Polymer Testing 68 (2018) 70–76

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Applying ultrasonic resonance vibrometry for the evaluation of impact damage in natural/synthetic fibre reinforced composites

D.A. Derusova[a,e,*], V.P. Vavilov[a,b], S. Sfarra[a,c], F. Sarasini[d], N.V. Druzhinin[e]

[a] *Tomsk Polytechnic University, 634028, Tomsk, Savinykh St., 7, Russia*
[b] *Tomsk State University, 634050, Tomsk, Lenin Av., 36, Russia*
[c] *Las. E.R. Laboratory, Department of Industrial and Information Engineering and Economics (DIIIE), University of L'Aquila, Piazzale E. Pontieri 1, I-67100, Monteluco di Roio, Roio Poggio - L'Aquila, AQ, Italy*
[d] *Department of Chemical Engineering Materials Environment and UdR INSTM, Sapienza-Università di Roma, Via Eudossiana 18, Rome, I-00184, Italy*
[e] *Institute of Strength Physics and Materials Science, Siberian Branch, Russian Academy of Sciences, 634050, Tomsk, Akademicheskii Av., 2/4, Russia*

ARTICLE INFO

Keywords:
Composite
Flax
Carbon fibre reinforced plastic
Ultrasonic laser vibrometry
Local defect resonance
Impact damage

ABSTRACT

Contemporary thermoset composites using natural fibres offer a wide range of strength performance. Recently, the combination of flax and carbon fibres has received an increasing attention, mainly dictated by the possibility of merging in a single material high damping properties of flax fibres and the well-known high mechanical properties of carbon fibres. Evaluation of low energy impact damage defects has received a little coverage even if these composites are well known to be susceptible to impact damage. In this study, the use of ultrasonic resonance vibrometry is proposed as an effective nondestructive tool to detect the extent of impact damage in natural/synthetic fibre reinforced composites with different stacking sequences. The results for impacts at 10 and 40 J highlighted the role played by the different stacking sequences with damaged areas being twice smaller in composites with flax skins and carbon core compared to carbon-flax-carbon sandwiches.

1. Introduction

In the last two decades, environmental concerns have triggered a renewed interest in natural fibres used as reinforcement in polymer matrix composites [1]. From available studies, it can be concluded that contemporary thermoset composites using natural fibres offer a wide range of strength performance even if surface modification by a plethora of physical or chemical methods is necessary to obtain significant improvements in performance [2]. Unfortunately, these improvements are not often suitable for semi-structural applications, and complete replacement of traditional glass fibre reinforced systems is not feasible because lignocellulosic fibres on average are weaker than man-made fibres, such as E-glass. Hybridization with synthetic fibres can therefore represent a suitable alternative that allows to broaden industrial applications of natural fibre composites. In this area, extensive literature is available [3,4]. However, mainly hybrids with glass fibres are typically reported, due to the improved mechanical properties in combination with reduced property scatter and moisture sensitivity. A less investigated hybrid configuration is the one including natural fibres and carbon fibres, likely due to the significant differences in strength, stiffness and cost. Recently the combination of flax and carbon fibres has received an increasing attention [5], mainly dictated by the possibility of merging in a single material high damping properties of flax fibres and the well-known high performance of carbon fibres [6–8]. In addition, this specific hybrid formulation can potentially deliver a more environmentally-friendly and low-cost composite at least for semi-structural applications. It is quite surprising that the response to impulsive loadings in such structures and, in particular, the evaluation of low energy impact damage defects, has received a little coverage even if composites are well known to be susceptible to impact damage. In fact, the need for composite toughening has been historically one of the key reasons for fibre hybridization [9]. Sarasini et al. [10] have recently investigated the damage tolerance after low velocity impacts of two different flax/carbon hybrid composites with a sandwich-like stacking sequence. The results pointed out that through hybridization it is possible to improve the damage tolerance with respect to only carbon laminates while preserving satisfactory residual flexural strength and stiffness. In particular, the configuration with a carbon core and flax skins exhibited a higher normalized residual strength and a slightly lower normalized residual stiffness compared to carbon fibre laminates. While optimizing composite response toward impact loadings, it is crucial to detect impact damage, especially when considering maintenance of composite structures. Because structural integrity of composite laminates is of a major concern in engineering applications,

---

[*] Corresponding author. Tomsk Polytechnic University, 634028, Tomsk, Savinykh St., 7, Russia.
E-mail address: red@tpu.ru (D.A. Derusova).

https://doi.org/10.1016/j.polymertesting.2018.03.053
Received 15 December 2017; Received in revised form 8 March 2018; Accepted 31 March 2018

efficient nondestructive testing (NDT) methods are necessary to provide a desired level of safety. In this regard, various methods have been proposed to detect damage in composite structures [11–17]. However, NDT of laminated composites still remains challenging, especially in composites with natural fibres, which are characterized by a variety of damage modes. Nondestructive evaluation of such materials is additionally complicated by material anisotropy leading to a directional dependence of wave velocity, by the difference in properties of individual constituents (for instance, thermal/electrical conductivity, stiffness and thermal expansion coefficients). All these factors make damage detection and quantification fairly difficult. In the recent years, many researchers have investigated the use of high frequency ultrasonic elastic waves which are capable of propagating over long distances in solids and of interacting with defects and flaws such as cracks and delaminations. Ultrasonic resonance vibrometry (URV) is an active NDT technique using external excitation by mechanical waves which, being injected into material, cause energy dissipation on structural defects accompanied by locally-enhanced material vibrations if a driving wave frequency is close to a resonance frequency of a defect. Propagation of mechanical waves in solids can be analyzed by means of scanning laser vibrometry that is characterized by a very high sensitivity to surface vibrations [18]. This technique allows the scanning of large areas thus being faster than conventional ultrasonic NDT. Moreover, URV is efficient in the inspection of objects with a complex geometry allowing measurement of vibration parameters at distances from 0.1 to 5 m. Recently, this technique has demonstrated promising quantitative results when detecting the damage caused by low velocity impacts in both laminates and sandwich structures [19,20].

