Onset of Resin Micro-Cracks in Unidirectional Glass Fiber Laminates with Integrated SHM Sensors: Experimental Results

Fabrizia Ghezzo,** Yi Huang† and Sia Nemat-Nasser*

Department of Mechanical and Aerospace Engineering, Center of Excellence for Advanced Materials, University of California, San Diego, 9500 Gilman Drive La Jolla, 92093-0416, CA USA

This article presents the results of experiments conducted in order to identify and locate the failure initiation in glass fiber/epoxy laminates with integrated structural health monitoring sensors (SHM) and electronics. Recent advances in health monitoring technologies have resulted in the development of micro-dimensional devices that can be embedded into composite laminates. Notwithstanding their small size, such inclusions may affect the response of the composite. Damage induced by the peak values of stress concentration around the embedded inclusion is, in fact, one of the main concerns in smart structures technology. To address this specific issue, unidirectional S2 glass fiber/epoxy laminated composites are fabricated with embedded small implants that mimic potential sensors and microprocessors. Quasi-static tensile tests are then performed on those samples while monitoring them by the acoustic emission (AE) technique. Additionally, the microstructure of the material with and without implants is explored. The AE results show that early low-medium amplitude events are detected at the implant location and the micrographic inspections reveal that micro-cracks initiate at the device-composite matrix interface and grow around the implant causing the debond of the external component from the surrounding resin system.

Keywords structural health monitoring · embedded device · stress concentration · composites · acoustic emissions · matrix micro-cracking

1 Introduction

In recent years, considerable effort has been devoted to adding health-monitoring functionality within composites without compromising the material integrity. Till date, many works have been focusing on the feasibility of the embedment of different kinds of sensors and devices both evaluating the durability of the integrated transducers and quantifying the strength and fatigue life of the host material. Notwithstanding the developments in sensor technology, the study of the effects of embedded transducers on the host composite is still of relevant importance. The presence of inclusions causes material and geometrical discontinuities that are responsible for
unwanted peak values of stress concentration with consequences on the reduction of the stiffness and the overall material performance.

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.

Warkentin and Crawley [1] studied the feasibility of embedding active integrated circuits on silicon chips within graphite/epoxy laminates. They explored the material manufacture as well as the durability of the sensors and composite under different testing conditions. The presence of the integrated device appeared to have no effect on the longitudinal mechanical properties while the results reported a 15% reduction of the maximum bearable stress.

The strengths under uniaxial compressive and three-point bending loads of embedded and noneMBEDDED graphite composites with thermosetting and thermoplastic resins were also studied by Kim et al. [2]. 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 analyzed.

To reduce the effects of the implanted device on the material integrity, several embedding techniques have also been proposed. Singh and Vizzini [3] analyzed the interlaminar stress state surrounding an active actuator integrated into a unidirectional composite laminate through an interlacing technique. They concluded that this technique increases the static strength of the composite structures with embedded actuators by redistributing through the thickness the load around the inclusion and the host/inclusion interface. The usefulness of the interlacing method was proved in another work by Vizzini and Shulka [4] where a different embedding procedure was performed to integrate thick dummy sensors within unidirectional graphite/epoxy laminates. The embedment was made by cutting the material around the embedded simulated sensors. Eight plies out of the 24 were cut around the inclusions, so that the strength of the material was based on the remaining plies. This process had severe consequences on the material strength and showed the favorableness of a dispersed interlacing technique in improving the embedded material strength. A few years later, Hansen and Vizzini [5] studied the effect of the interlacing configuration on the structural integrity of the host and the host/device interface in fatigue loading conditions. Unidirectional graphite/epoxy specimens with embedded glass slices were tested under static tension and tension–tension fatigue. Their results showed significant differences in the static and fatigue strengths for different embedding techniques. Particularly, they showed that the fatigue life of embedded samples, where the real sensors were simulated by integrating the glass slices, was severely degraded if the embedment was accomplished by using a cutout method; the results were compared to those where the interlacing technique was applied.

In the fabrication of materials with integrated devices, different techniques were recently investigated by Ghasemi-Nejhad et al. [6] for embedding active piezoceramic actuators and patches within the woven carbon/epoxy material. Specifically, the integration of piezoelectric patches into composite panels was accomplished by cutout holes and molded in holes methods. Techniques to take the piezoelectric wires out of the panel are also proposed in their work.

The damage mechanisms due to the effects of embedding active piezoelectric (PZT) sensors on the strength and fatigue behavior of quasi-isotropic graphite/epoxy laminates were investigated by Mall and Coleman [7]. They performed tensile monotonic tests and inspected the edges of the samples for the presence of micro-cracks every time the stress was increased by 50 MPa. This procedure was repeated until 350 MPa. Afterwards, the samples were tested to failure. In monotonic tensile tests, both the average ultimate strength and Young’s modulus of the laminates with or without PZT were within 4% of each other and their fatigue lives were also very close. Similarly, Paget and Levin [8] studied the strength reduction due to the embedment of thin (0.13 mm) PZT transducers in cross-ply carbon/epoxy composites. They found that the embedded PZT sensors with their interconnectors did not reduce the strength of the laminate. Moreover, in static tensile and compressive tests, the final
failure did not coincide with the embedded PZT location in the composite.

