



DETECTION OF DELAMINATIONS IN DAMAGED COMPOSITE PLATES VIA LOCAL DAMAGE RESONANCE APPROACH

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Abstract

This study aims at presenting a technique for damages characterisation in composite plates (i.e., delaminations). The proposed approach exploiting interactions of the structure with vibrational waves produced by piezoelectric sensors bonded onto the same element, allows to perform Structural Health Monitoring (SHM). The technique involves the excitation of the structure by means of stationary sinusoidal waves: the presence of subharmonics in the frequency response spectrum at a receiver point indicates the presence of damage in the composite plate. In addition, through a simplified analytical model it could be possible to relate the frequency of specific subharmonic to damage length and depth. This simplified analytical model was used to understand the subharmonic phenomenon. Both experimental campaign and numerical models were carried out on composite plate with Teflon film as artificial delamination, using piezoelectric sensors (one exciting and one receiving). The good numerical-experimental correlation confirms the validity of the proposed approach.

Keywords: Structural Health Monitoring, Local Defect Resonance, Nonlinear Elastic Wave Spectroscopy, Composite plates, Kissing Bond.

1. Introduction

The concept of damage refers to a change introduced into a system that negatively affects its current or future performances. Specifically, the term “damage” identifies a change in material properties [1] or geometry [2] of the system, including changes in the initial conditions [3]. The damage always begins at the material level, and then propagates at the geometrical point of view under the effect of certain loads, causing damages to a system component. This does not imply a total loss of damaged component functionality but indicates that the system is no longer able to function in its optimal conditions. In the last decades, a process of identifying and evaluating damages present in a component was developed and it is called Structural Health Monitoring (SHM). The SHM aims to provide at every moment of a structure life a diagnosis of components and materials states [4].

During that period, composite thin laminates are attracting great interest for their potential application in several structural applications, with their high stiffness and specific strength characteristics. Despite the groundbreaking of this customizable material, composite manufacturing process is susceptible to contamination of stacking plies during manufacture [5] and environmental deterioration [6] in actual operating conditions [7]. These may cause the generation of so-called delaminations that can dramatically alter the strength of the composite element, leading to premature

failures [8].

The identification of this kind of damages can be carried out in combination with related SHM disciplines that include Condition Monitoring (CM), Non-Destructive Evaluation (NDE), Static Process Control (SPC) and Damage Processing (DP) [9]-[12]. The presented work focuses on NDE approach, which is usually performed after the damage has been localized. The NDE is mainly used to characterise the damage and to check its influence on the normal functioning of the structure when its position is already known [13]. Nonlinear ultrasonic techniques have shown great potential for monitoring composite delaminations, as able to localise loss of structural continuity within the material, with the material remains in contact across the defect (i.e., “kissing bonds” phenomenon [14]). These techniques work with piezoelectric sensors permanently installed on the structural composite element, thus enabling online and in-situ inspection.

Specifically, Contact Acoustic Nonlinearity (CAN) [15] leads to the appearance of harmonics in the spectral response when an elastic wave travels and passes through a sensorised delaminated composite elements: the contact interface opens and ends giving rise to the kissing bonds phenomenon. The generator sensor sends a vibrational signal that travels through the structure and reaches the receiver sensor. If the structure does not present damages and the signal does not present distortions due to the instrumentation, the received signal includes only the excitation frequency (i.e., linear behaviour). Whereas if the structure is damaged, the received signal will include a rich variety of frequencies that depend on the excitation frequency and damage size and/or position (i.e., nonlinear behaviour). These phenomena could be analysed with both linear and non-linear techniques, for metallic and composite plates, finding analytical-experimental-numerical correspondence [16]. Finite Element Analyses (FEAs) by using cohesive elements can be performed to simulate the damages behaviour in structural components [17]. Nonlinear vibrational simulations of these simple structures with contact elements using FE models demonstrate that transient signals (with relative frequency spectra) and damage dimensions are strongly correlated [18].

The presented study investigates the Nonlinear Elastic Wave Spectroscopy (NEWS) via Local Damage Resonance (LDR) effects in the presence of kissing bonds in composite plates. By altering the mechanical properties of the laminate (via experimental and numerical point of view), the main scope of the presented work is to evaluate whether the frequency spectra of a damaged composite structure crossed by harmonic vibrational waves are altered, in accordance with delaminations features (i.e., length and depth).

