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Nondestructive determination of local material properties of laminated composites with the impulse excitation technique / Boursier Niutta, C.; Tridello, A.; Belingardi, G.; Paolino, D. S.. - In: COMPOSITE STRUCTURES. - ISSN 0263-8223. - 262:(2021), pp. 1-10. [10.1016/j.compstruct.2021.113607]

Availability:

This version is available at: 11583/2875349 since: 2025-02-14T15:10:16Z

Publisher:

Elsevier

Published

DOI:10.1016/j.compstruct.2021.113607

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<http://dx.doi.org/10.1016/j.compstruct.2021.113607>

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Nondestructive determination of local material properties of laminated composites with the Impulse Excitation Technique

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Abstract

An innovative experimental methodology for the nondestructive assessment of local elastic properties of composite materials is proposed in this paper. A local region of rectangular shape is isolated on the investigated laminate with a proper clamping system. The first resonant frequency of the retained region with clamped boundaries is determined through the Impulse Excitation Technique. In order to take into account the anisotropy of the composite laminate, values of the resonant frequency are measured after rotating the clamping system with respect to the composite plate. The material constants are finally obtained from the measured frequencies through an inverse optimization algorithm based on Finite Element analysis.

The proposed methodology is validated on a unidirectional composite plate with known elastic properties. Boundaries of the investigated region are clamped by pressing two rectangular frames to the plate through a testing machine, thus localizing the measure of the resonant frequencies. The first resonant frequency is measured at different angles (0° , 30° , 60° and 90°) between fibers direction and main axis of the rectangular region. Dynamic elastic properties are finally assessed through the proposed inverse optimization algorithm. The small differences between the nominal and the estimated mechanical properties prove the effectiveness of the proposed methodology.

Keywords: Non-destructive testing, material properties determination, laminated composite, Impulse Excitation Technique (IET)

1. Introduction

Thanks to their optimal mechanical properties, especially if related to their limited weight, composite materials have replaced metals in many applications in the aerospace and automotive industries. However, their diffusion in the realm of structural components is severely limited by the complexity of their damage mechanism. The inherent non-homogeneous nature of composite materials results in several interacting failure modes of difficult prediction [1]. Further, before the complete failure occurs, composites show a stable and progressive increase of the damage level, especially if compared to metals [2, 3]. As the material progressively wears out, the uncertainty in the prediction of the mechanical behavior becomes critical. The variability of the mechanical response still raises doubts about their use in structural applications where high standard safety requirements are to be met.

The progressive damaging mechanism of composites thus enhances the importance of assessing the actual health state of a component [4]. In this regard, nondestructive methodologies are increasingly invoked and vibrational methods are among the most suitable techniques for quality control [5, 6]. The dynamic response of a plate, in terms of vibration modes and frequencies, is exploited to estimate the material elastic constants of composites. To be more precise, as vibrational methods consist in dynamic tests, the “dynamic” elastic properties are assessed [7]. The formulation of the inverse problem, which intends to compute the material constants from the experimental vibrational tests, is based on a modal analysis of a numerical model of the

component. Analytical formulas, semi-analytical methods, such as the Rayleigh-Ritz method, and finite element models are the most employed approaches, even in combination [8]. Four frequencies are usually sufficient to obtain a reasonable set of estimates for the four elastic parameters of a composite plate [9]. In order to increase the accuracy, a combination of modes and frequencies has been proposed by several authors [10, 11, 12].

Among the methodologies for the assessment of the dynamic elastic properties of materials, the Impulse Excitation Technique (IET) is widely employed and standardized for metals [13]. Recently, the IET has been successfully extended to orthotropic composites [14]. Song et al. [15] firstly implemented a combined numerical-experimental method to assess the elastic properties, i.e. the dynamic Young's moduli, the dynamic shear modulus and the Poisson's ratio, of a laminated composite plate. Paolino et al. [16] demonstrated the suitability of the IET for assessing the residual elastic properties of damaged composite laminates. Maciel et al. [17] adopted the IET to measure the progressive damaging of composite specimens in fatigue tests. However, these methodologies analyze the global vibrational response of the system, thus concealing local material variations and in situ anomalies [16]. Indeed, local defects can consistently affect the mechanical behavior of the component. As pointed out by Garnier et al. [18], current methodologies do not allow a local detection of material characteristic variations.

In the present paper a new experimental methodology which allows to assess the local elastic properties, i.e. the Young's moduli in longitudinal and transverse directions, the dynamic shear modulus and the Poisson's ratio, is proposed. In particular, a local region of the investigated composite laminate is isolated by compressing two rectangular metal frames on the plate. The first resonant frequency of the isolated region is thereafter assessed through the IET. In order to take into account the anisotropy of the composite laminate, values of the resonant frequencies are measured after having rotated the clamping frames at different angles with respect to the composite plate. The material constants are finally obtained from the measured first frequencies at different angles through an optimization algorithm based on modal Finite Element analysis of the plate.

The proposed methodology has been validated on a composite plate with unidirectional long fiber reinforcement with known nominal mechanical properties, proving its effectiveness in accounting for in situ material variations.

2. Materials and Methods

In this section, the investigated material is firstly detailed. The proposed experimental methodology is then described in detail. Finally, numerical calculations are presented: the optimization problem is formulated and the modal analysis performed on a finite element model of the plate is discussed.

2.1 Materials

Experimental tests are performed on a laminated composite plate. The composite laminate consists in seven layers of unidirectional carbon fiber reinforcement impregnated with epoxy resin. 300 gsm unidirectional reinforcement is used in each layer, while the epoxy matrix is specifically developed for good surface finishing. Unidirectional prepreg plies are stacked in parallel and vacuum bagged. The prepreg plate is finally cured in autoclave at 130°C for 90 minutes under the pressure of 6 bar. The resulting unidirectional composite plate is shown in Fig. 1. The stacking sequence is $[0]_7$.

