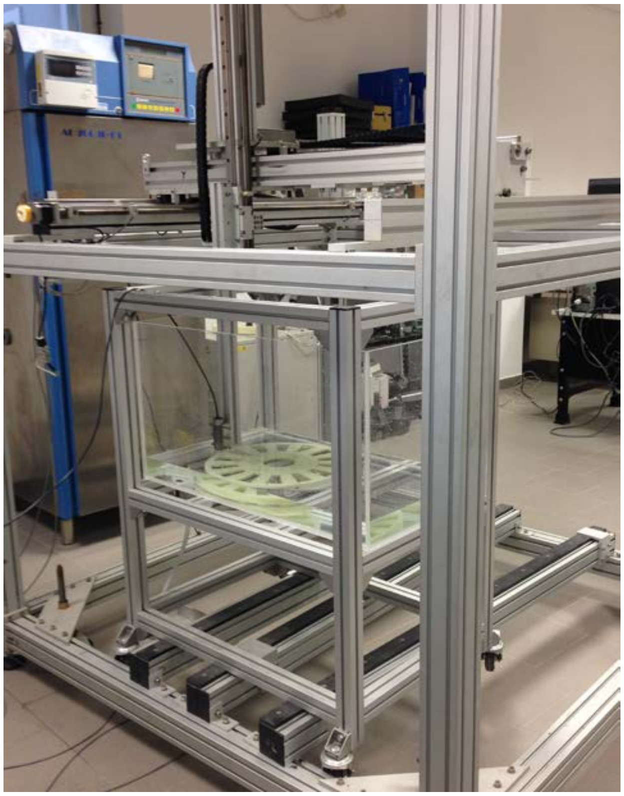

Fig. 2 The C-Scan setup: water tank and probe manipulator.

For the test, the GFRP composite disk was immersed in the water tank. We considered a scan area of 70 x 75 mm^2 with a 0,1 mm amplitude of the scanning step along both X and Y directions (Fig. 3).

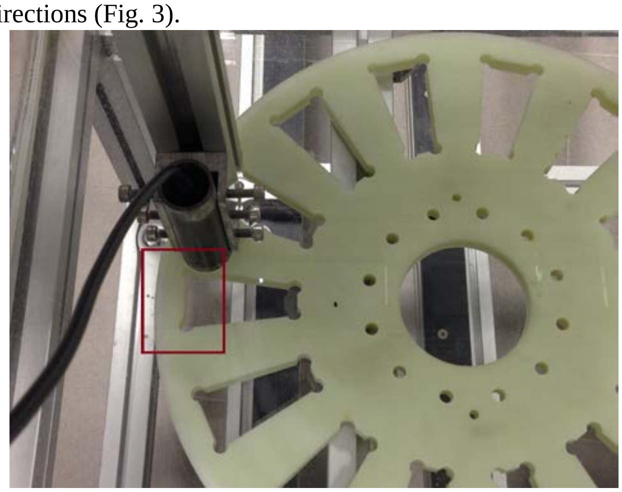

Fig. 3 The scan area for the GFRP composite sample.

C. The C-Scan test results

In Figure 4 we show a typical A-Scan presentation of the ultrasonic propagation in the water tank without the specimen. The first peak is the ultrasonic main bang pulse, and subsequent peaks represent the reflections of the ultrasonic waves on the surface of the Plexiglas water tank.

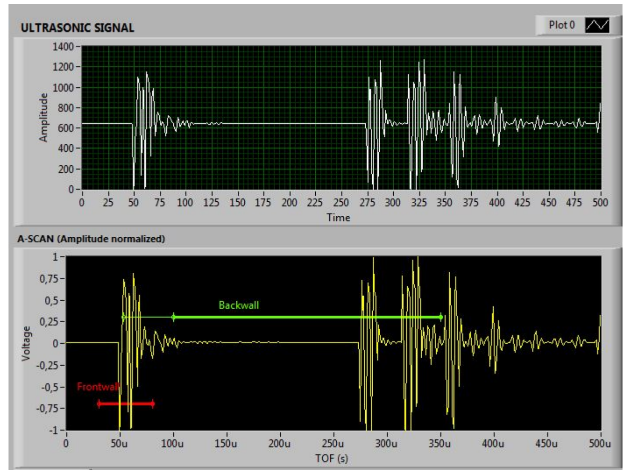

Fig. 4 A-Scan without the GFRP composite sample.

