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Use of piezoelectric as acoustic emission sensor for in situ monitoring of composite structures

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ABSTRACT

In this paper, the influence of the integration of several sensors in composite structures is investigated. The plates and the structures in simple shapes, composed of laminated and sandwich materials, are considered. The mechanical behaviour, the acoustics activity and the location of damage sources in various structures with and without piezoelectric implant are compared. The analysis of results allowed a better identification of the influence of the impact of piezoelectric implant on the mechanical behaviour of different structures under different loads. Then, the analysis and the observation of Acoustic Emission (AE) signals led to the identification of the main acoustic signatures of different damage modes dominant in each type of composite materials (laminates and sandwich). Viewpoint comparison between integrated and non-integrated structures, acoustic activity is more significant in the case of integrated material. The location of the sources of damage has shown that acoustic events occurred far from the positions of integrated sensors.

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1. Introduction

The recent development of Non-Destructive Testing (NDT) techniques opens up new opportunities to ensure the integrity of composite structures. In fact, the presence of sensors within a structure provides specific information about its health status (location and size of the defect), automatically and without human intervention. These processes constitute a first step to “smart” structures. The development of a real-time, in-service and smart material based Structural Health Monitoring (SHM) method has attracted the attention of a large number of industrial and laboratory researchers in the world [1].

Nowadays, many researches have investigated the feasibility of the embedment of different types of devices and sensors to evaluate the durability of the integrated transducers. Optical fibre, piezoelectric materials and MEMS sensors are some typical examples. The selection of suitable sensors depends on the mechanical integration with the host material and the reliability of sensors under service loading conditions and environments [1,2]. The researchers have also evaluated the strength and life time of smart composite materials and they have studied the damage mechanisms and the mechanical behaviour of materials under different types of loading e.g. static, fatigue, etc. The presence of these inclusions causes geometrical discontinuities that are responsible for the reduction of mechanical properties, failure strength and the overall material performance [1–3]. So, it is important to study the effects of embedded sensors on the host composite materials. For example, Warkentin and Crawley [4] tested graphite/epoxy coupons with embedded integrated circuits on silicon chips. They showed a 15% decrease in ultimate strength of the host laminate with the embedded chips. The strengths under uniaxial compressive and three-point bending loads of embedded and non-embedded graphite composites with thermosetting and thermoplastic resins were also studied by Kim et *al.* [5]. The embedment of sensors for health monitoring capabilities was simulated by integrating strain gauges or thermocouples within the prepreg material. The results showed that the embedded sensors had a negligible influence on the strength of the materials analysed.

The implant of optical fibre is studied by Read et *al.* [6]. They have studied the acoustic emission technique based damage

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detection experiment in a large carbon fibre composite structure. This structure was dynamically loaded after damage. Optical fibre sensors detected acoustic emission events during load cycles. Experiences demonstrate that acoustic emission is suitable for damage detection in the structures and that optical fibre sensor is sensitive enough for damage detection. Also they have demonstrated the functionality of both embedded and surface mounted sensors. Embedded sensors offer the potential of structures with self-diagnostic capabilities. Such smart structures could have greatly reduced maintenance costs. Also, Holl and Boyd [7] evaluated the strength and failure modes of graphite laminates in tensile and compressive static loads. The results displayed that the failure did not initiate near the optical fibre sensors in unidirectional laminates and no sensitivity to the embedded sensor was seen in quasi-isotropic cases. Nevertheless, the transverse strength was reduced.

