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Nonlinear behaviour of glass fibre reinforced composites with delamination

M. Hammami [a, b, *], A. El Mahi [a], C. Karra [b], M. Haddar [b]

[a] Université du Maine, LAUM, UMR CNRS n°6613, Av. O. Messiaen, 72085 Le Mans Cedex 9, France
[b] Laboratoire Modelisation Mecanique et Production, Ecole Nationale d'Ingenieurs de Sfax, Tunisia

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ABSTRACT

The aim is to assess the nonlinear behaviour of glass fibre composite having controlled delaminations. The experimental analysis focused on the variation of nonlinear parameters as function of delamination size. Through a set of increasing resonance amplitudes applied on a delaminated glass fibre reinforced composite, the frequency shift and the specific damping coefficient shift were evaluated as a function of strain amplitude. The nonlinear elastic and dissipative parameters related respectively to the frequency and damping, were determined for different bending modes and different delamination lengths. These parameters were compared with the linear vibration parameter. The results show that nonlinear parameters are more sensitive to the presence of delamination in composite.
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1. Introduction

Delaminations are the major defects in composite laminates since they appear at a weak inter-laminar stress. Delaminations are barely visible from external view and may arise during manufacturing or during service. It is well known that delamination detection in composites using vibration analysis is a challenging task. This is mainly attributed to the fact that delamination has no comparable damaged mechanism in other materials [1].

The presence of delamination may cause changes in the vibration characteristics of the composite structures. It leads to changes in natural frequencies, modal shapes and damping ratios [2]. The vibration testing method investigates those changes in the structure to detect internal damages, as reviewed in Refs. [1,3]. The shift in frequencies is generally investigated to identify the presence of delamination. This method provides reliable and accurate data [4,5]. Natural frequencies can be accurately measured with a single sensor [6–8]. An excellent overview of the vibration of delaminated composite can be found in the review of Della [9].

It is worth noting that after an impact, more than one delamination is usually present in damaged composite laminates. It was approved that multiple delaminations significantly affect the dynamic characteristics of composite beams [10–12].

Damping is of prime importance in the study of composite structures vibration behaviour. However, the dissipative properties of composite materials have not yet been completely identified. Saravanos [13] elaborated an analytical model to evaluate the effect of the delamination size on the modal damping of fibre reinforced composites. Experimental results were performed on a beam with a single delamination. Recently, an experimental study was developed in order to evaluate the modal damping of fibre reinforced composites provided by Refs. [14–17].

It is usually anticipated that the sensitivity of nonlinear experimental methods are much more sensitive to the presence of delamination in composites than the linear approach [7]. Experiments based on the nonlinear resonance technique were used by Meo [18] to detect the micro-damage and the barely visible crakes in composites. The technique aimed to induce the specimen around one of its bending resonance modes with an increasing excitation amplitude. The resonance frequency shift and loss factor variation were analyzed as a function of the excitation amplitude. Nonlinear dissipative and nonlinear elastic parameters determined from the down shift of the resonance frequency as well as the augmentation of the loss factor as function of strain amplitude was illustrated by Idriss [19] for sandwich materials. It is often proved that the measurement of nonlinear parameters using nonlinear processes is more sensitive to the presence of internal damage than the linear parameters measured through the linear method [19–21]. Therefore this method was applied for complex shape structures by Ref. [22]. Nonlinear methods are mostly applied on cracked metal

* Corresponding author. Université du Maine, LAUM, UMR CNRS n°6613, Av. O. Messiaen, 72085 Le Mans Cedex 9, France.
E-mail address: Maroua.Hammami@univ-lemans.fr (M. Hammami).

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material [23,24] granular material, rock, concrete, ceramic or synthetic slate [25]. The investigation of nonlinear methods in composite structures is still limited [26].

In the present study, nonlinear resonance vibration in laminate composite having two delaminations was investigated to examine the effect of delamination size on the linear and nonlinear dynamic behaviour of composites. Experimental findings of linear vibration and nonlinear vibration are presented in order to characterize the elastic and dissipative behaviour of delaminated composites. Then, the evolution of nonlinear elastic and dissipative parameters for variable delamination lengths is presented and discussed for several bending modes. Finally the sensitivity of this method is discussed.