Figure 5 shows a typical A-Scan presentation of the ultrasonic signals in a generic instant during a C-Scan test of the undamaged composite specimen. Now subsequent peaks represent the reflections at the interfaces between the water and the sample.

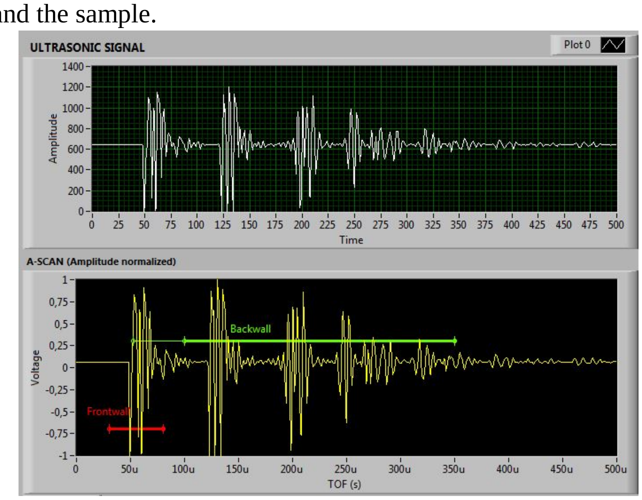

Fig. 5 A-Scan in the undamaged GFRP composite sample.

Starting from the waveform data collected for each point of the scan (A-Scan presentations) it is possible to identify variations of the ultrasonic amplitude and/or of the ultrasonic velocity, due to damage and defects. To this aim, it is possible to use suitable “gates”, named Frontwall gate (in red) and Backwall gate (in green) in Figures 4-5. Finally, the data has been represented in a C-scan presentation, where a false color scale indicates the variation of the ultrasonic longitudinal velocity (m/s) in the scanning area for the undamaged composite material specimen (Fig. 6).

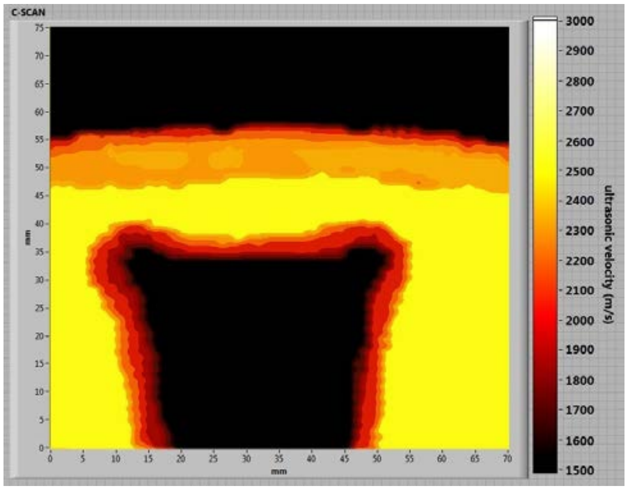

Fig. 6 C-Scan for the undamaged GFRP composite sample.

The range of the velocity of ultrasonic longitudinal waves measured in the undamaged GFRP composite specimen is 2700 ÷ 2800 m/s. Different values of ultrasonic velocity are recorded only in proximity of the edges of the housing of the magnet (1700 ÷ 2200 m/s) and of the outer edge of the rotor (2000 ÷ 2300 m/s). We expect that these differences arise from the manufacturing process of the examined component.

Beside the above mentioned points, the analysis of the experimental data do not show difference in the values of the velocities and the amplitudes of ultrasonic waves which may be symptoms of defects or damage already existing at this stage of the experiment.

