Effects of embedded SHM sensors on the structural integrity of glass fiber/epoxy laminates under in-plane loads

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ABSTRACT

This experimental research is focused on examining the effects of stress concentration due to the embedded Structural Health Monitoring (SHM) sensors on the structural integrity of glass fiber/epoxy laminates subjected to in-plane tensile loads. Recent advances of health monitoring technologies have resulted in development of micro-dimensional sensors that can be embedded into composite laminates. Notwithstanding their small sizes, such inclusions may affect the response of the composite. Damage induced by the peak values of stress concentration around the embedded devices is, in fact, one of the main concerns. To assess this and related issues, we have fabricated a series of samples with and without embedded (dummy) sensors and micro-processors in S2 glass fiber/epoxy laminates, and systematically tested the samples while continuously monitoring the response by the acoustic emission technique. In this manner we have sought to address the process of damage initiation and evolution within the material. The results show that acoustic events begin earlier on during the loading process, in specimens with embedded sensors and the source of the damage is located near the sensors. These early events are associated with matrix failure at the sensor-resin interfaces through micrographic observations.

Keywords: Structural health monitoring, Stress concentration, Acoustic emission, Damage, Composites

1. INTRODUCTION

In recent years, health monitoring of composite structures and components has become one of the major concerns among the engineering community. Recent advances in the microelectronics industry are clearly showing progress at achieving smaller chip and sensors sizes of consuming less power, while steadily increasing the processing and functionality. However, such inclusions may affect the local integrity of fiber-reinforced polymers. Notwithstanding the developments of the sensors technology, the study of the effects of the embedded transducers on the host composite is still an important issue. The presence of inclusions causes material and geometrical discontinuities that are chiefly responsible of unwanted peak values of stress concentration with consequences on the reduction of the stiffness and the overall material performance [1-3]. For this reason, considerable effort has been devoted so far into adding monitoring functionality into composites without compromising the material integrity. Many works have been focusing particularly on the feasibility of the embedment of different kind of sensors and devices both evaluating the durability of the integrated transducers and quantifying the strength and fatigue life of the host material.

With regard to the effects on the material strength and failure, several experimental studies have been performed with both passive (or simulated) and active embedded devices [4-11].

As continuation of these studies, the present paper shows the experimental results of the tests conducted on unidirectional S2 glass fiber/epoxy samples with embedded (dummy) sensors. To assess the initiation of the damage within the material, the samples fabricated have been tested and continuously monitored using the acoustic emission technique. In this manner the mechanical response and failure initiation of two different systems, which will be referred as blank samples and samples with embedded dummy sensors, have been compared.

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The present work has been developed at the Center of Excellence for Advanced Material, University of California San Diego, and is part of a project which involves multidisciplinary efforts combining material manufacture and embedding techniques enhancements, structural integrity studies and microelectronics design for the development of a new type of smart material with integrated dense, small and advanced sensors network in a way that enables internal damage sensing.

2. EXPERIMENTAL METHOD

The material under research is a multilayered composite made of S2 fiber glass BT250E-1LV epoxy resin prepreg by Bryte Composite Technologies Inc. Panels 250mm long and 250 mm wide with thickness varying between 0.4 - 2.4mm were manufactured manually stacking different sequences of layers. During the fabrication process, 0805 chip resistors by Koa Speer Electronics Inc., were embedded as dummy sensors within the prepreg on the neutral plane of the laminate, in a way to result centered with respect the two in plane global axis of the final machined samples. The curing of the resin was accomplished by following the procedure recommended by the material supplier.
Afterwards, specimens for tensile tests according with ASTM standards [12] were cut from the panels using a diamond wheel saw. The samples were also provided with end tabs, made using the same material, to avoid failure at the grips.
Table 1 lists the lamina main mechanical properties together with the laminates lay-ups tested.
The material properties were assessed testing unidirectional $[0]_n$, $[90]_n$, $[\pm 45]_n$ laminates instrumented with strain gages to measure the transversal and longitudinal strains. For a better understanding of the acoustic emission results, as well as for assessing the early damage initiation in laminates with integrated dummy sensors we dedicated part of our efforts in exploring the material microstructure. Standard optical metallographic techniques allowed the characterization of void size, percentage and distribution of flaws as well as the analysis of the sensor-matrix resin interface.

