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Mechanical behaviour and health monitoring by acoustic emission of sandwich composite integrated by piezoelectric implant

Sahir Masmoudi *, Abderrahim El Mahi, Rachid El Guerjouma

LUNAM University, Maine University, Acoustic Laboratory of Maine University (LAUM) CNRS UMR 6613, Avenue Olivier Messiaen, 72085 Le Mans CEDEX 9, France

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ABSTRACT

The feasibility of embedding piezoelectric sensor to detect the acoustic emission (AE) activities in sandwich composites has been investigated experimentally. A series of sandwich specimens with and without embedded piezoelectric sensor were tested in three-point bending in static and fatigue loading while continuously monitoring the response by the AE technique. Experimental results show that the incorporation of piezoelectric sensor causes low degradation of mechanical properties of material. The analysis and observation of AE signals leads to the identification of the acoustic signatures of four damage mechanisms in sandwich 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

The acoustic emission (AE) technique is a non-destructive technique which can be used to detect damage in materials or structures through the detection of transient ultrasonic waves due to damage development within the materials under load [1–3]. Recently, this technique has been applied on sandwich materials to detect damage mechanisms [4]. Sandwich composites structures have been widely used in aerospace structures, ship building, infrastructure, etc. A sandwich composite material results from the bonded assembly (or welding) of two thin skins typically made of materials having good characteristics in tension (high strength and high Young's modulus) and a much thicker core with low density possessing good compression properties [5].

In the classic AE technique, the sensor is coupled to the surface of the material. The coupling material own different acoustic impedance from that of sandwich material and thus increases the wave loss during wave transmission as a result of the acoustic impedance mismatch. In addition, because sandwich material with foam core is a type of material of high attenuation, AE waves are highly attenuated and distorted after long distance propagation in sandwich. Therefore, it is not applicable to monitor large-scale sandwich structures by traditional methodology. Moreover, some structures are difficult to be accessed and traditional AE sensors cannot be applied. To overcome the aforementioned problems, the use of small piezoelectric sensors, which can be embedded into the structure during fabrication of the material, can be the best solution [6]. A material implanted with piezoelectric sensor is referred to smart material [7] which is characterized by the capability of respond to changes in their environment and actuates a desired response in an advantageous manner. Research activities of smart materials and structures present now a significant potential of technological innovations. In the field of smart structures, piezoelectric sensors/actuators and fibre optic sensors are widely known and their technology readiness allows testing their capabilities in many applications [8–11]. But, the presence of these inclusions causes geometrical discontinuities that are responsible for the reduction of mechanical properties, failure strength and the overall material performance [12]. So, it is important to study the effects of embedded sensors on the host composite materials.

Nowadays, many researchers [6,11–17] are investigating the feasibility of embedding sensors in composite materials. For example Mall and Hsu [13] carried out tests on the performance of PZT (lead zirconate–titanate) embedded in graphite/epoxy laminate subjected to combined mechanical and electrical cycling loading conditions. They have showed that embedded PZT performed better in the out-of-phase (application of positive voltage) than in-phase (application of negative voltage) conditions. Lin and Chang [6] have developed a manufacturing method for integration of a network of distributed piezoceramic sensors onto carbon/epoxy composite. Their method was performed to monitor the progress of composite cure using diagnostic signals generated by the embedded piezoceramics. They pointed out that 'SMART Layer' (Stanford Multi-Actuator-Receiver Transduction Layer) does not degrade the structural integrity of the host composite structures.

* Corresponding author. Tel.: +33 (0) 243 83 34 56; fax: +33 (0) 243 83 31 49.
E-mail address: Sahir.Masmoudi.Etu@univ-lemans.fr (S. Masmoudi).

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Moreover, they concluded that embedded sensors can be used for structural applications without significant compromise. Paget et al. [14] investigated the performance of embedded piezoceramic (PZT) transducers in composite materials subjected to monotonic and fatigue loading. The embedded PZT transducers used as Lamb wave generators. 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 the integrated fibre glass/epoxy composites by AE is studied by Ghezzo et al. [12,15]. Tensile tests were performed on samples while continuously monitoring their AE behaviour. Results show that material properties in tensile tests are substantially the same of the material with and without integrated sensors. The embedment process causes material and geometrical discontinuities within the composite. De Rosa and Sarasini [16] showed that poly (vinylidene 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 system. Masmoudi et al. [17] investigated the effects of embedded piezoelectric (PZT) sensor on the integrity and mechanical response of the E-glass/epoxy composites. Three-point bending 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 three acoustic signatures of three damage modes in the E-glass/epoxy composites: matrix cracking, fibre/matrix debonding and fibre breaking. Konka et al. [18] studied the effects of embedding the piezoelectric fibre composite sensors (PFCS) in sandwich composites subject to static and fatigue tensile tests. They have investigated the output voltage response of the embedded PFCS during tests. The tensile tests showed that both the average ultimate strength and the modulus of elasticity of specimens with and without embedded PFCS are within 7%. The fatigue tests showed that the fatigue lives and strengths of both type of specimens are close to each other, as well. Also they demonstrated that the PFCS are effective in detecting of the initiations of damages like delamination inside the sandwich structures using modal analysis method.