IV. The Damage Characterization by Ultrasonic C-Scan

A. The artificial damaging of GFRP rotor

In order to study the effect of the damage in the GFRP component on the ultrasonic behavior of the material through C-Scan tests, we have artificially damaged the rotor by a mechanical test machine. In particular, in order to simulating the pressure exerted by the magnets on the rotor during the rotation of the disc (6000 rpm), due to the centrifugal force, we applied a tensile load along one of the rays of the rotor crossing the housing of a magnet.

We calibrate the value of the load by a preliminary analysis of a numerical FEM model of the mechanical test by using the Solid Mechanic module of the code COMSOL Multiphysics.

In particular, once generated an accurate geometric model of the rotor in the preprocessing phase, we assigned the mechanical properties of the orthotropic elastic material, according to the previously described measurements (see Table 1). We developed several numerical models, each of them characterized by different load conditions. The analysis of the obtained results suggested us to damage the specimen by applying a tensile force of 5.000 N, higher than the load exerted in service by the single magnet (about 1.800 N), but lower than the failure load of the GFRP component.

In the following, we present the results of the numerical analysis obtained for a tensile load of 5.000 N. In particular, Figures 7 show the distributions of the von Mises stresses, taken as a representative measure of the overall stress state.

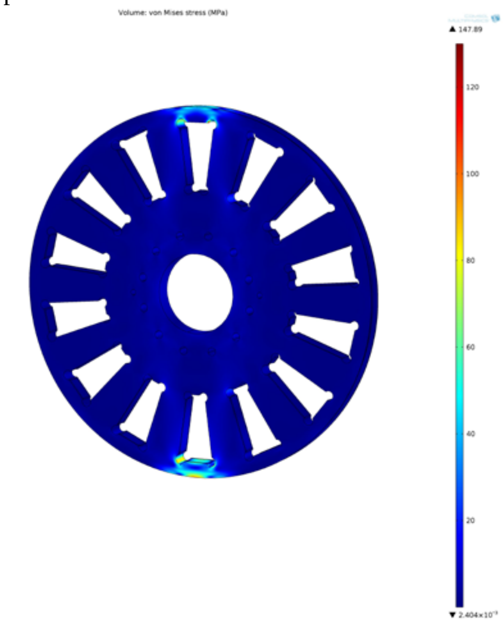

Fig. 7 Von Mises stress (MPa).

Notice that the maximum value of the von Mises stress is 148 MPa, and that this value is obtained in proximity of the inner edges of the magnet housing, in the area analyzed by the C-Scan ultrasonic test (Fig. 8).

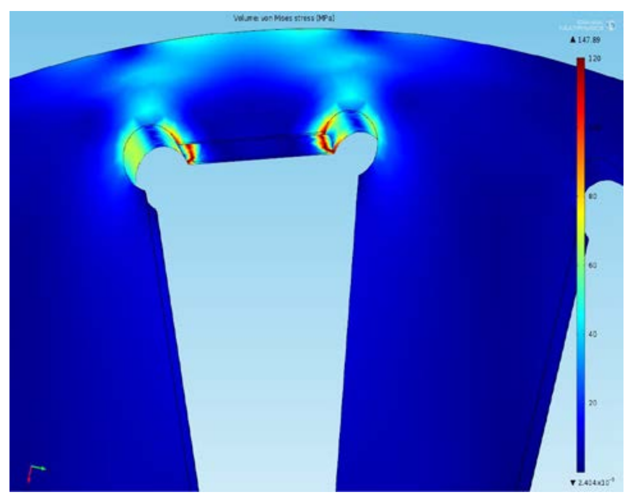

Fig. 8 Von Mises stress (MPa) in the C-Scan area of the composite.

Finally, Figure 9 shows the experimental setup employed for artificially damaging the specimen: the GFRP disk has been placed in an electromechanical Instron testing machine. The test has been performed until a tensile load of 5000 N has been reached.