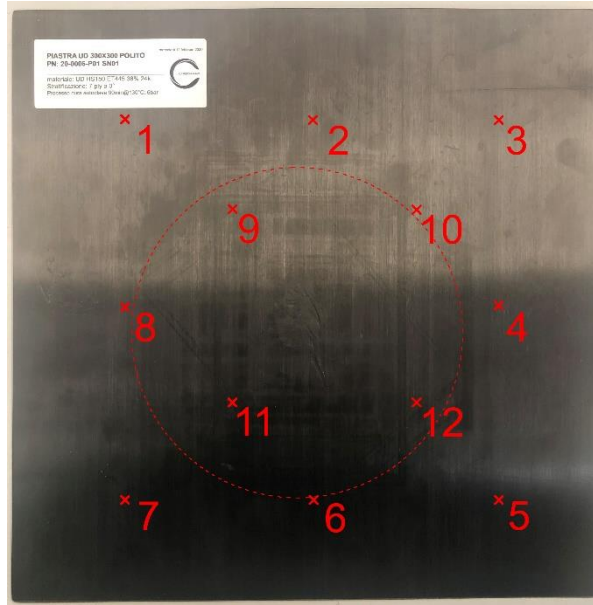


Figure 1: Unidirectional composite plate

The dimensions of the unidirectional plate are 300 mm x 300 mm. Regarding the thickness, as its value consistently affects the frequency response and in particular the value of the first fundamental frequency of a clamped plate, twelve measures at different locations on the plate have been considered. These locations are shown in Fig. 1. As reported in Table 1, the thickness varies from a minimum value of 0.94 mm to a maximum value of 1.13 mm.

In order to assess local elastic properties, the measurement of first fundamental frequency is localized through a clamping system, which will be described in detail in Section 2.2. In particular, investigations concerned the region shown in Fig. 1 through the dotted line. This includes points 6, 8, 9, 10, 11 and 12, whose average thickness of 1.08 mm has been considered in the numerical calculations.

Reference Point	Thickness [mm]
1	1.11
2	1.11
3	1.12
4	0.94
5	1.06
6	1.08
7	1.13
8	1.04
9	1.08
10	1.05
11	1.09
12	1.11

Table 1: Thickness variation (highlighted in red the maximum and minimum thicknesses in the plate)

The nominal material properties of the composite plate (Young's moduli, shear modulus and Poisson's ratio) have been provided by the supplier, according to the orthotropy axes. These values are reported in Table 2. The Poisson's ratio in the transverse direction ν_{21} , calculated from data reported in Table 2, results equal to 0.019.

Property	Value	Unit
Density	1.55	g/cm^3
Young's modulus in longitudinal direction E_{11}	131	GPa
Young's modulus in transverse direction E_{22}	7	GPa
Shear modulus G_{12}	3.93	GPa
Poisson's ratio ν_{12}	0.35	-

Table 2: Material Properties

The nominal material properties have been nondestructively verified by analyzing the free vibrational response of the plate. In particular, the IET has been adopted to test the freely-supported plate and results have been compared to a modal analysis of the plate with free boundaries. The mechanical vibrations have been measured through an accelerometer properly positioned. The first torsional mode, the first flexural mode in the longitudinal direction and the first flexural mode in the transverse direction have been retained and the corresponding fundamental frequencies are equal to 15 ± 2 Hz, 99 ± 2 Hz and 19 ± 2 Hz, respectively. The resulting frequency response functions are reported in Fig. 2.

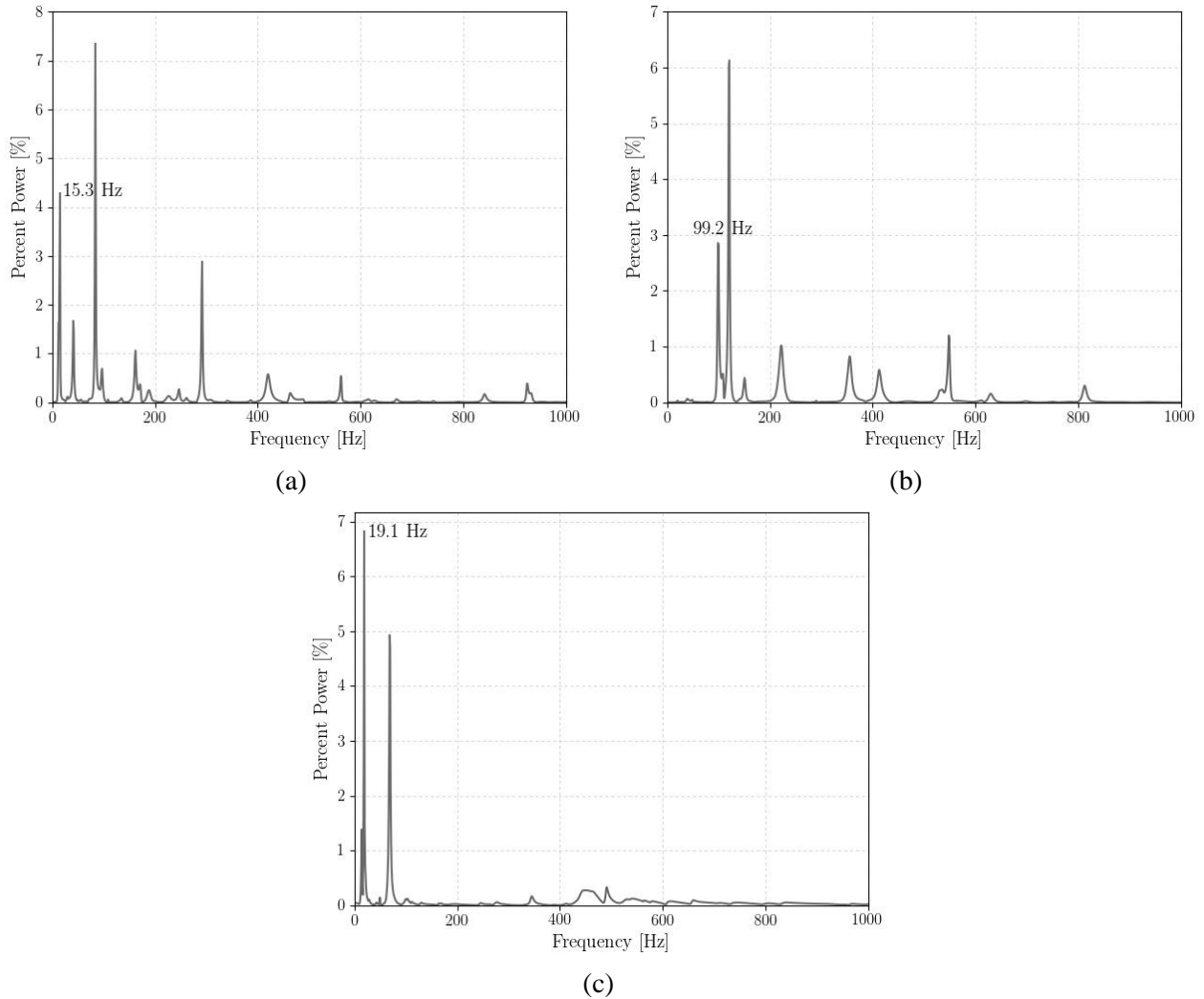


Figure 2: Frequency response functions: (a) torsional mode, (b) first flexural mode in longitudinal direction (c) first flexural mode in transverse direction