In general, the AE technique was used to discriminate the different damage mechanisms from the detected AE signals in composite materials. Multi-parametric classification of the main parameters extracted from AE signals is increasingly used to separate and identify the sources of different mechanisms. In this context, many studies [1–3] were conducted on composite materials.

The damage mechanisms of sandwich materials which are very complex composite materials (two skins and core) are less investigated. Moreover, there are a few studies on the non-destructive evaluation of sandwich materials by AE technique. For example, Quispitupa et al. [4,19] investigated the damage modes in sandwich composites subjected to static and fatigue loading. The study of AE signals collected during tests made it possible to identify four damage mechanisms: the core damage followed by resin cracking, interfacial debonding and fibres breaking.

The study of effects of integrated PZT sensor in the sandwich materials is new [18] and it is very unusual. In this context, our contribution consists of an experimental investigation of the behaviour and the damage modes of sandwich materials integrated by piezoelectric implant subject to three-point bending in static and fatigue tests. The material investigated consists of a core of expanded PVC foam, the skins being a cross-ply laminate glass/epoxy. This type of sandwich material, which combines good mechanical properties at a relatively low cost, is particularly adapted to a wide range of industrial applications [20]. A series of sandwich specimens with and without embedded piezoelectric sensor were tested while continuously monitoring the response by the AE technique. The results of mechanical tests and AE signals collected during tests for specimens with and without integration were compared. The *k*-means method [21] is applied to classify the signals emitted by damage mechanisms using the Noesis software [22].

2. Material and experimental procedure

2.1. Material

The material considered in this work is a sandwich composite which is manufactured in the laboratory (LAUM) using a vacuum bag moulding technique. The skins are a cross-ply laminate $[0_2/90_2]_s$ consisting of unidirectional glass fibres of weight 300 g m^{-2} and epoxy resin SR 1500/SD2505 is marketed by SICOMIN Company. This lay-up's stacking sequence is chosen for this work since it was found to have strong fatigue resistance compared to other stacking sequences [23,24]. The foam is constructed from PVC (polyvinyl chloride) in density 60 kg/m^3, which provided by the Airex Company and also marketed by SICOMIN Company in panels of 20 mm thickness. The manufacture of the sandwich, the skins and the joining of the core, was carried out at the same time with the laying up of the skin plies and then by interposing the core and the second skin.

The PZT sensors were embedded during the manufacturing stage, the dimensions of the piezoelectric sensors are given in Table 1. The incorporated sensors were placed between the top skin and the foam by causing a hole in the foam in the same size as the sensor implanted, in a way to result in 87 mm from the edge of the specimen (Fig. 1). The sandwich was impregnated at room temperature, and then was vacuumed at a pressure of 30 kPa for 10 h inside the mould. Before any tests, the plates were left at room temperature for 2–3 weeks in order to allow a complete polymerization of the epoxy resin. The specimens (Fig. 2b) were cut out using a diamond saw from plates of 300×300 mm^2. The dimensions of specimens are: L = 300 mm, w = 40 mm and th = 25 mm, where L, w and th are the length, width and thickness respectively.

2.2. Experimental procedure

The effect of embedding the sensors in the sandwich material was studied. At ambient temperature, the specimens are subjected to three-point bending in static and fatigue according to ASTM D790-86 standard, at a span length of 250 mm (Fig. 1). Experimental tests were carried out on a standard hydraulic machine INSTRON 8801. The capacity of machine is ±100 kN, which can be used for static and fatigue tests. The machine is interfaced with a

Table 1
Dimensions of piezoelectric sensors embedded in the composite materials.

Piezoelectric sensor	Small sensor: SS	Large sensor: LS
Diameter (mm)	5	10
Thickness (mm)	0.5	1