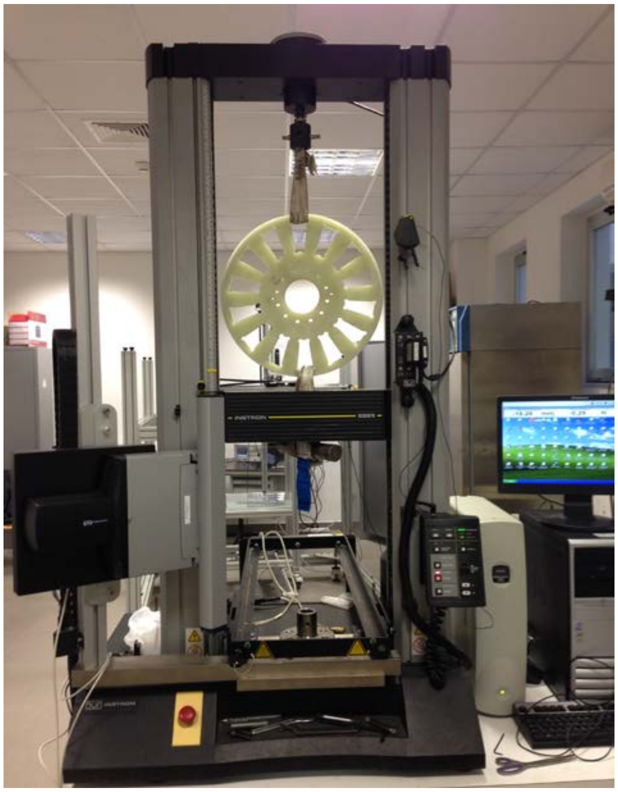

Fig. 9 Artificial damaging of the rotor

B. The ultrasonic evaluation of the damage

At the end of the artificial damage, the GFRP disk was removed from the testing machine and placed in a water tank in order to perform another ultrasonic C-Scan in the same area of the first scan, i.e., around the area where the tensile load was applied (near the housing of a magnet).

Figure 10 show the A-Scan presentation of the ultrasonic waves travelling through the damaged composite material; Figure 10 refers to the same point of the disk considered in Figures 5.

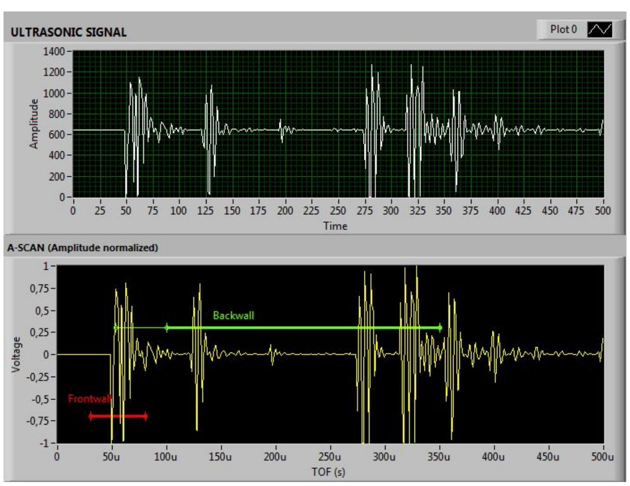

Fig. 10 A-Scan for the damaged GFRP composite sample.

Figure 11 shows the C-Scan presentation of the ultrasonic results for the damaged composite material. This image, when compared to Figure 7 (concerning the undamaged composite) clearly enlighten the state of damage of the composite through a striking diffuse variation of the ultrasonic longitudinal velocity in the material. This variation is relevant especially in proximity of the inner edge of the magnet housing and in the area between this edge and the outer edge of the disk. As explained above, these areas contain the points which have been subject to the largest values of the stress during the tensile test.

Indeed, in these areas much lower speed values (1.700 ÷ 2.300 m/s) have been recorded. Notice that a significant reduction of the ultrasonic velocity (1.900 ÷ 2.100 m/s), due to the presence of damage, has also been detected in other points, outside these areas.