In order to verify the material properties provided by the supplier, the measured frequencies have been compared to the corresponding modes, obtained through the modal analysis. In particular, the modal analysis

has been performed on a finite element model of the plate with free boundaries, where the elastic constants provided by the supplier are considered. The resulting resonances are 16 Hz for the torsional mode, 98 Hz for the first flexural mode in the longitudinal direction and 20 Hz for the first flexural mode in the transverse direction, which are in good agreement with the free vibrational tests. The corresponding mode shapes are shown in Fig. 3.

The material properties provided by the supplier can be considered as the global material properties of the plate.

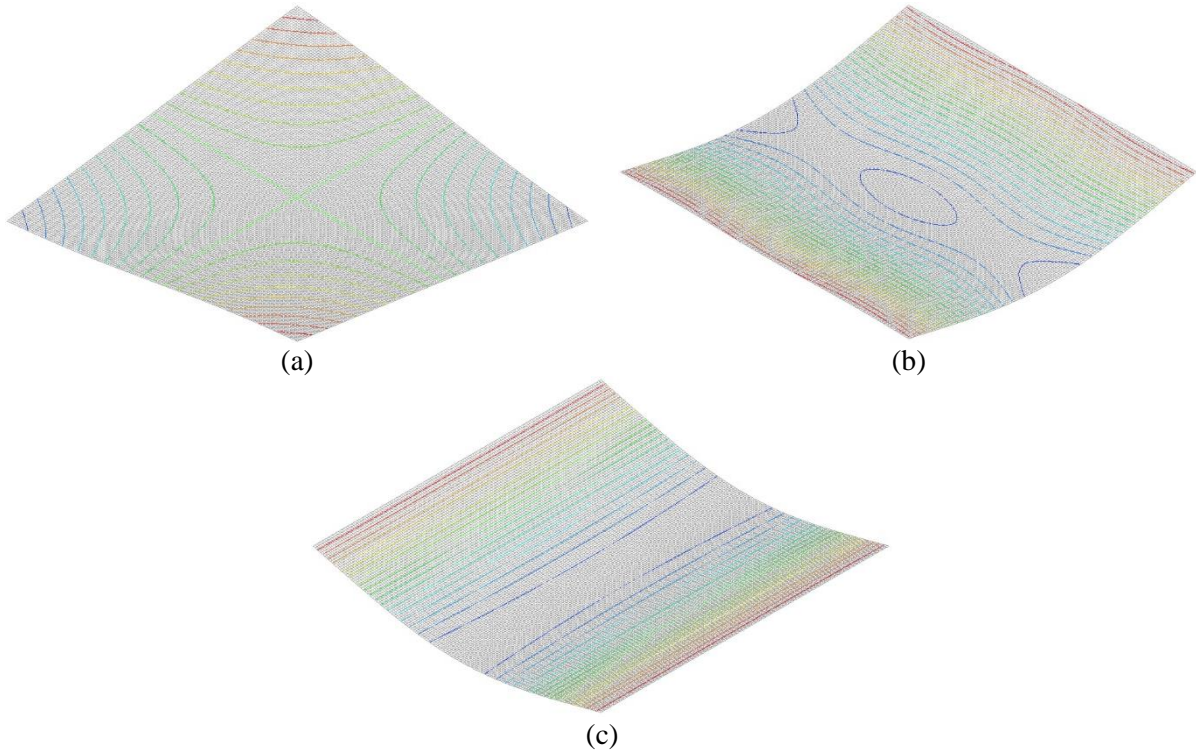


Figure 3: Free vibrational modes: (a) torsional mode, (b) first flexural mode in longitudinal direction (c) first flexural mode in transverse direction

2.2 Experimental Setup

The proposed methodology is based on the IET test and aims at assessing the local dynamic Young's modulus in the longitudinal direction E_{11} , the local dynamic Young's modulus in the transverse direction E_{22} , the local dynamic shear modulus G_{12} and the in-plane local Poisson's ratio ν_{12} . An impulser is used to excite the plate and the resulting mechanical vibrations are measured through an accelerometer, positioned at the center of the considered region, which provides the output signal for the z-axis, i.e. the axis perpendicular to the plate. The accelerometer is attached to the plate by means of beeswax and has a mass of 15 g. The signal is transferred to a data acquisition system (National Instruments NI USB-6210) and to an analyzer (Buzz-o-sonic®), which provides the fundamental resonant frequency. The data acquisition system has a sample rate of 25 kHz and the signal is analogic-to-digital converted with a resolution of 16 bits. The analyzer performs the Fast Fourier Transform of the signal with a resolution smaller than 1 Hz.

In order to determine the local material properties, the vibrational response must be mostly related to the retained region, with limited influence of the excluded surrounding material. This can be achieved by clamping the investigated region at its extremities. Clamped boundaries are usually made by means of frames screwed to the composite plate [19]. However, holes required by the screws cause irreversible damages to the plate. Here clamped boundaries are made by compressing, one against the other, two rectangular aluminum frames, symmetrically disposed above and below the plate, as shown in Fig. 4. A universal testing machine, Zwick Roell Z100, equipped with compression blocks, is used to compress the frames. The compression provided by the testing machine allows to clamp boundaries of the retained region, without damaging the composite plate.