2. Material & Methods

2.1 Analytical Model

The presented results are supported by a theoretical approach based on the solution of the nonlinear reduced model, under the assumption that the damaged area is a system with undamped nonlinear harmonic oscillators subject to harmonic forcing. More specifically, the hypothesis is that the defect (i.e., delamination) behaves like a Kirchhoff plate [19] ($\text{del} \times t \times b$), clamped along b edges (Figure 1). The harmonic signal excites the vibrational modes, i.e., the interactions (contacts) between the damages and the remaining structure.

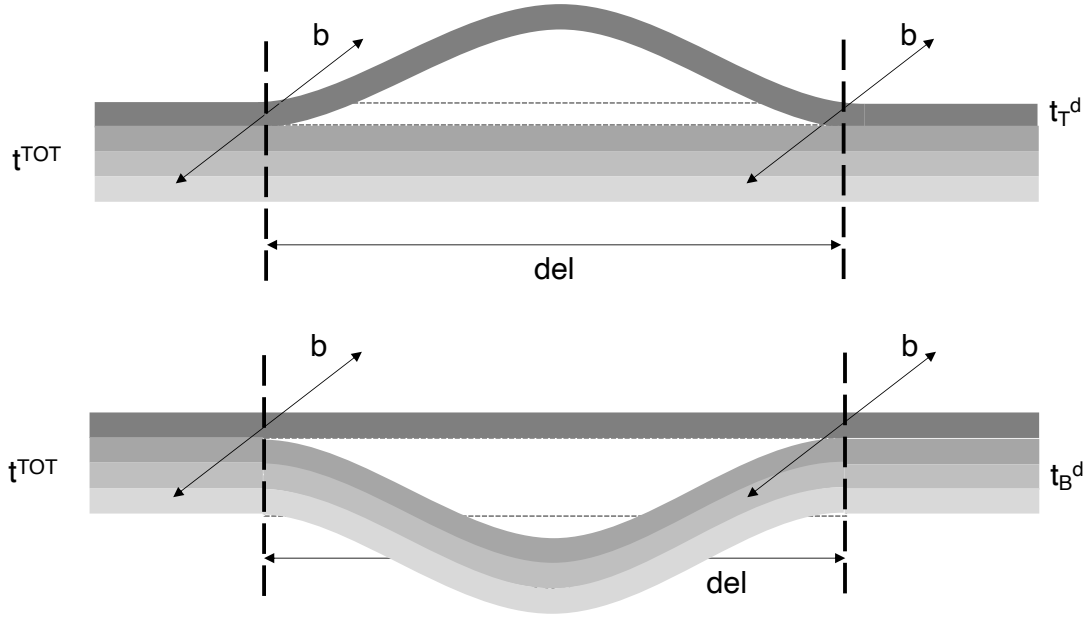


Figure 1 – Delamination model (clapping behaviour of damages, top with thickness t_T and bottom with thickness t_B , represented by dark grey and dashed lines).

The well-known first natural frequency of the fixed-fixed plate is:

$$f_{del} = f_{n_1} = \frac{4.73^2}{2\pi} \sqrt{\frac{E(t^d)}{(1-\nu^2)} \left(\frac{b \cdot t^d^3}{12} \right)} = \frac{4.73^2}{2\pi} \frac{t^d}{del^2} \sqrt{\frac{E(t^d)}{12\rho(1-\nu^2)}} \quad (1)$$

where $E(t^d)$ is the calculable elastic modulus of the damaged areas, function of damage thickness. So, by following the conclusions of [18], when nonlinearities appear in the response spectrum of the entire system, the subharmonic frequency equal to half of exciting frequency represents also the first natural frequency of the damage (one per each kissing bond face, top and bottom respectively). Eventually, from Equation (2) the delamination length and depth can be evaluated (taking into account that $t_T^d + t_B^d = t^TOT$).