Piezoelectric materials show a particularly good capacity to satisfy exigent applications. Most research has indicated piezoceramic elements, specifically PZT (lead zirconate titanate), to be the most suitable for practical Structural Health Monitoring (SHM) efforts since these wafers have balanced actuator and sensor constants, they are accessible, have well vetted properties and reasonable thermal stability [8]. Also, piezoelectric sensor embedded within composite structures gives the opportunity to develop smart materials and structures [1,2,9]. Piezoelectric implants are used in the fields of ultrasonic [10,11], electromechanical technique [9], noise and vibration control [12,13], Acoustic Emission [14,15] etc. For instance, Crawley and de Luis [16] found that the ultimate strength of a graphite/epoxy laminate had been reduced by 20% when a piezoceramic was embedded in the composite. Chow and Graves [17] performed an analytical study that showed interlaminar stresses had been five times higher with the embedment of an inert rectangular implant in a graphite/epoxy laminate. They indicated that the integrity of smart structures was affected due to the insertion of sensors/actuators. Also, Paget and Levin [18] investigated the strength reduction due to the embedment of a piezoceramic transducer (lead zirconate–titanate, PZT) in a carbon/epoxy laminate with cross-ply lay-up. They tested specimens in both tensile and compressive static loading conditions. They found that the embedded piezoceramic transducer did not reduce the tensile and compressive strength of the composite.

Mall et *al.* [9,19] carried out tests on the performance of piezoceramic (PZT) embedded in composite laminates subjected to combined mechanical and electrical cycling loading conditions. In tensile loading case, the embedded piezoceramic transducer reduced the ultimate strength of the composite by 4%. In fatigue loading, the transducer did not significantly reduce the strength. They showed that embedded PZT had performed better in the out-of-phase (application of positive voltage) than in-phase (application of negative voltage) conditions. Mall [20] incorporated a piezoelectric material (PZT) in a composite panel to investigate the effect on tension failure stress and tension–tension fatigue. The PZT material was either inserted into a cut-out area, or directly inserted in the layup and co-cured. Both configurations, as well as specimens with no PZT were loaded in axial tension to failure. The failure stress and damage sequence were nearly identical for all three cases. Similarly, tension–tension fatigue loading of the same type specimens showed no difference in fatigue life for the specimens with embedded PZT. In these tests, the PZT material was not actuated.

Lin and Chang [2] developed a manufacturing method for integrating a network of distributed piezoceramic sensors onto laminated carbon/epoxy composite. 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. Moreover, they concluded that embedded sensors can be used for structural applications without significant compromise. Paget et *al.* [10] 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. Qing et *al.* [21] developed the technique to embed a sensor network inside composite structures using a different fabrication process. Mechanical tests on composite coupon specimens with and without embedded SMART Layers show that the presence of the SMART layer neither noticeably affects the strength of the host composite structure, nor promotes delamination, but rather defers it.

The control of the integrated composites by Acoustic Emission (AE) was studied by Ghezzo et *al.* [14,22]. Tensile tests were performed on samples while continuously monitoring their AE behaviour. Results showed that material properties in tensile tests were substantially the same of the materials with and without integrated sensors. Early acoustic events are detected at the sensor location at almost one quarter of the stress that is observed to induce acoustic activity in the material without implants. Moreover, the amplitude of the events acquired is usually higher than those noticed in samples without implants. De Rosa and Sarasini [15] have demonstrated 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. Masmoudi et *al.* [23,24] investigated the effects of embedded piezoelectric (PZT) sensor on the integrity and mechanical response of the composite materials. Three-point bending 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. Comparing embedded sensor to sensor mounted on the surface, the embedded sensor showed a much higher sensitivity.

To locate damage, Kirikera et *al.* [25] studied the passive structural neural system (SNS) for damage detection on aluminium and composite panels. The asymmetric Lamb wave propagation representing acoustic emissions is modeled based on a superposition of plate bending vibration modes. The simulation demonstrates that the SNS with four channels of data acquisition can localize damage within a grid of sensors irrespective of the number of sensors in the network. They have demonstrated that the SNS could become part of an Integrated Health Monitoring System for metallic/composite structures including wind turbines and aircraft. Wenger et *al.* [26] investigated the suitability of piezoelectric bimorph sensors as in-situ acoustic emission sensors, embedded into glass epoxy laminated plate. The bimorphs have essentially differentiated between the two types of plate wave propagation, although the differentiation has been determined by the wavelength of the acoustic wave compared to the sensor dimensions. In comparison of monomorph

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