Mall [9] also investigated the integrity of graphite/epoxy laminates with embedded PZT sensors under quasi-static and fatigue loads. The investigation was carried out on samples with material cut outs and samples where the sensors were embedded within two plies without cutting the material around them. Yet, the results showed that neither the static strength nor the fatigue life was affected by the embedded sensor and by the embedment technique.

There are also the studies of the integration of Fiber Optic sensors (FO) into composites. Holl and Boyd [10] 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 fiberoptic sensors in unidirectional laminates as well as no sensitivity to the embedded sensor was seen in quasi-isotropic cases. Nevertheless, the transverse strength was reduced.

Sirkis and Singh [11] also addressed the issue of whether or not the failure mechanisms in laminated thick composites with embedded optical fiber sensors and piezoceramic actuators are influenced by the inclusions, using optical microscopy and Moiré interferometry. Their conclusions differ from previous similar works [12–14] showing that no perturbation in the strain state can be attributed to the embedded optical fibers. They concluded that the lay-up of the material examined and its thickness could be responsible for the dissimilarities.

From the above references it appears that in cases where the thickness of the implant did not alter significantly through-the-thickness geometry of the host material, the local stress concentration values remained very small, thus with negligible effects on the material integrity. Otherwise, where the integrated devices were of not negligible size, the reduction of the strength of the embedded material as well as the damage mechanisms had to be quantified and investigated.

Recently, Shivakumar and Emmanwori presented the results of the experimental and numerical work [15,16] conducted on the effects of embedded fiberoptic sensors on the integrity of carbon/epoxy laminates. They focused on the issue of the damage initiation and propagation within the material. According to their experimental observations the in-plane properties of the material were unaffected by the fiberoptic sensors and a small reduction (10%) of the tensile strength was observed. Besides, the compressive strength was greatly reduced (40%). A key feature of their study was the investigation of the material microstructure and the inspection of the progression of the damage at different levels of the applied stress. The site of damage initiation was found numerically to be at the tip of the eye-shaped resin pockets located around the integrated sensor. The failure was attributed to delamination growth due to high values of the transversal stress.

In conclusion, due to the variety of sensors and actuators commercially available, the constant enhancement of polymeric materials' properties, the large range of reinforcing materials, and different fabrication processes and embedding techniques, further investigation of the local effects of an external device integrated within composite materials is still of considerable interest.

The present article is therefore the continuation of the studies on the structural integrity of laminated composites with embedded passive or simulated sensors and electronics.

The experimental investigation outlined in this article is specifically addressed to the identification of the failure mechanisms in a unidirectional fiberglass/epoxy laminate containing thick inclusions. It is known how peak values of stress concentration due to the presence of notches and discontinuities can trigger the initiation of matrix micro-cracks in laminated composites. Therefore, the identification of the failure initiation in layered composites with integrated electronics and the quantification of the effects that the implanted devices may have on the local integrity of the host material have been studied.

The analysis of a unidirectional laminate is taken into account in this work since it represents the most critical case. If implants are embedded into unidirectional plies, micro-cracks into the resin can propagate very quickly and in unstable manner along the fibers direction causing a fast degradation of the material in terms of mechanical properties and structural performance.
The consequent severe drop of stiffness of the unidirectional plies can lead to sudden material failure. A numerical analysis on this specific case has been conducted in a companion paper [17]. The microprocessors are simulated by integrating small chip resistors within the material and monitoring the material behavior under monotonic tensile loads using the acoustic emission (AE) technique. Amplitude and frequencies of the first acoustic signals acquired during the loading history have been analyzed.

2 Sample Fabrication

The material employed for this experimental investigation is a fiber glass S2/BT250E-1LV epoxy prepreg tape by Bryte Technologies Inc. Two, four, and six layers were laid up by hand to obtain \([0]_2\), \([0]_4\), \([0]_6\) laminates, with average thickness of 0.42, 0.8, and 1.28 mm respectively. The panels, 250 mm wide, 250 mm long, and of various thicknesses were then fabricated using the vacuum bagging and compression molding technique. Particular care was taken in debulking the material during the hand lay-up procedure. The curing of the resin followed the manufacturer’s recommendations and this was achieved by hot pressing the material at 121°C under 0.34 MPa pressure. The curing temperature was reached in a slow ramp (2°C/min) and held constant for 1 h.

Two sets of panels were fabricated in this way: blank panels (without embedded dummy sensors/microprocessors) and panels with integrated devices. The embedment of structural health monitoring (SHM) sensors and electronics was simulated by integrating 0805 chip resistors (by Koa Speer Electronics Inc.) at the mid-plane of the material stacking sequence.