In this study, a rectangular region of sides a equal to 140 mm and b equal to 90 mm has been considered, as shown in Fig. 4a. The average thickness in this region, evaluated from the datapoints 6, 8, 9, 10, 11 and 12 in Table 1, is equal to 1.08 mm. The maximum load of 1 kN is applied for clamping. This allows to recover clearances in the system while limiting in-plane stresses induced in the plate. Indeed, the applied load causes small deformations of the frames. Due to the friction, the deformations of the frames induces a spurious in-plane stress in the investigated region, which can significantly alter the measure of the resonant frequency. The proposed experimental equipment thus allows to localize the measure of the resonant frequencies. As the elastic unknowns are four, namely E_{11} , E_{22} , G_{12} and ν_{12} , at least four measures of the resonant frequency are required to extract a reasonable set of estimates. In order to obtain different measures of the resonant frequency, the anisotropy of composite materials is exploited.

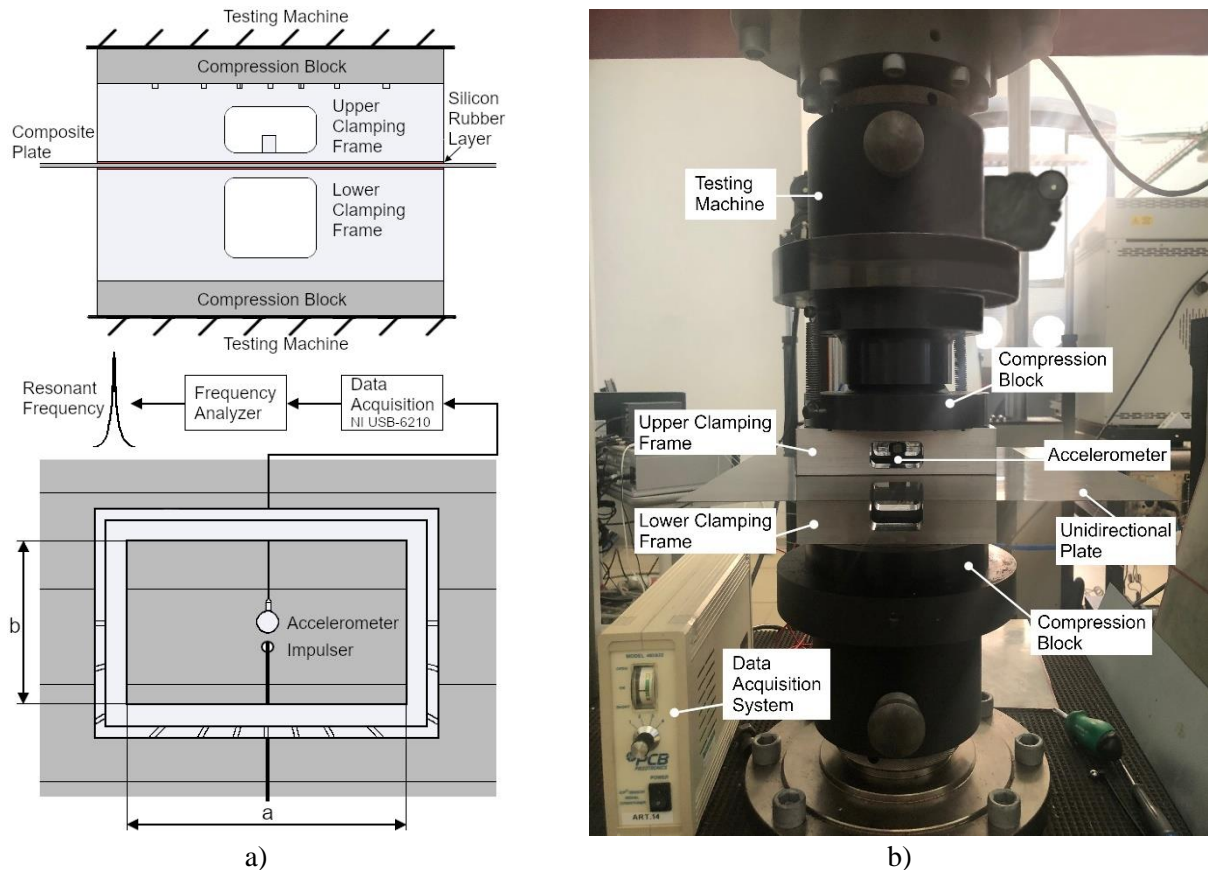


Figure 4: Testing setup: a) scheme; b) experimental setup.

Due to the material orthotropy, elastic properties are directionally dependent. Therefore, by rotating the clamping frames with respect to the composite plate, the elastic properties of the clamped region vary. Accordingly, the relative orientation between the clamping frames and the plate influences the measured resonant frequencies. Only the first resonant frequency of the rectangular clamped region is thus retained for each orientation. In this study, four measures of the first resonant frequency are performed in order to assess the local elastic properties. By considering the angle between fibers direction and the main axis of the frames, IET test is performed at 0° , 30° , 60° and 90° , as shown in Fig. 5. The dependency of the resonant frequency on the material orientation is emphasized by the asymmetry of the rectangular shape of the examined region. Indeed, as the ratio a/b between the dimensions of the rectangle increases, the variation of the resonant frequency with the material orientation increases. In contrast, a circular shape suppresses the dependency of the resonant frequency on the relative orientation between the frames and the plate. Therefore, by rotating the upper and lower frames with respect to the composite plate, different values of the resonant frequency are measured.

Finally, in order to compensate the thickness variation, a 0.5 mm layer of silicon rubber has been adopted at the frame contour, as shown in Fig. 4a. As highlighted in Section 2.1, thickness varies along the plate. Plate

flatness is critical for establishing a uniform contact between frames and plate [20]. The variation of the thickness can result in a local loss of clamped boundaries. Indeed, location of the clamped boundaries is strictly affected by the contact between frames and plate. When loaded, the silicon rubber can deform, thus establishing a uniform contact with the plate.