Lamina properties								
E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	υ_{12}	υ_{13}	σ_f (MPa)
47	9.8	9.8	3.77	3.77	-	0.29	0.29	1730
Blank samples			$[0]_2$		$[(\pm 45)_5]_s$		$[90]_{12}$	
Samples with embedded inclusions			$[0]_4$		$[(\pm 45)_5]_s$		$[90]_{12}$	

Table 1 S2/BT250E-1LV material properties and lay ups.

3. RESULTS

Quasi static tensile tests were performed in ambient laboratory conditions using a standard servo-hydraulic MTS testing machine, equipped with 100kN load cell, at the constant displacement rate of 0.02 mm/sec. The samples behavior was continuously monitored by a PCI-2 acoustic emission system by Physical Acoustic Corporation. The AE activity was detected through R50D sensors with peak frequency at 175 kHz and the data collected and analyzed with AE win software. For the repeatability of the acoustic results, Hsu-Nielsen tests were first considered [13].
Since composites are well suited for amplitude distribution analysis [14-16], the following results are mainly presented as comparison of the damage events amplitude identified in samples with and without integrated dummy sensors. The following plots present the distribution of the events amplitude versus the increasing of the external load. Due to the uniqueness of each test, only some of the results obtained are here reported. However, at least five samples per type were tested and the results were found consistent and repeatable.

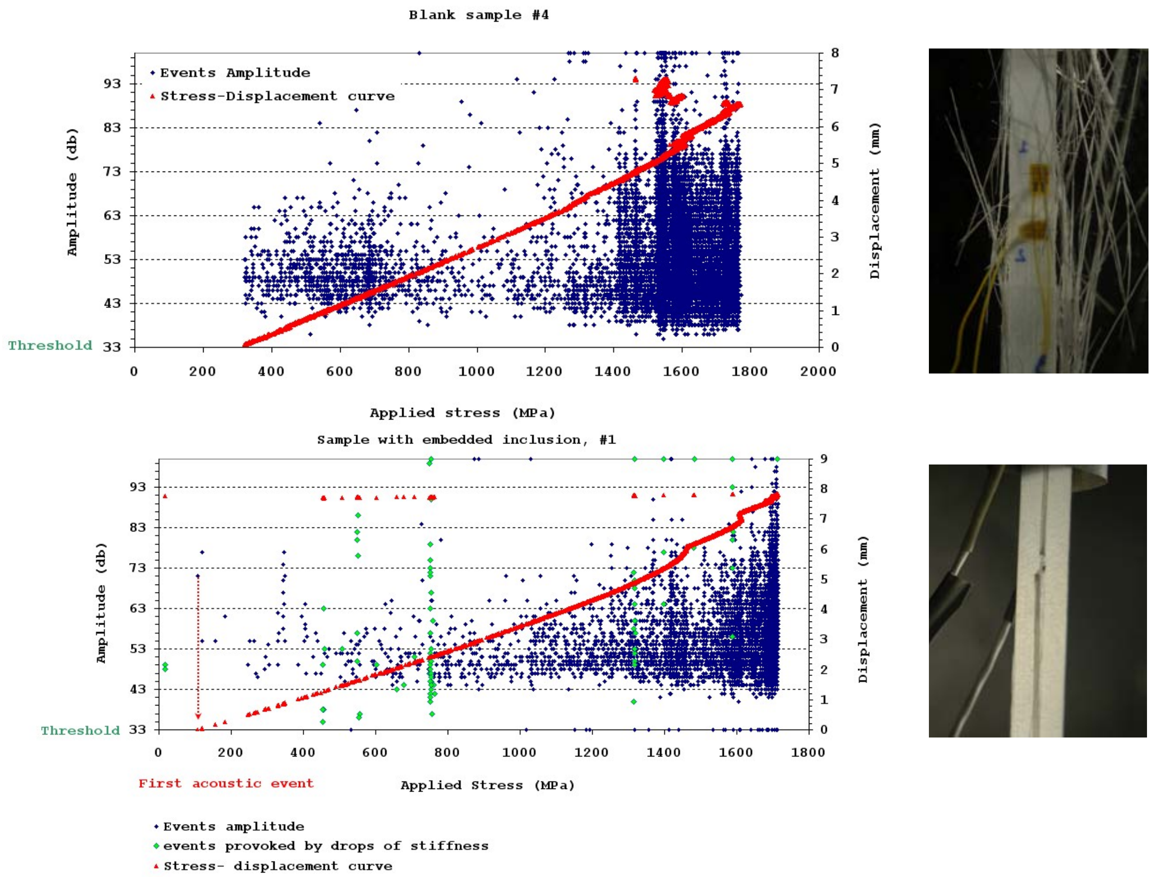

Figure 1 Failure mechanism and acoustic behavior of $[0]_4$ samples without and $[0]_6$ with embedded inclusions