2. Experimental setup

The composites were prepared to investigate the effects of delamination and curvature on the stiffness, natural frequency and modal damping. Composite material made of unidirectional layers of E-glass fibres and epoxy matrix, with the stacking sequence $[0_2/90_2]_S$. The fibre volume ratio was in the range of 58–60%. Hand lay-up procedure was adopted to create laminates using SR 1500 epoxy resin, SD 2505 curing agent and unidirectional glass fibres. Composite plates were carried out under 30 kPa as pressure, at room temperature and using the vacuum moulding process. Double superposed delaminations were artificially made using Teflon tape during manufacturing the composites at the interfaces between plies having different fibre directions. Obtained specimen had 250 mm length, 20 mm width and 2.5 mm depth. The centres of the cracks were always located at 95 mm from the clamped end of the beam. Fig. 1 is a schematic presentation of the specimen.

The resonance method was performed by inducing the specimen to a flexural wave. The experimental equipment is shown in Fig. 2. The test specimen is supported in a cantilever configuration with a clamping block. An analyzer, *Stanford Research Systems SR785*, generated swept-sine signals. Then, the signal was amplified by a *Power Amplifier PA25E*, with constant gain. The shaker *BK480* induced the beam with flexural vibrations in its clamped end. The beam response was detected using an accelerometer with a practically negligible mass, BK 352c22 fixed at the free end of the specimen. The accelerometer [9.75 mV/g] was connected to a conditioner with a frequency band. The excitation was controlled and the response was digitalized using *GPIB* card via *LABVIEW* interface. The data were saved for post processing. The beam responses were identified in the frequency domain using analysis and fitting the experimental frequency responses using *Matlab* toolbox. Then, the identification procedure allowed us to obtain the values of the natural frequency *f* and the loss factor. This test was carried out according to the ASTM C 393 standard [27].

A chirp sweep was used to induce the specimen on a frequency range around a given bending mode of the specimen. The frequency sweep was then repeated for 10 increasing amplitudes from 30 mV to 300 mV. This procedure was repeated for the first six bending modes for undamaged specimen and specimen with increasing length of delamination from 10 up to 130 mm every 10 mm [19,28].

3. Linear vibration

3.1. Frequency

To examine the effect of delamination length on the frequency of the composite beam in linear vibration, it is important to be aware of the possibility of entering to the nonlinear elastic behaviour domain. The specimens were tested at low amplitude excitation to satisfy this condition.

Fig. 3 shows the variation of the natural frequencies as a function of delamination parameter for the six first modes. Where, the delamination parameter is the ratio of delamination length by the free length of the specimen.

In this graph, natural frequencies decreased with delamination lengths, for all bending modes. Delamination reduced the natural frequencies, due to the reduction of specimen stiffness. However, the reduction of frequencies as function of delamination lengths was not the same for all bending modes. In fact, the frequency of intact composite specimen for the first mode was 26 Hz and is

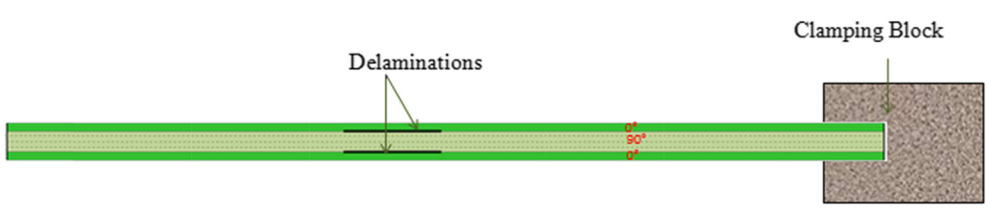

Fig. 1. Composite specimen with delamination.

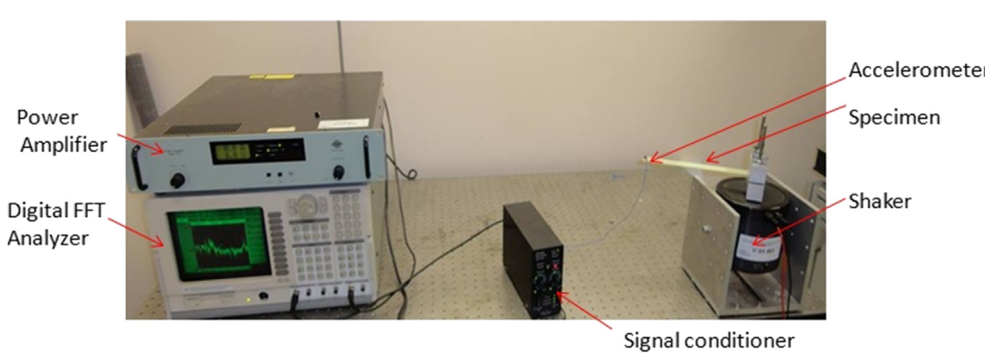

Fig. 2. Experimental setup.

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