2.2 Specimen & Experimental Setup

Experimental campaigns were conducted on a specimen made by using the Vacuum Assisted Resin Transfer Molding (VARTM) technique. In this process, dry preformed fibres were placed in an open mold between release films and peel plies with a plastic vacuum bag placed on top of the mold (see Figure 2). Right-side mold was connected to a resin source, left-side mold to a vacuum pump. The liquid resin flows into the carbon fibres thanks to the vacuum created through the mold (see Figure 3). The complete resin infusion kit was supplied by Easy Composite LDT [20]. The fibres used are dry carbon fibres, the resin and hardener are produced by Easy Composites: the base resin used is IN2 INFUSION EPOXY RESIN, the hardener is AT30 SLOW EPOXY HARDENER. The recommended quantity of Hardener is 30% by weight of the base resin.



Figure 2 – Vacuum Bag.

The delamination was artificially inserted by a Teflon film with a thickness of 20 μm between appropriate layers: the Teflon creates a discontinuity capable of preventing the layers adhesion, simulating the damage.

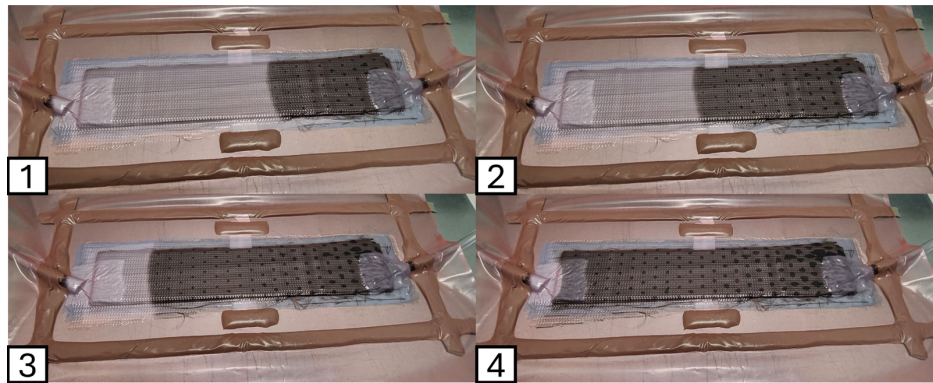


Figure 3 – Infusion phases.

The obtained plates are composite laminates of eight layers (0.25 mm thick per each layer) with $[(0)_2/(90)_2]_s$ stacking sequence, for a total dimension of $250 \times 50 \times 2 \text{ mm}^3$. In this first study stage, the artificial delamination was inserted only in the middle of the thickness, with a dimension of $\text{del} = 20\text{mm}$. The mechanical properties of single layer are summarized in Table 1, using the Easy Composite data sheets and the Autodesk Heliux Composite software.

Table 1 - Mechanical properties of lamina (XC130-IN2/AT30).

E_x [GPa]	164.3
E_y [GPa]	8.84
E_z [GPa]	8.84
ν_{xy}	0.275
ν_{xz}	0.275
ν_{yz}	0.291
G_{xy} [GPa]	4.849
G_{xz} [GPa]	4.849
G_{yz} [GPa]	3.423
ρ [kg/m ³]	1642

Once the specimens have been obtained, the experimental setup was arranged in the AS.S.E. Lab [21]: two piezoelectric transducers [22] were applied to each specimen, one acting as actuator, transmitting the vibrational signal and the other as receiver, reading the output signal. During the tests, the specimen is placed on foam rubber to simulate the free-free boundary condition.

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The operating procedure for data acquisition follows the left-right verse of Figure 4.

1. The signal generator produces a harmonic signal (pure sine) with customise amplitude and unique carrier frequency.
2. The signal is multiplied by 50 via power amplifier.
3. The left bonded piezoelectric transducer excites the damaged composite plate.
4. The piezoelectric sensor bonded to the right of the damage, receives the transmitted wave and sends the signal to the oscilloscope (with collection time equal to 100 ms/div and number of samples equal to 400 kS).
5. The real-time acquisition of the propagated wave is performed using Picoscope6 software and eventually analysed using Matlab scripts to process the FFT of the acquired signal.