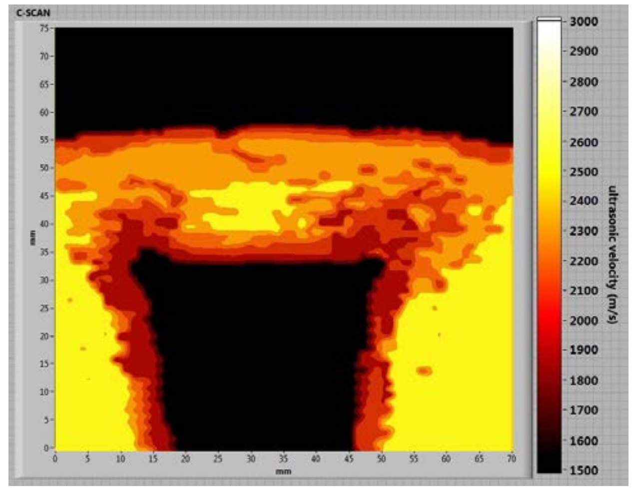

Fig. 11 C-Scan presentation for the damaged GFRP composite sample.

Starting from the velocity measurements, for each point of the scanned area we determined by (3) the damage parameter D, which ranges in the interval 0,23 ÷ 0,49. The lowest values of D (less damaged points) have been determined in the area between the edge of the magnet housing and the outer edge of the rotor, whereas the higher values of D (more damaged points) have been measured in the points near the edge of the magnet housing and near the outer edge of the rotor.

V. Conclusions

The ultrasonic immersion tests are an effective tool for the mechanical characterization of anisotropic materials such as composites [1-8] and for the analysis of the damage of construction materials [22]. Here, we show that by applying a damage model developed within the CDM theory and directly based on the results of an ultrasonic C-Scan, it was possible to characterize the damage in an artificially damaged GFRP aeronautical rotor. In particular, the new scalar damage parameter D here introduced, depending on the square of the ultrasonic wave velocity, may be an effective measure for an overall quantification of the damage and then for the estimation of the residual in-service life of the component.

The C-Scan presentation clearly shows the distribution of the damage – here induced by applying a tensile load to the specimen – and may also give useful suggestions for optimizing the design of the examined component.

REFERENCES

[1] A. Baratta, I. Corbi, O. Corbi, "Bounds on the Elastic Brittle solution in bodies reinforced with FRP/FRCM composite provisions", J. *Composites Part B: Engineering*, 2015, Vol. 68, pp. 230-236, doi: 10.1016/j.compositesb.2014.07.027.

[2] Baratta, A., Corbi, O. , "Closed-form solutions for FRP strengthening of masonry vaults", *J. Computers and Structures*, 2015, Vol. 147, pp. 244-249, doi:10.1016/j.compstruc.2014.09.007.

[3] Baratta, A., Corbi, O., "Heterogeneously Resistant Elastic-Brittle Solids under Multi-Axial Stress: Fundamental Postulates and Bounding Theorems", *J. Acta Mechanica*, 2015, Vol. 226(6),pp. 2077-2087 , doi: 10.1007/s00707-015-1299-1.

[4] K. Balasubramaniam, S. C. Whitney, "Ultrasonic Through - transmission Characterization of Thick Fibre-reinforced Composites", *NDT & E International*, Vol. 29, 1996, 225-236.

[5] A. Castellano, P. Foti, A. Fraddosio, S. Marzano e M.D. Piccioni, "Mechanical Characterization of CFRP Composites by Ultrasonic Immersion Tests: Experimental and Numerical Approaches", *Composites Part B: Engineering*, Vol. 66, 2014, pp. 299-310.

[6] A. Castellano, P. Foti, A. Fraddosio, S. Marzano e M.D. Piccioni, "Mechanical Characterization of Apricena Marble by Ultrasonic Immersion Tests", *Key Engineering Materials*, Vol. 628, 2014, pp. 109-116.

