Applied Acoustics 108 (2016) 50–58

Contents lists available at ScienceDirect

Applied Acoustics

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

Fatigue behaviour and structural health monitoring by acoustic emission of E-glass/epoxy laminates with piezoelectric implant

Sahir Masmoudi [a,b,*], Abderrahim El Mahi [a], Saïd Turki [b]

[a] LUNAM University: Maine University, Acoustic Laboratory of Maine University (LAUM) CNRS UMR 6613, Avenue Olivier Messiaen, 72085 Le Mans CEDEX 9, France
[b] Sfax University, Faculty of Sciences of Sfax, Department of Physics, BP1171, 3000 Sfax, Tunisia

ARTICLE INFO

Article history:
Available online 26 November 2015

Keywords:
Composite laminates
Piezoelectric implant
Fatigue test
Damage
Failure
Acoustic emission

ABSTRACT

This paper represents the continuation of our research on built-in piezoelectric sensor for structural health monitoring of composite materials. Experimental research is focused on examining the effects of the embedded sensors on the structural integrity of composite laminates subjected to mechanical tests. A series of composite specimens with and without embedded sensor are tested in fatigue loading while constantly monitoring the response by acoustic emission technique. The acoustic signals are analysed using the classification *k*-means method in order to identify the different damage mechanisms and to follow the evolution of these mechanisms for both types of composite materials (with and without sensor). The mechanical behaviour of composites with and without embedded sensor shows no difference in the form. The incorporation of piezoelectric sensor causes low degradation of mechanical properties of composites. Comparing embedded sensor to sensor mounted on the surface, the embedded sensor showed a much higher sensitivity. It is thus verified that the embedded acoustic emission sensor had great potential for acoustic emission monitoring in fibre reinforced composite structures.

1. Introduction

The application of smart-structure technology to aerospace systems has been widely investigated in recent years. Distributed sensors and actuators incorporated within a structural component can provide a system with vibration control and health monitoring for aircraft structures, etc. Nowadays, many works [1–3] are investigating the manufacture of composites incorporating new functional materials. Piezoelectric, optical fibre and magnetostrictive/electrostrictive materials are some typical examples. The presence of inclusions causes geometrical discontinuities which are responsible for the reduction of mechanical properties, failure strength and the overall material performance [4]. So, it is important to study the effects of embedded sensors on the host composite. Researchers are evaluating the life time of smart composites and they studied the damage mechanisms and the mechanical behaviour of composite materials in various types of loading.

Piezoelectric shows a particularly good capacity to satisfy exigent applications, due to unique mechanical strength, wide frequency response range, and favourable costs [5]. In order to characterise embedded piezoelectric sensor, Chen et al. [6] proposed a method of measuring the concrete load by detecting the characteristics of the embedded sensor. They used a network analyser to monitor the changes of the parameters during loading cycles in which loadings are applied on a concrete specimen with an embedded piezoceramic (PZT) sensor. To describe the characteristic change from the aspect of energy losses, three dissipation factors are also obtained from the piezoelectric equations. They concluded that piezoelectric dissipation factor performs a relative good monotonicity and reproducibility, and is recommended as load indicator for load measurement. Mall and Hsu [7] carried out tests on the performance of embedded PZT in graphite/epoxy laminate subjected to mechanical and electrical cycling loading. The mechanical fatigue was achieved by loading the specimens up to 0.2% of strain with a load ratio of 0.1. They demonstrated that embedded PZT performed better in the out-of-phase (positive voltage) than in-phase (negative voltage) conditions. Lin and Chang [8] developed a manufacturing method for integrating a network of distributed piezoceramic sensors onto laminated carbon/epoxy composite structures. Their method was performed to monitor the progress of composites cure using diagnostic signals generated by the embedded piezoceramics. They demonstrated that 'SMART Layer' (Stanford Multi-Actuator-Receiver Transduction Layer) does not degrade the structural integrity of the host composite structures. Also they concluded that embedded sensors can be used

* Corresponding author at: LUNAM University: Maine University, Acoustic Laboratory of Maine University (LAUM) CNRS UMR 6613, Avenue Olivier Messiaen, 72085 Le Mans CEDEX 9, France. Tel.: +33 (0) 243 83 34 56; fax: +33 (0) 243 83 31 49.

E-mail address: masmoudi.sahir@yahoo.fr (S. Masmoudi).

http://dx.doi.org/10.1016/j.apacoust.2015.10.024
0003-682X/

for structural applications without significant compromise. Paget et al. [9] investigated the performance of embedded piezoceramic transducers in composite material subjected to monotonic and fatigue loading. The generation of Lamb wave was carried out by using the embedded PZT transducer. They showed that the Lamb wave response remained unchanged after a large number of fatigue cycles. Also they demonstrated that the embedded transducers revealed a large working range in the static tests at least up to 90% of the final failure. In addition, any damage occurring at the transducer location did not affect the transducer performance in either static or fatigue loading. The transducer could therefore function even after the occurrence of the damage.