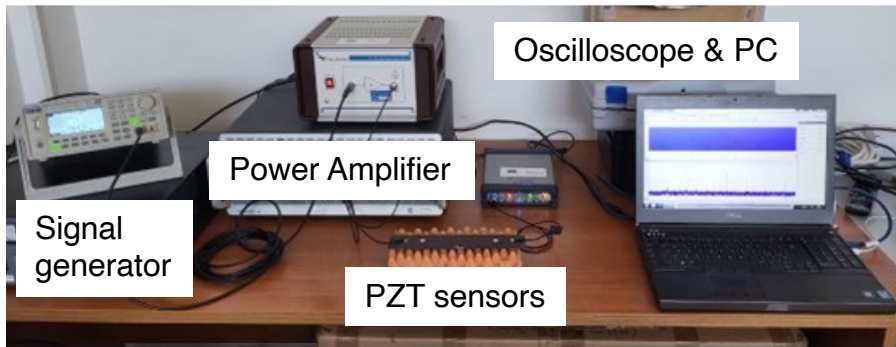


Figure 4 – Experimental Setup.

2.3 Finite Element Model

Two-dimensional Finite Element simulations using nonlinear Ansys Workbench model were carried out to support experimental results for the identification of the LDR frequency and the generation of nonlinear resonance effects [18]. The simulated composite plate consisted of the same material and stacking sequence presented in the previous paragraph. A 2D model (250 mm × 2 mm) was developed by using Design Modeler Ansys module. Parametric dimensions and split surfaces were used to properly simulate different depths delaminations. The element size was set to be a fortieth of the wavelength propagating in the composite plate by the exciting frequency (see Figure 5, two elements along the thickness direction for each layer). The plate was meshed by 2D structural solid element PLANE183, defined by six nodes with two degrees of freedom at each node (translation in x and y directions).

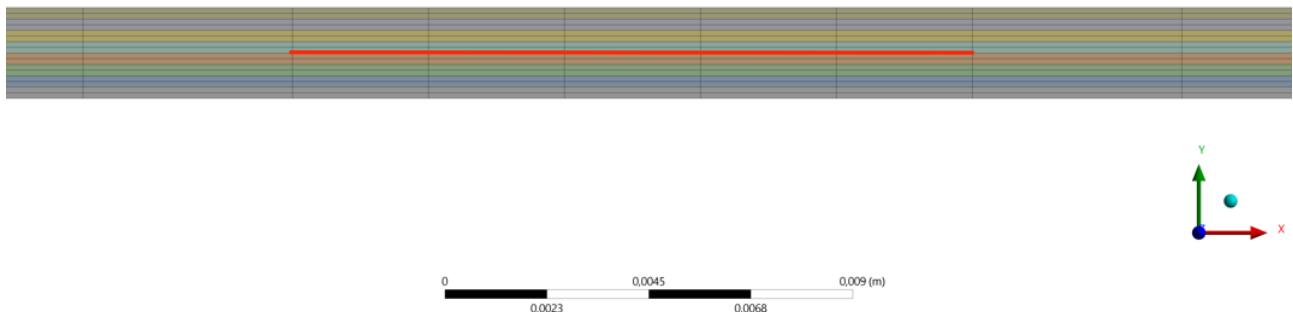


Figure 5 – Mesh model (the red line indicates the delamination interface).

The layers were coupled using the node merge command, while the delamination was simulated with frictionless contact. Contact conditions were inserted to simulate interactions between separate bodies. The delaminated region was modelled by a frictionless contact [23], by the following conditions (see Equation (1) and Figure 6):

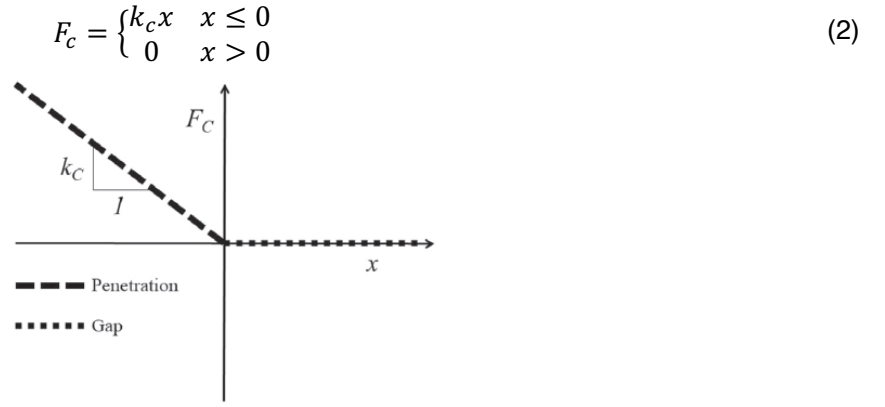


Figure 6 – Frictionless contact law in FEM [24].