[7] A. Castellano, P. Foti, A. Fraddosio, S. Marzano e M.D. Piccioni, "Ultrasonic Immersion Tests for Mechanical Characterization of Multilayered Anisotropic Materials". In: *EESMS 2014, 2014 IEEE Workshop in Environmental, Energy and Structural Monitoring Systems Proceedings*, Naples, Italy, September 17-18, 2014, ISBN: 978-147994989-2, DOI: 10.1109/EESMS.2014.6923266.

[8] A. Castellano, P. Foti, A. Fraddosio, S. Marzano, M. D. Piccioni, "On the ultrasonic analysis of damage in GFRP composites", In: *Proceedings of the 11th International Conference on Applied and Theoretical Mechanics* (Mechanics '15 - Kuala Lumpur, Malaysia, April 23-25, 2015), vol. 45, pp. 32-39, ISBN: 978-1- 61804-304-7.

[9] M. Diaferio, D. Foti, N.I. Giannoccaro, S. Ivorra. "Optimal model through identified frequencies of a masonry building structure with wooden floors". *International Journal of Mechanics*, Vol.8, 2014, pp. 282-288.

[10] M. Diaferio, D. Foti, N.I. Giannoccaro, "Non-destructive characterization and identification of the modal parameters of an old masonry tower". In *EESMS 2014, 2014 IEEE Workshop in Environmental, Energy and Structural Monitoring Systems Proceedings*, Naples, Italy, September 17-18, 2014, ISBN: 978-147994989-2, DOI: 10.1109/EESMS.2014.6923266.

[11] M. Diaferio, D. Foti, C. Gentile, N.I. Giannoccaro and A. Saisi, "Dynamic testing of a historical slender building using accelerometers and radar", In: *6th International Operational Modal Analysis Conference*, IOMAC 2015; Abba HotelGijon; Spain; 12 May 2015 through 14 May 2015, Code 112375.

[12] A. Fahr, A. Y. Kandeil, "Ultrasonic C-Scan Inspection of Composites Materials", *Engineering Journal of Qatar University*, Vol. 5, 1992, pp. 201-222.

[13] R. Talreja, "Assessment of the Fundamentals of Failure Theories for Composite", *Composites Science and Technology*, Vol. 105, 2014, pp. 190-201.

[14] W. Harizi, S. Chaki, G. Bourse, M. Ourak, "Mechanical Damage Characterization of Glass Fiber – Reinforced Polymer Laminates by Ultrasonic Maps", *Composites Part B: Engineering*, Vol. 70, 2015, pp. 131–137.

[15] D. Palumbo, F. Ancona, U. Galietti, "Quantitative damage evaluation of composite materials with microwave thermographic technique: feasibility and new data analysis", *Meccanica*, Vol. 50/2, 2014, pp. 443- 459.

[16] D. Krajcinovic, "Continuum Damage Mechanics", *Appl. Mech. Rev.*, Vol. 37, 1984, pp. 1-6.

[17] L. M. Kachanov, "Introduction to continuum damage mechanics", Martinus Nijhoff, Dordrecht, The Netherlands, 1986.

[18] J. Lemaitre, "A course on damage mechanics", Springer – Verlag, New York, 1992.

[19] J. Lemaitre, J. Dufailly, "A damage measurements", *Engineering Fracture Mechanics*, Vol. 28/5-6, 1987, pp. 643-661.

[20] S. Baste, B. Audoin, "Ultrasonic Evaluation of Stiffness Tensor Changes and Associated Anisotropic Damage in a Ceramic Matrix Composite," *J. Appl. Mech.*, Vol. 61, 194, pp. 309-316.

[21] Ph. Margueres, F. Meraghni, "Damage induced anisotropy and stiffness reduction evalution in composite materials using ultrasonic wave transmission", *Composites Part A: Applied Science & Manufacturing*, Vol. 45, 2013, pp. 134-144.

[22] A. Castellano, P. Foti, A. Fraddosio, U. Galietti, S. Marzano e M.D. Piccioni, "Characterization of Material Damage by Ultrasonic Immersion Test", *Procedia Engineering*, Vol. 109, 2015, pp. 395-402.