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Mechanical behavior and health monitoring by Acoustic Emission of unidirectional and cross-ply laminates integrated by piezoelectric implant

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ABSTRACT

Recent progress in sensor technologies, signal processing and electronics has made it possible to fulfill the need for the development of in-service structural health monitoring (SHM) systems. This study presents a health monitoring of composite materials integrated by piezoelectric sensor using Acoustic Emission (AE) technique. A series of specimens of composite laminates with and without piezoelectric implant were subject to three-point bending in static and creep tests while continuously monitoring the response by the AE technique. The analysis and observation of AE signals lead to the identification of the acoustic signatures of damage mechanisms in composite laminates. The mechanical behavior of composites with and without integrated sensor shows no difference in the form. The incorporation of piezoelectric sensor influences specially the fracture load and causes low degradation of mechanical properties of materials. One of the major differences between the two types of materials (with and without embedded sensor) is the intense acoustic activity in the integrated material.

1. Introduction

There is a growing need for the development of in-service structural health monitoring systems to rapidly assess the health condition and durability of composite structures. Recent progress in sensor technologies, signal processing and electronics has made it possible to fulfill this demand. New scientific and technological tools are now studied and implemented. They should allow the manufacture of composites incorporating new functional materials that are active or passive electromechanical devices. Piezoelectric, optical fiber and magnetostrictive/electrostrictive materials are some typical examples. The presence of inclusions causes geometrical discontinuities that are responsible for reduction of mechanical properties, failure strength and the overall material performance [1]. So, it is important to study the effects of embedded transducers on the host composite.

Many works have been investigated concerning the feasibility of implantation of sensors and devices in composite materials. Also they have evaluated the life time of smart composite materials and they have studied the damage mechanisms and the mechanical behavior of materials under different types of loading e.g. static, fatigue, etc. For example the implant of fiber-optic is studied by Measures [2]. He has reported on several advances and he has made towards the development of fiber-optic sensors for smart structures. This includes tests of a prototype damage-assessment system based on an embedded network of especially damage-sensitized optical fibers. He has used the Michelson fiber-optic strain sensors for the detection of damage induced Acoustic Emission and for exploring the potential of an optoacoustic cure monitoring concept. Also he has investigated the use of the intrinsic Fabry–Perot strain sensors and the Bragg grating sensor embedded within composite materials.

Piezoelectric materials show a particularly good capacity to satisfy exigent applications. These elements can be used as sensors by measuring voltage differences across parallel electrodes when cyclically strained, or alternatively they can be used as actuators by inducing expansion and contraction with an applied alternating electric field. Materials with piezoelectric properties are particularly attractive for SHM applications due to their high-frequency response and overall wide-bandwidth characteristics. Most research has indicated piezoceramic elements, specifically PZT (lead zirconate titanate), to be the most suitable for practical

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SHM efforts since these wafers have balanced actuator and sensor constants, they are accessible, have well vetted properties and reasonable thermal stability [3]. For example the embedment of piezoelectric sensors within composite structures gives the opportunity to develop smart materials and structures [4–6]. Piezoelectric implants are used in the fields of ultrasonic [7,8], electromechanical technique [5], noise and vibration control [9,10], Acoustic Emission [1,11], etc. For example, Mall and Hsu [5] carried out tests on the performance of embedded piezoceramic (PZT) in graphite/epoxy laminate subjected to combined mechanical and electrical cycling loading conditions. 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 than in-phase conditions. Lin and Chang [6] have 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 composite 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 for structural applications without significant compromise. Paget et al. [7] investigated the performance of embedded piezoceramic (PZT) 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 have shown 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 the integrated fiber glass/epoxy composites by Acoustic Emission (AE) was studied by Ghezzo et al. [1,12]. Tensile tests were performed on samples while continuously monitoring their AE behavior. Results showed that material properties in tensile tests were substantially the same of the materials with and without integrated sensors. The embedment process causes material and geometrical discontinuities within the composite. De Rosa and Sarasini [11] have demonstrated that poly (vinylidene fluoride) (PVDF) sensors can be successfully embedded in composite structures without significantly affecting the mechanical behavior 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.

Acoustic Emission method was used to analyze the different damage mechanisms detected in laminates. AE is an efficient method to monitor, in real time, damage growth [13–15]. This technique represents the generation of transient ultrasonic waves due to damage development within the material under load [13–15]. Any generated AE signal contains useful information on the damage mechanism. 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 signals of AE is increasingly used to separate and identify the different mechanisms sources. In this context, many studies [16,17,23] were conducted on composite materials. These works made it is possible to identify at least four types of signals: A, B, C and D which correspond respectively to four damage mechanisms: the matrix cracking, debonding in the fiber-matrix interface, fibers breaking and delamination. In order to improve the classification process for complex composite materials, Moevus et al. [17] have used the *k*-means algorithm to distinguish the different types of damage modes in composite. The aim of *k*-means method is to minimize the sum of squared distances between all the vectors of a cluster and its center. The *k*-means algorithm is described in [18].

This study presents an experimental study in-real time and in-situ health monitoring structure of integrated composite laminates subject to three-point bending in static and creep tests. Tests applied to the specimens with and without embedded piezoelectric sensor are conducted in order to characterize the effects of introducing the sensor into the host composite material. The results of mechanical tests and AE signals collected during tests for specimens with and without integration were compared. The *k*-means method is applied to classify the signals emitted by damage mechanisms using the Noesis software [19].

2. Materials and experimental procedure

2.1. Materials

The materials considered were manufactured in the laboratory (LAUM-France). They are an unidirectional $[0_{24}]$ and a cross-ply $[0_6/90_6]_S$ composite laminates fabricated by hand lay-up process from E-glass fibers 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 using vacuum bagging technique. The piezoelectric sensors (Fig. 1(a)) were embedded during the manufacturing stage. They were 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 the specimen (Fig. 1(b)), the sensor sizes are given in Table 1. The composite specimens with and without sensor have been cut up using a diamond disk. 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. Eventually, we obtain three types of specimens: specimen without sensor WS, specimen embedded with small sensor SS and specimen embedded with large sensor LS.

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 creep tests until failure. Experimental tests were carried out on a standard hydraulic loading machine INSTRON 8801 of 10 kN capacity. The span between the outer supports was taken to 120 mm. 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 for each test in order to check the repeatability of the results. Experimental set-up is shown in Fig. 1(c). 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 performed in order to determine the monotonic three-point bending properties: stiffness, failure load and failure displacement. In creep tests, the specimens were subjected to a constant load level and maintained in isotherm condition at room temperature. Then we recorded the increase displacement in time.

2.3. Acoustic Emission

During loading, Acoustic Emission signals sensed by PZT sensors were recorded. The acquisition of the signals was carried out using