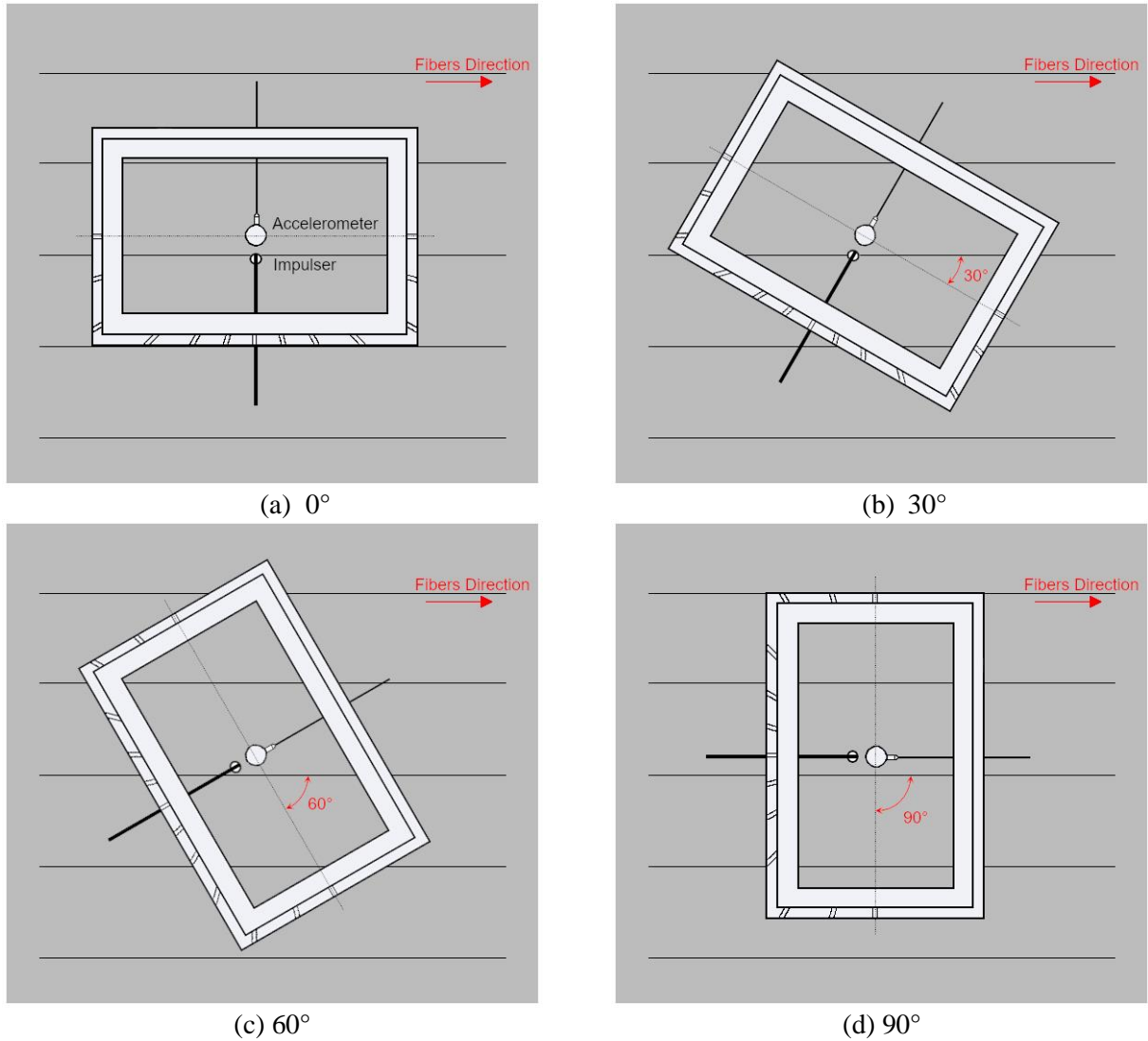


Figure 5: Experimental procedure: measures at different orientations

2.3 Numerical Calculations

Local elastic properties are determined from the measured frequencies. The inverse problem combines a Finite Element (FE) analysis and an optimization process in order to compute the material constants. In particular, FE modal analysis is performed within an optimization problem, where elastic parameters, namely E_{11} , E_{22} , G_{12} and ν_{12} , are handled as design variables. The material constants are determined by minimizing the difference between the experimental and numerical resonances. The structural optimization problem is formulated as follows:

$$\min_{\underline{x}} \sum_i \left| \frac{f_{exp,i} - f_{num,i}(\underline{x})}{f_{exp,i}} \right| \quad (1)$$

where $\underline{x} = [E_{11}, E_{22}, G_{12}, \nu_{12}]$, f_{exp} is the measured frequency, f_{num} is the numerical resonance and subscript i refers to the i -th orientation between the clamping frames and the composite plate. The objective function is

given by the sum of the relative errors between measured frequencies and numerical resonances for each orientation.

The commercial software LS-Dyna has been used for the numerical calculations. The resonant frequencies are extracted through the Lanczos method [21]. The finite element model consists in a rectangular plate of dimensions 140 mm and 90 mm, clamped at the extremities, as shown in Fig. 6. The Belytschko–Tsay four nodes shell elements formulation with 6 degrees of freedom per node are used to model the structure. A mesh size of 1 mm, with 12600 elements and 75600 degrees of freedom, has been considered to discretize the structure. The plate has uniform thickness of 1.08 mm. In accordance with the number of unidirectional layers, seven integration points have been assumed through the thickness, while one integration point in the element plane is used.

Fibers direction is set through a user-defined vector in LS-Dyna environment, thus specifying the different material orientations. The inertial effect of the accelerometer has been accounted through a lumped mass. Its value has been equivalently distributed on the central nodes of the plate in correspondence of the accelerometer location, as shown in Fig. 6.

According to the values assumed by the elastic constants at each iteration, modal analysis of the rectangular clamped plate is performed for each orientation of the fibers. The first fundamental frequency is retained and compared with the corresponding experimental frequency. The difference between the experimental and the numerical frequencies is thus minimized by varying the elastic properties, according to Eq. (1). The zero-order Nelder-Mead algorithm has been adopted for the optimization [22]. Local elastic properties are thus assessed for the retained region.