In this study, we use the technique of URV for the detection of impact damage in natural/synthetic fibre reinforced composites aiming to increase reliability of such materials in demanding industrial applications.

2. Materials and methods

A number of various implementations of URV are being continuously developed to enhance inspection efficiency. In particular, Solodov et al. proposed a technique of local defect resonance (LDR) which involves stimulation of materials with low-power ultrasonic waves at frequencies which are resonant for defect areas [21,22]. A main advantage of this technique is a lower excitation power compared to stimulation with single-frequency magnetostrictive transducers for which electric power may reach some kW. Resonance frequencies can be determined with a good accuracy (± 10 Hz) by applying a method of laser vibrometry, and further stimulation of resonant vibrations in defects allows their detection under fairly low ultrasonic load.

The efficiency of resonance ultrasonic spectroscopy depends on the transfer of energy from an ultrasonic source to a defect area. In sound materials, the mean energy carried by elastic waves diminishes exponentially with increasing distance from a stimulation source. Presence of local discontinuities in a bulk material decreases material rigidity and creates a local oscillator characterized by a particular resonant frequency.

The LDR technique has been successfully applied by the authors to analyze resonance frequencies in real aviation components (unpublished results). For example, Fig. 1a (on-line in color) shows the determination of local resonance frequency (3.97 kHz) while detecting a delamination in an airplane rib made of carbon fibre reinforced plastic (CFRP). Distribution of total vibration pattern on an aileron in a wide-band excitation mode is presented in Fig. 1b, while Fig. 1c shows resonant vibrations at 43.78 kHz appearing in a CFRP panel with impact damage in the center.

Presently, promising materials in the transportation field are represented by hybrid composites combining synthetic and vegetal fibres. In this study, the emphasis is made on the analysis of practically important composites made of carbon and flax layers arranged in a sandwich-like architecture and subjected to impact damage, as the positioning of the layers in an interlayer hybrid composite has been found to be crucial, leading to changes in the flexural stiffness and strength, as well as in the damage mechanisms. In many instances, in symmetric layups, by positioning the fibres with lower elongation in the middle, the penetration impact resistance can be significantly increased [23]. The LDR technique has been used as a validation NDT method.

The laminates investigated in this study were manufactured by vacuum-bagging followed by autoclave processing using two unidirectional prepreg material systems based on epoxy matrix (180 g/m^2 for flax (F) and 300 g/m^2 for carbon (C)) supplied by Lineo and DeltaPreg S.p.A., respectively [10]. Two different types of hybrid laminates were manufactured according to the following configurations: FCF $[(0_2/90_2)^F/(0_2/90_2)^C/0^C]_S$ and CFC $[(0_2/90_2)^C/(0_2/90_2)^F/0^F]_S$, both characterized by an overall fibre volume fraction equal to 0.60. The 100 × 150 mm test coupons were impacted at room temperature according to ASTM D7136 at target impact energies of 10 J and 40 J. These two impact energy levels correspond to energies higher (40 J) and lower (10 J) than the respective barely visible impact damage (BVID) thresholds, which were found to occur at 30 J and 15 J for FCF and CFC laminates respectively by applying a criterion of residual indentation depth [10]. Low velocity impact tests were performed using an instrumented drop-weight impact testing machine (CEAST/Instron 9340) equipped with a hemispherical tip (diameter of 16 mm). A constant total mass of 4 kg was used while the impact energy was varied by changing the height of release of the mass.

3. Impact damage assessment in FCF and CFC composites

Ultrasonic resonance vibrometry involves determination of resonant frequencies in materials with local defects by analyzing vibrations on a test surface. As mentioned above, the occurrence of local defects leads to a local decrease in sample rigidity, and this phenomenon results in more intensive (by the order of magnitude) vibrations in the damaged area compared to sound material. Absolute vibration amplitudes are typically low not exceeding fractions of mm/s but their variations can be still detected by using scanning laser vibrometry. Any type of material delaminations caused by impact damage, crack propagation or water ingress represents an independent resonator being a source of elastic waves in accordance with the Huygens principle. Hence, by determining resonant frequencies of vibrations, one can make material intensive vibrations in damaged areas to be detected by means of a laser vibrometer.

There is an evident correlation between defect size and ultrasonic signal frequency, or ultrasonic wave length [22]. Therefore, high resonance frequencies are related to defects with size of few millimeters while bigger defects (tens of mm) require the use of lower frequencies.

It has been found experimentally that fundamental resonance frequencies accompanying impact damage with energy over 10 J are in the kHz range [24]. Test object surface vibrations can be better analyzed by applying laser scanning and processing data in the Fourier transform mode. Such procedure results in an amplitude-frequency characteristic thus allowing to determine optimal defect resonance frequencies.

This methodology has been applied to the analysis of impact damage at energies of 10 J and 40 J in hybrid composites with a sandwich-like structure (see Fig. 2). The micrographs of the samples have been obtained by means of an Altami optical microscope MET 1C equipped with the 50 × magnification.

To experimentally determine defect resonance frequencies, one should evaluate vibrations on the sample surface under acoustic stimulation in a wide frequency band. We have combined the techniques of low-power acoustic stimulation and vibration measurements by using a scanning laser vibrometer PSV-500-3D from Polytec (Table 1). Such combination of acoustic excitation and vibration analysis enables determining all possible resonances in the vibration spectrum at each sample point. The specimens were placed on a polyurethane support