The control of integrated fibre glass/epoxy composites by acoustic emission (AE) is studied by Ghezzo et al. [4,10]. Tensile tests were performed on samples while constantly monitoring their AE behaviour. Results showed that composite material properties in tensile tests are substantially the same for the material with and without embedded sensors. The embedment process causes material and geometrical discontinuities within the composite. De Rosa and Sarasini [11] demonstrated that polyvinylidene fluoride (PVDF) sensors can be successfully embedded in composite structures without significantly affecting the mechanical behaviour of laminates tested in tension and three-point bending. In addition, it was verified that embedded PVDF sensors can be used as AE sensors, thus providing an on-line insight into the different damage mechanisms. They concluded that embedded PVDF can be considered as basis of an effective Structural Health Monitoring (SHM) system which is thought to be reliable, low cost and in-situ. Masmoudi et al. [12] investigated the effects of embedded piezoelectric (PZT) sensor on the integrity and mechanical response of the laminated composite materials. Flexural static and creep tests were performed on specimens while constantly monitored the response by the AE technique. Results show that the mechanical behaviour of composites with and without integrated sensor has no difference in the form; the incorporation of piezoelectric sensor influences specially the fracture load and causes low degradation of mechanical properties of materials. The analysis and observation of AE signals sets the acoustic signatures of the damage modes in the different type of composite studied.

Acoustic emission method is an efficient method to monitor, in real time, damage growth in structural components [13–15]. This technique represents the generation of transient ultrasonic waves due to damage development within the material under load. Any generated AE signal contains useful information on the damage mechanisms. One of the main issues of AE is to discriminate the different damage mechanisms from the detected AE signals. Multi-parametric classification of the main parameters extracted from the AE signals is increasingly used to separate and identify the different mechanism sources. In this context, many studies [16–18] were conducted on E-glass/epoxy laminates. These works made it possible to identify four types of signals: A, B, C and D which correspond respectively to four damage mechanisms: the matrix cracking, debonding in the fibre-matrix interface, fibre breaking and delamination.

In the order to develop the concept of smart materials, this work represents the continuation of this paper [12], the same specimens are subject to three-point bending in fatigue loading to characterise the effects of introducing the sensor into the host composite materials. Also, to discriminate the acoustic signature of the different damage mechanisms in the laminated material and to follow the evolution of these mechanisms for both types of composite materials (with and without sensor). The results of mechanical tests and acoustic emission signals collected during tests for specimens with and without integration are compared. The k-means [19] method is applied to classify the signals emitted by damage mechanisms using the Noesis software [20].

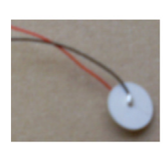
2. Materials and experimental procedure

2.1. Materials

The composite materials considered in this work were manufactured in the laboratory (LAUM-France). They are an unidirectional $[0_{24}]$ and a cross-ply $[0_6/90_6]_s$ laminates fabricated by hand lay-up process from E-glass fibres of weight 300 g m^{-2} and resin epoxy of type SR1500/SD2505. Composite plates were cured at room temperature with pressure of 30 kPa for 10 h by using vacuum bagging technique. The piezoelectric sensor (Fig. 1a) was embedded during the manufacturing stage. The diameter and thickness of the embedded sensor were respectively 5 and 0.5 mm. It was placed within the plies on the neutral plane of the composite, in a way to result in 45 mm from the edge, regarding the length, of each specimen (Fig. 2b). The specimens with and without embedded sensor (Fig. 1b) were cut out using a diamond disc from laminated plates of 300 × 300 mm^2. The dimensions of specimens are: L = 150 mm, w = 30 mm and th = 8 mm, where L, w and th are the length, width and thickness respectively.

2.2. Experimental procedure

The effect of embedding piezoelectric sensor on the mechanical properties of composites was studied in flexural tests. At ambient temperature, the specimens were subjected to three-point bending in static and fatigue loading until failure. Experimental tests were carried out on a standard hydraulic machine INSTRON 8801 of 10 kN capacity (Fig. 2a). The span length between the outer supports was taken equal to 120 mm (Fig. 2b). The displacement can be measured using a linear displacement transducer (LVDT). The machine was interfaced with a dedicated computer for control and data acquisition. Three to five specimens were tested statically to failure for each material in order to check the repeatability of the results. The specimens were tested in static three-point bending until fracture at a constant rate of 2 mm min^{-1}. The load and displacement of specimens were recorded during tests. Static tests were carried out in order to evaluate the basic mechanical properties (e.g. stiffness and strength...) of each composite. The key issue in the structural integrity of smart structures is their behaviour under applied cyclic loading. The fatigue cyclic tests were conducted with load control of sinusoidal waveform at a constant frequency rate of 5 Hz. The mean load F_m was kept constant which represents 70% of the failure load in static test. The displacement evolution of specimens was recorded during tests.



(a)

(b)

Fig. 1. (a) Piezoelectric sensor, (b) studied specimens (specimens without sensor (WS) and specimens with embedded piezoelectric sensor (ES)).