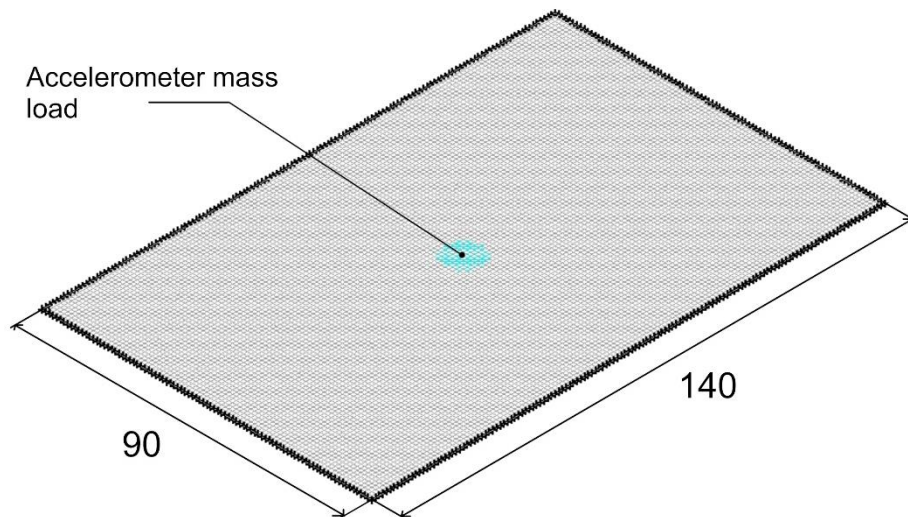


Figure 6: Numerical model

3. Results and Discussion

IET test is performed at different orientations. From the measured frequencies, local elastic properties are determined. The calculated values are compared to their reference values as given in the provided datasheet.

3.1 First Fundamental Frequencies

In this Section, the experimental results are analyzed. As described in Section 2, the first resonant frequency is measured for fibers oriented at 0° , 30° , 60° and 90° with respect to the main axis of the rectangular frame. Five replications for each fiber orientation are performed. Measured scatter is extremely limited with a range equal to ± 2 Hz. The frequency response functions are shown in Fig. 7 for each orientation (Fig. 7a for 0° , Fig. 7b for 30° , Fig. 7c for 60° and Fig. 7d for 90°). Due to the material anisotropy, the first fundamental frequency varies from 246 Hz to 410 Hz. In anisotropic plates, the elastic properties are directionally dependent. The orientation of the material with respect to the clamped boundaries influences the bending stiffness, thus resulting in a variable resonant frequency. In contrast, the inertial effect of the accelerometer mass reduces the frequency variation with the fiber orientation.

According to Fig. 7, the first resonance peak is clearly visible and well isolated from the other resonance peaks, thus highlighting the effectiveness of the experimental measures. The differences between measured frequencies is emphasized by the rectangular shape of the isolated region. In rectangular plates, the bending stiffness is mostly related to the elastic properties in the direction of the rectangle short edge, i.e. the transverse direction [23]. Indeed, the different proximity of the constraints enhances the sensitivity of the bending stiffness to the elastic properties in the transverse direction. This sensitivity to the material properties in the transverse direction increases with the ratio between the dimensions, a and b , of the rectangle. Therefore, by rotating the rectangular frames with respect to the unidirectional plate from 0° to 90° , a substantial increment of the bending stiffness and, accordingly, of the resonant frequency, is experimentally found.

In particular, when the fibers are parallel to the long edge a of the frames, i.e. oriented at 0° , the stiffness of the analyzed region is mostly related to the Young's modulus in the transverse direction E_{22} . The bending behavior is thus governed by the epoxy matrix. When the fibers are parallel to the short edge b of the frames, i.e. oriented at 90° , the Young's modulus in longitudinal direction E_{11} mostly affects the stiffness, thus leading to a higher value of the resonant frequency. At 90° , the bending behavior is governed by the fibers. Therefore, in very anisotropic materials, as a unidirectional plate, the wide range of elastic properties leads to a measurable variation of the resonant frequencies. The rectangular shape of the frames thus allows to exploit the anisotropy of composite materials, enhancing the dependency of the resonant frequency on the material orientation.