In all $[0]_n$ samples with embedded dummy sensors, the acquisition of isolated but high amplitude events started almost at one quarter of the external stress applied on blank specimens, figure 1. The amplitude of the early emissions is generally higher than that observed in blank cases. Moreover, the linear location feature of the acoustic emission system identified the position of these events at the dummy sensor location. Of notice is that the strength of the material with implant was estimated to be 2-4% less with respect the one of the blank sample case although a different failure mechanism was observed.

In $[90]_{12}$ samples the failure and the acoustic behavior is presented in figure 2 and figure 3.

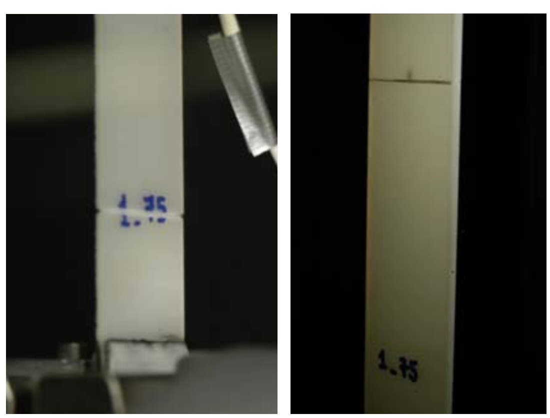

Figure 2 Failure of $[90]_{12}$ samples without and with integrated dummy sensor

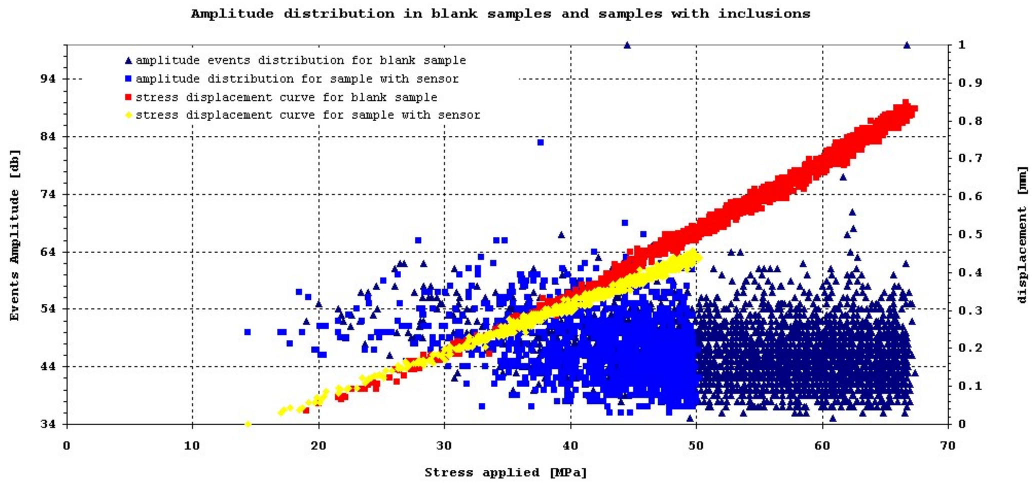

Figure 3 Acoustic emission amplitude distribution of $[90]_{12}$ samples without and with embedded inclusions

One of the major differences between the two types of sample, Figure 3, is the fact that the failure in samples with inclusions occurs at considerable lower stress than in blank cases. The strength of the material with implants presents a reduction of 24% and the damage initiation begins at the sensor location with the net cross section failure. Moreover, the average of the events amplitude in case of material embedded inclusion and the number of counts per event is generally higher as observed in previous 0-degree orientation tested.