The Pure Penalty formulation was used for frictionless contact (see Figure 7). So, the delamination region is characterized by two faces that are free to separate and move away from each other causing structural stiffness changes and, consequently, nonlinearities on global response.

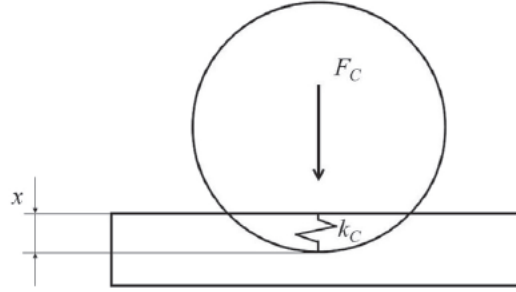


Figure 7 – Contact penetration in FEM [24].

The other surfaces were joined with node merge command with a tolerance of 1.0e-5m (Figure 8).

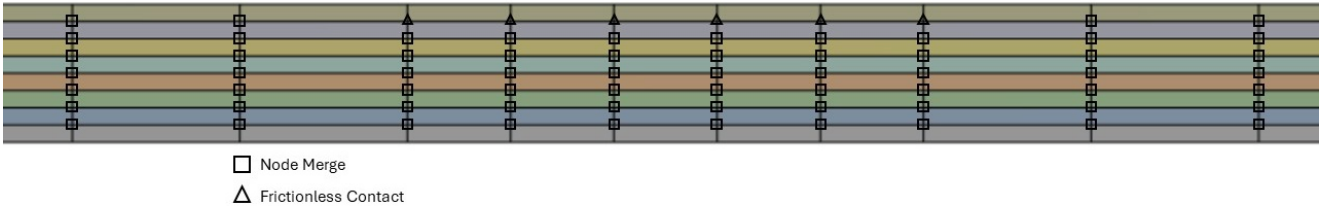


Figure 8 – Mesh model, frictionless contact.

The time step was set to 1/20 of the exciting signal period. Free-free boundary conditions were used to represent the experimental setup constraints.

The contact Stiffness Factor (SF) was varied in such a way as to easily achieve convergence of the results. The best results in terms of subharmonic appearance were obtained for low values of SF.

3. Results & Discussion

In the following Figures and Table, the numerical results are presented for each value of depth delaminations with $\text{del} = 20 \text{ mm}$ and the comparison of the simulations with the results provided by the simplified analytical model is reported. In Table 2, the numerical single subharmonic at $f_e/2$ and the relative analytical results are reported: the agreement is not so evident for all cases. This not perfect correlation highlights that the analytical model based on the Kirchhoff theory confirms that $f_e/2$ represents the first damage natural frequency, but the delamination does not exactly behave like a double clamped plate.

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Table 2 – Numerical and analytical results for del = 20 mm and several depths.

del [mm]	Damage Position		FEM		Analytical
			$f_{\text{sub}} = f_e/2$ [kHz]	SF	f_{n1} [kHz]
	Layer	Interface			
20	1	T	5.93	0.01	6.42
		B	20.83	0.35	29.77
	2	T	10.52	0.01	12.85
		B	14.63	0.01	12.73
	3	T	9.44	0.1	12.82
		B	14.17	0.1	11.88
	4	T/B	9.37	0.01	11.74

In Figure 9 to Figure 11 the occurrence of multiple numerical subharmonics can be noticed (f_e and $f_e/2$ indicated with continuous and dashed red lines in the following figures, respectively): all of them are centred in pairs on $f_e/2$, named high and low subharmonics in [18].