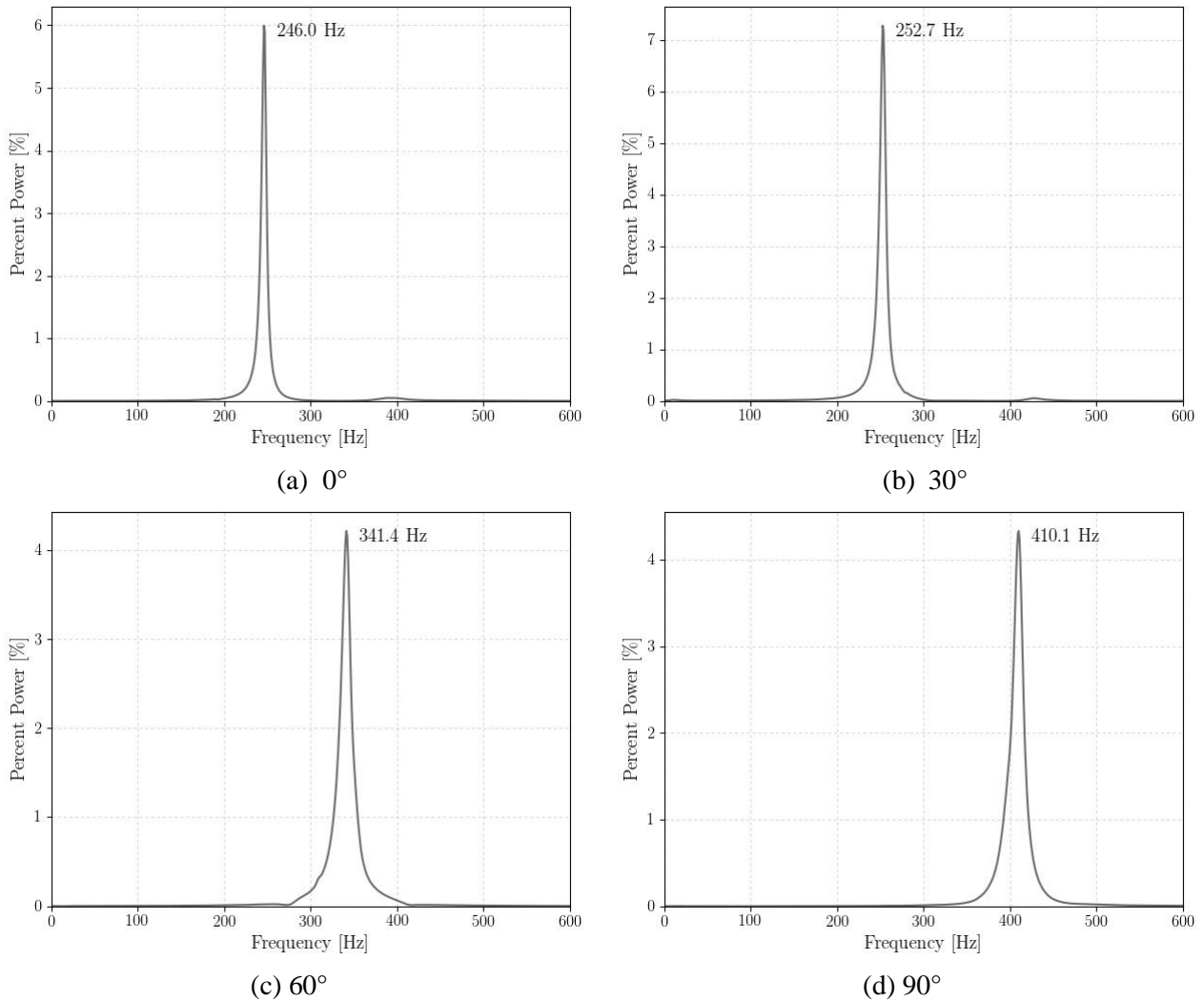


Figure 7: Frequency response function at different orientations: a) 0° ; b) 30° ; c) 60° ; d) 90° .

3.2 Estimation of material constants

The assessment of the material constants is carried out according to the Eq. (1). For the thickness, an average value of 1.08 mm has been assumed in the numerical calculations. The local elastic properties, as determined through the optimization process, are reported in Table 3. The obtained values are compared to the nominal material constants provided by the supplier, resulting in very good agreement.

Property	Nominal value	Local value	Percent Discrepancy
E_{11} [GPa]	131.1	126.1	-3.8%
E_{22} [GPa]	7.0	6.8	-2.9%
G_{12} [GPa]	3.93	3.8	-3.3%
ν_{12} [-]	0.35	0.34	-4%

Table 3: Comparison of local and nominal elastic properties

The difference between local estimates and nominal elastic properties is smaller than 4%. In particular, the actual local properties are smaller than the corresponding reference values provided by the supplier. In regard to this deviation, three main aspects can be highlighted. Firstly, the methodology here proposed adopts a dynamic test to assess the material constants. Static and dynamic tests can lead to different results [7], even though differences are typically limited [13]. Further, in the proposed procedure, flexural behavior of the plate is tested. In composites, flexural material properties typically differ from the corresponding values assessed through tensile testing [24]. Finally, the variability of the thickness along the plate, which is not accounted in the numerical calculations, affects the measure of the resonant frequency and, consequently, of the local elastic properties. Plate thickness is mostly influenced by the manufacturing process. In particular, the fabrication causes local variations in the amount of epoxy matrix and, consequently, in the plate thickness. This affects in turn the local percentage of volume fibers and accordingly the local elastic properties. In regard to the resonant frequency, its value decreases as the plate becomes thinner. However, as the amount of matrix decreases, the local elastic properties increase, thus partially compensating the effect on the resonant frequency. The effect of thickness variation is further discussed in the next section.

In Table 4, the measured resonant frequencies are compared to the corresponding numerical results, as obtained with the computed elastic estimates.

Orientation	Measured frequency [Hz]	Numerical frequency [Hz]	Percent Error
0°	246	246.9	-0.4%
30°	252.7	257.4	1.8%
60°	341.4	351.5	-2.9%
90°	410.1	403.4	1.6%

Table 4: Comparison of experimental and numerical resonant frequency

The relative error between experimental and numerical frequency, namely the objective function of the optimization problem in Eq. (1), is reported for each orientation. As shown in Table 4, the most significant discrepancies between experimental and numerical frequencies are obtained at 30° and 60°. Indeed, uncertainty in frame positioning particularly affects these intermediate orientations. However, the differences are limited and smaller than 3%, thus proving the effectiveness of the proposed experimental methodology.

Fig. 8 shows the modal shape for each orientation as resulting from the numerical analysis. Contour lines of the first fundamental mode are also represented.