Unlike the previous cases analyzed, samples with $[\pm 45]_n$ lay-ups showed a different acoustic behavior and failure mechanism. As shown in figure 4, the failure did not occur at the dummy sensor location, and this fact was observed in all samples tested. Besides, the mechanical response of the material was the same for both types of samples.

Localized high damage such as resin-sensor interface debonding, cracks opening, and fiber matrix debonding near the dummy sensor was identified in a series of micrographic inspections. Although localized damage started at the implant location, other distributed sources of damage initiation were detected within the specimen and the final failure, in fact, occurred far from the embedded device. The propagation of early micro-cracks at the sensor-matrix interface therefore seemed to be restrained.

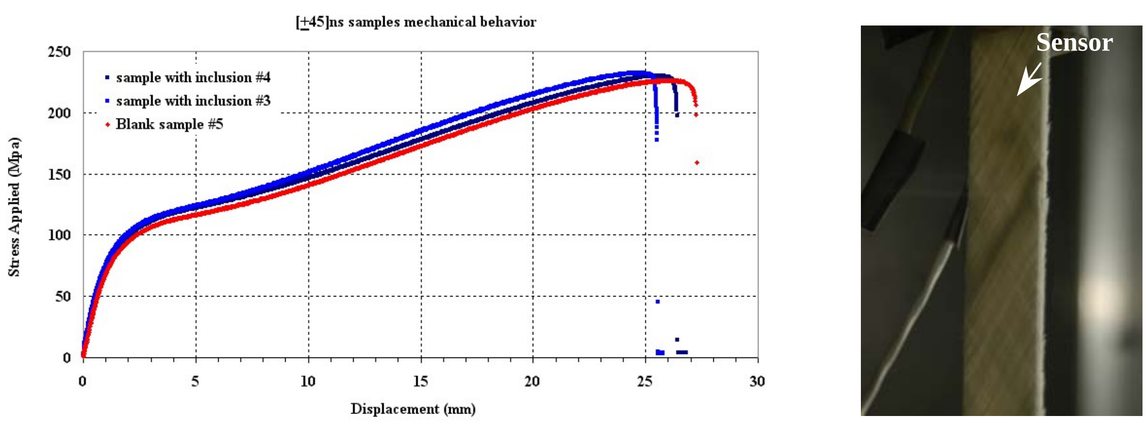

Figure 4 Mechanical response of $[\pm 45]_{5s}$ samples and typical failure of samples with integrated dummy sensors.

As previously observed in $[0]_n$ and $[90]_{12}$ samples, acoustic emission events began early in sample with integrated chip resistors at almost ¼ of the external stress applied on blank samples which is seen to cause damage emissions. The distribution of these events amplitude is characterized by higher values than those observed in blank sample type.

4. CONCLUSIONS

In this experimental work the investigation of the effects of embedded simulated SHM sensors on the integrity of unidirectional glass fiber laminates has been presented. Tensile quasi-static tests were performed on samples with embedded dummy sensors while constantly monitored by the acoustic emission technique.

The outcome of this research highlights a significant difference of the mechanical behavior, damage growth and location in samples with integrated implants and different lay ups. Overall, the data acquired by testing different laminates is consistent and indicates similar trends in all the experiments. Some of the major results follow.

The failure mechanism initiates at the dummy sensor location in $[0]_n$, $[90]_n$ and $[45]_n$ laminates. Stress concentration due to the presence of material and geometrical discontinuities is certainly responsible for early micro-cracks events around the embedded device. In $[0]_n$ the micro-damage propagates freely along the fiber orientation within the resin matrix. Nevertheless, the material tensile strength seems not to be compromised.

A net cross section failure at the sensor location was instead observed in $[90]_n$ laminates with a significant reduction of the material overall strength (24%). Finally, $[45]_n$ laminates with embedded chip resistors showed a different failure behavior. Although subjected to shear loading and in presence of stress concentration areas at the dummy sensor-resin matrix interfaces, the failure of the sample never occurs at the sensor location.

The aforementioned conclusions demonstrate that non-zero fiber orientations seem more suitable for the embedment of sensors and devices within glass/fiber laminates made by prepreg material, although the laminate lay up optimization for bearing the desired loads is, of course, needed. Furthermore, the damage initiation detected in samples with embedded devices has been always identified at the sensor location and characterized by high values of the signals amplitude so that the enhancement of the embedment and manufacture techniques will be of paramount importance for the final material performance.

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