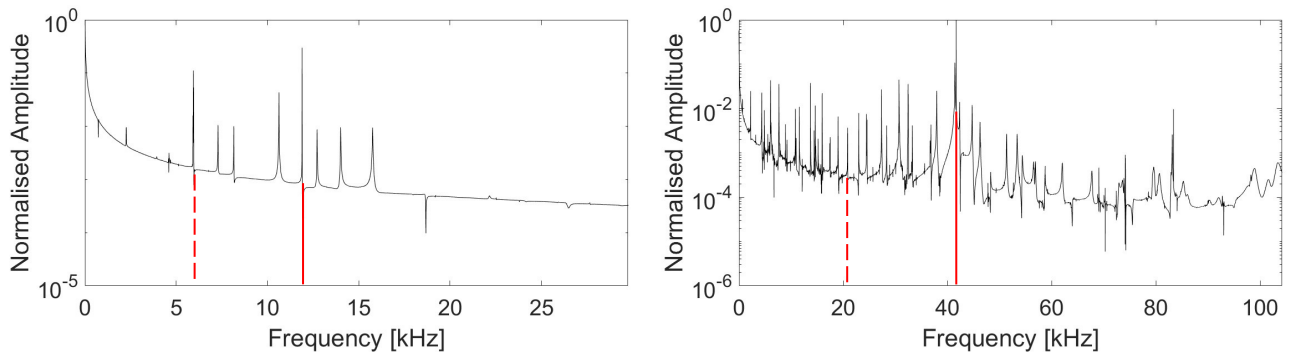


Figure 9 – Damage length 20 mm, layer 1, top damage (left) and bottom damage (right) FFT.

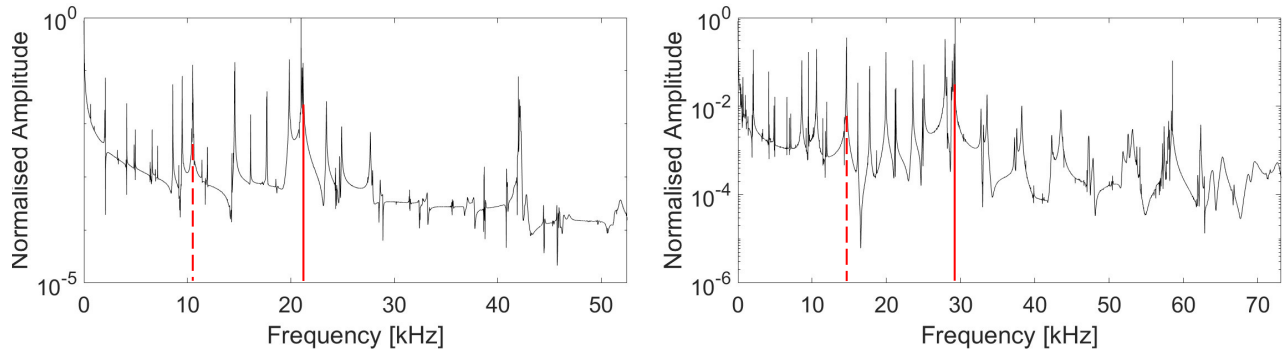


Figure 10 – Damage length 20 mm, layer 2, top damage (left) and bottom damage (right) FFT.

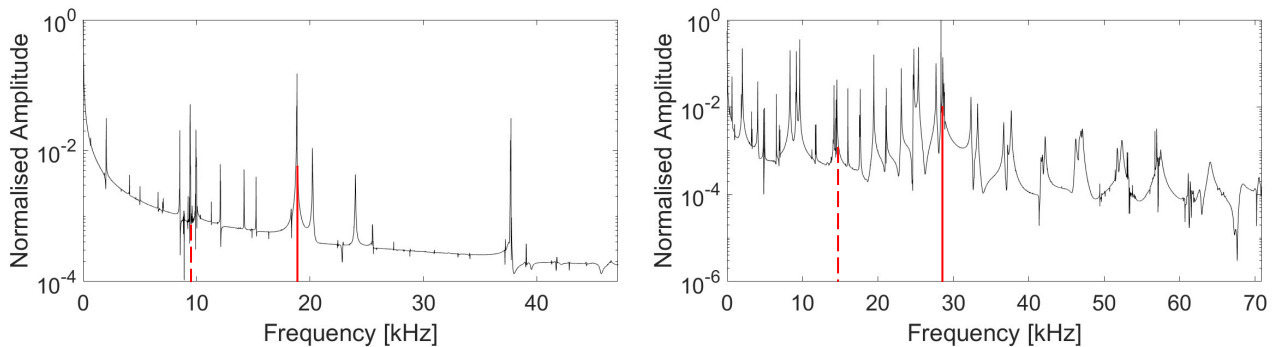


Figure 11 – Damage length 20 mm, layer 3, top damage (left) and bottom damage (right) FFT.