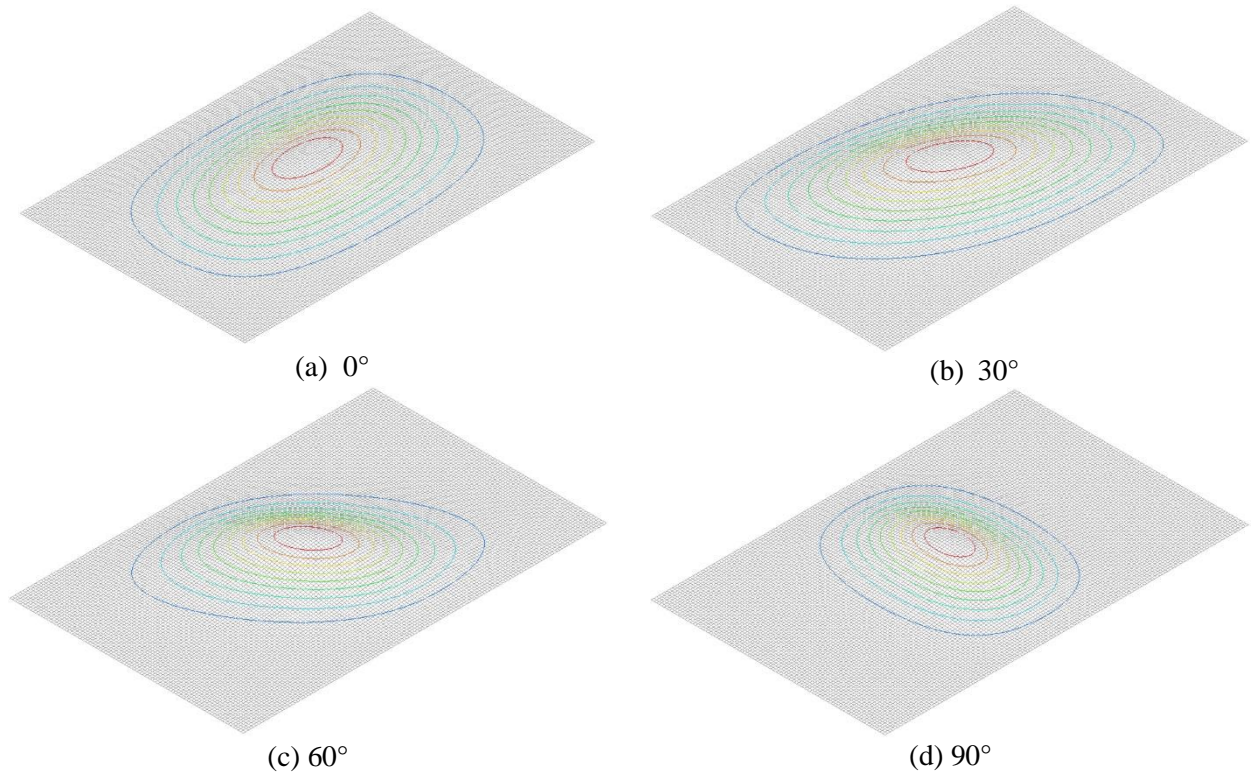


Figure 8: Mode shape with contour lines at different orientations: a) 0°; b) 30°; c) 60°; d) 90°.

According to Fig. 8, the modal shape varies with the material orientation. In particular, the isolines follow the fiber direction. As the orientation varies from 0° to 90°, the vibrating phenomenon involves lower amount of plate material, in accordance with the increasing values of the resonant frequencies.

3.3 Sensitivity analysis: effect of thickness variation

The variability of the thickness along the plate consistently affects the measure of resonant frequency. In particular, its value decreases as the plate becomes thinner. Given the inverse problem formulated in Eq. (1), which computes elastic properties from measured resonant frequencies, thickness variability influences in turn the estimation of material constants.

In order to show this effect, the optimization process in Eq. (1) is repeated considering both the maximum and minimum thickness in the plate, even though these two thicknesses do not belong to the isolated region in the plate. Local elastic properties are assessed assuming in the numerical model firstly the uniform value of 0.94 mm, i.e. the minimum thickness, and then the uniform value of 1.13 mm, i.e. the maximum thickness.

Table 5 shows the results of the sensitivity analysis, compared to the elastic properties obtained with the average thickness of the isolated region in the plate, equal to 1.08 mm.

Property	Local value t=1.08 mm	Local value t=1.13 mm	Local value t=0.94 mm	Nominal value
E_{11} [GPa]	126.0	112.1	186.0	131.1
E_{22} [GPa]	6.8	6.0	10.0	7.0
G_{12} [GPa]	3.8	3.0	5.6	3.93
ν_{12} [-]	0.34	0.31	0.35	0.35

Table 5: Effect of thickness scatter on local material properties

The marked discrepancy highlights the sensitivity of the inverse problem formulated in Eq. (1) with the thickness of the plate. The sensitivity of the IET to the laminate thickness is a further evidence of the need for a local measure. Only in case of small isolated regions, the thickness variation is limited and it does not significantly affect the estimation of the material properties. Indeed, manufacturing defects, which include

large thickness variations in the plate as well as local weaknesses in the laminate, can be effectively identified with the proposed approach.

4. Conclusions

In the paper an innovative experimental methodology for the nondestructive assessment of the elastic properties of anisotropic materials has been proposed. The methodology is based on the Impulse Excitation Technique (IET) and the material elastic properties are locally determined, i.e. the assessment concerns an isolated region of the material. In particular, with the IET, the first resonant frequency of the investigated local region is measured. Differently from the literature, only the first resonant frequency is considered. In order to take into account the anisotropy of composite plates, the measurement of the first resonant frequency is repeated by varying the angle between the fiber direction and the main axis of the frame. The material properties are finally obtained through an optimization procedure based on Finite Element Analysis, which aims at finding the elastic properties that minimize the differences between the experimental and the numerical resonant frequencies.

The proposed procedure has been successfully validated on a unidirectional carbon fiber composite plate. A rectangular region, 140x90 mm, has been isolated by clamping its boundaries with two frames placed above and below the plate. A testing machine equipped with compression blocks has been used to compress these frames against the unidirectional plate, without damaging the plate.

The IET test has been performed by exciting the retained region at its center and by measuring the acceleration at the same location with an accelerometer. Anisotropy of the material has been exploited to obtain four different measures of the first fundamental frequency. In particular, clamping frames have been oriented at 0°, 30°, 60° and 90° with respect to the fibers, thus resulting in different material orientations with respect to the boundaries.

Dynamic elastic properties have been assessed from measured frequencies. A combination of numerical analysis and optimization process has been considered for the inverse problem. In particular, modal analysis has been performed on a finite element model of the rectangular plate. The elastic parameters, namely E_{11} , E_{22} , G_{12} and ν_{12} , have been iteratively varied with the objective of minimizing the difference between the experimental and the numerical resonant frequencies.

Results showed that resonant frequency increases from 246 Hz to 410 Hz by increasing the angle from 0° to 90°. The rectangular shape of the clamping frames has allowed to exploit the anisotropy of composite materials, enhancing the dependency of the resonant frequency on the material orientation. In particular, the different proximity of the constraints has been shown to emphasize the sensitivity of the bending stiffness to the elastic property in the direction of the rectangle short edge. Thereafter, the estimated elastic properties have been compared to the reference values as given in the manufacturer's specifications. The difference between the estimated and the nominal elastic properties has been within a limited range, particularly smaller than 4% and has been mainly due to the local material deviation and defects (i.e., thickness variations or local weaknesses).

To conclude, it has been shown that the presented methodology allows to assess local elastic properties of composite materials through nondestructive testing. The methodology can be used to quantitatively evaluate actual local properties of a composite component as well as to monitor its structural integrity and manufacturing quality.

Acknowledgements

This work has been supported by the Research Project AMICO (code ARS01_00758) funded by the Italian Ministry of Education, University and Research.

Data availability

The raw and processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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