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Several parameters concerning the FE nonlinear analysis must be further tuned to obtain an output signal whose FFT will provide a single dominant subharmonic. Eventually, the preliminary experimental campaign and the related nonlinear transient analysis with $\text{del} = 20 \text{ mm}$ and $t_r^d = t_B^d$ show the generation of subharmonics via the dependence of the relation between the excitation fundamental frequency and LDR ones.

Table 3 – Experimental and numerical results for $\text{del} = 20 \text{ mm}$ and middle depth.

del [mm]	Damage Position		Experiment	FEM		Error
	Layer	Interface	$f_{\text{sub}} = f_e/2 \text{ [kHz]}$	$f_{\text{sub}} = f_e/2 \text{ [kHz]}$	SF	Exp. vs FEM [%]
20	4	T/B	9.44	9.37	0.01	0.74

Experimental campaigns and numerical simulations highlight the formation of LDR phenomenon at a specific value of exciting frequency by using PZT sensors. For the experimental point of view, a frequency sweep excited the damaged composite plate to monitor the dynamical response at the receiver position: this response is nonlinear, and it shows a variety of sub and super harmonics. These multiple frequencies generally do not provide useful information about the actual length and delamination position (through the thickness) but if the excitation frequency is tuned to show just one single dominant subharmonic, this excitation frequency is related to del length and depth (see Equation (2)).

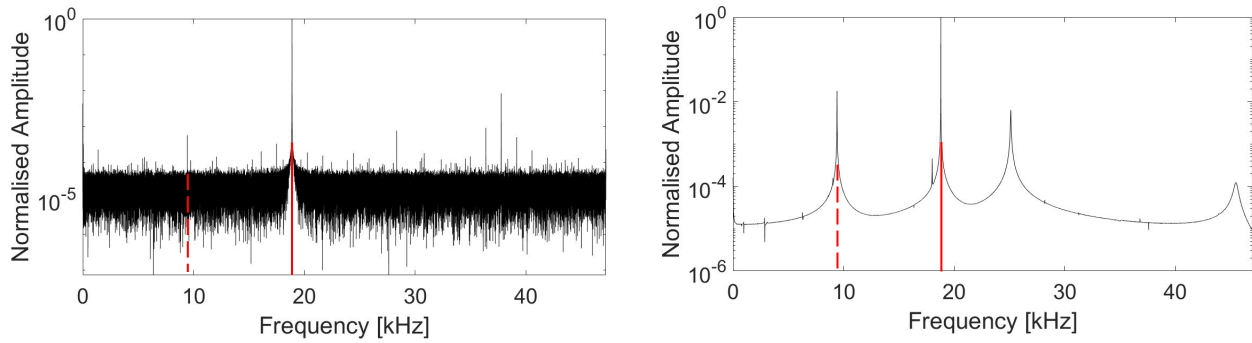


Figure 12 – Damage length 20 mm, interface 4, experimental (left) and numerical (right) FFT.

Regarding Table 3 and Figure 12, with a specific experimental and numerical exciting frequency (18.88 kHz and 18.74 kHz, respectively) one subharmonic at $f_e/2$ (the first natural frequency of the delamination) appears in the structural response together with several and minor other subharmonics.

The agreement between experimental/numerical results and the partial correlation with the analytical model reveal that a monitoring approach combining Nonlinear Elastic Wave Spectroscopy and Local Damage Resonance could be an extremely efficient and sensitive tool for ensuring integrity and safety of structural composite elements.

4. Conclusions

Delaminated composite plates were simulated and tested for SHM purposes. The specimen and the numerical model were made of composite material with an artificial defect (i.e., delamination) introduced in the plate with a Teflon film of 20 mm. From the experimental point of view, two PZT sensors were used, one working in actuating mode, the other one in receiving mode. Two different approaches were followed: the first one consisting in an experimental harmonic excitation aimed at exciting the artificial defect to promote Local Defect Resonance conditions; the second one based on the simulation of the same scenario. Both methods were physically interpreted with a simplified analytical model useful to characterise the delamination in terms of length and depth through the

defect first natural frequency. The numerical/experimental correlation together with the early-stage analytical model and the FE models demonstrated the validity of the proposed approach for the SHM of delaminated composite plates.

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