Particularly, the results of six-layer panels with embedded dummy microprocessors and two-layer unidirectional specimens without inclusions are presented. No change in the failure mechanisms and acoustic behavior among blank samples with different number of plies were observed in all the experiment conducted. However, at least four layers were necessary to properly integrate a 0.5 mm thick device. Owing to the pressure applied on the material during its fabrication, in fact, the rigid inclusion can indent the prepreg material and damage the fibers. As the result of practical observations, this fact can be avoided if the thickness of the material above and below the implant is at least the same of the one of the integrated device. For this reason the results on \([0]_6\) laminates with integrated inclusions are presented. The results in terms of amplitude and frequency and other parametric features of the acoustic emissions were not affected by the number of plies that constitute the samples analyzed, but the number of events occurring within the material, if the overall material behavior is considered, may change considerably. Only the analysis of the characteristic features of the events related to the failure initiation and their classification is here reported.

The structure, materials, and the dimensions of the embedded device as well as the lamina properties are given in Table 1.

Samples, according to the ASTM 3039 standard for tensile tests [18], were cut from the panels using a diamond wheel saw. For the panels with integrated chip resistors, the samples were cut in order to have the devices centrally located with respect to the two global in-plane axes of the specimens.

Fiber glass/epoxy tabs were bonded at the specimens’ extremities to prevent failure at the grips.

Small samples (25 mm × 25 mm and various thicknesses) were also cut in order to determine the fiber volume content [19], \(V_f\), which was found to be 53% for all the fabricated panels. Strain gauges were attached to the samples and they were tested in tension, finding that both types of samples, with and without embedded inclusions, displayed the same behavior in quasi-static tensile tests. The dummy sensor did not seem to affect the in-plane material properties and had a negligible effect on the samples’ tensile strength. However, the failure process was remarkably different, as discussed in the following section.

3 Experimental Procedure

Quasi-static tensile tests were performed in ambient laboratory conditions using a
servo-hydraulic MTS testing machine equipped with 100 kN load cell. The monotonic load was applied at a constant 0.02 mm/s displacement rate.

All the tests were monitored continuously by a PCI-2 AE system produced by Physical Acoustic Corporation (PAC). The AE activity was detected through external R50D sensors with peak frequency at 175 kHz and the data were collected and analyzed using AEWIN software [20].

Hsu–Nielsen tests were first considered [21] to determine the wave speed for the material with different fiber orientations. For this purpose, a unidirectional \([0]_24\) S2/epoxy panel without embedded inclusions with four acoustic sensors mounted on one surface was used to characterize the signal produced by the standard pencil lead breakage event. As a consequence of those tests the PAC system was used with the following settings: PDT (peak definition time) equal to 50 μs; HDT (hit definition time) 300 μs; LDT (lock out definition time) 800 μs; and sampling rate of 2 MHz.

The quasi-static tensile tests were performed using two and, in some cases, four acoustic sensors clamped on the surface of the sample with vacuum grease couplant to improve the transmission of the signals through the sensor-sample surface interface. Additionally, the threshold was fixed at 33 db and pre amplification at 40 db.

Different AE information was acquired during the tests, such as: events amplitude, events duration, number of counts per event, signal waveforms and its associated energy, and all the information regarding the very first events occurring in the load history was specifically examined. Ten samples were tested until failure and their behavior compared. Additional information about the material failure modes, however came from the observation of the material microstructure.

To this end, prior to testing, four samples of each type were cut, polished, and analyzed using standard optical microscopy. Some of the samples with integrated dummy microprocessors were cut in correspondence of the implant orthogonally to

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**Table 1** Materials and their in-plane mechanical properties.

<table>
<thead>
<tr>
<th>BT250E-1LV in-plane properties</th>
<th>S2/BT250E-1LV lamina in-plane properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (GPa)</td>
<td>Longitudinal modulus (GPa)</td>
</tr>
<tr>
<td>3.86</td>
<td>47.8</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>Transverse modulus (GPa)</td>
</tr>
<tr>
<td>75.0</td>
<td>9.8</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>Shear modulus (GPa)</td>
</tr>
<tr>
<td>1.39</td>
<td>3.7</td>
</tr>
<tr>
<td>Shear strength (MPa)</td>
<td>Longitudinal tensile strength (MPa)</td>
</tr>
<tr>
<td>35</td>
<td>1730</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>Transverse tensile strength (MPa)</td>
</tr>
<tr>
<td>0.39</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>In Plane shear strength (MPa)</td>
</tr>
<tr>
<td></td>
<td>55</td>
</tr>
</tbody>
</table>

Embedded 0805 chip resistor: materials and properties

![Diagram of chip resistor](image)

*Table data* and *diagram are courtesy of koa speer electronics inc.*

The protective coating is assumed to be an epoxy resin with same or similar properties of the composite matrix.
the fiber direction, others along them. Figure 1 shows part of the cross section of a six-layer sample with inclusion. The presence of few distributed voids within the resin matrix can be easily seen, at the lowest magnification (50×). The metal coating of the resistor, whose schematic is given in Table 1, is also well distinguishable. It can be recognized as the bright thin layer between the inclusion core and the surrounding composite material in Figure 1.

![Cross-section at the dummy sensor location in unidirectional samples; view orthogonal to the fiber direction.](image1)

Figure 1

Figure 2 presents a further amplification of the same sample cross section which focuses on the sensor-resin interfaces, while Figure 3 shows the side view, i.e., along the fiber orientation, of another sample cross section at the dummy sensor location.

As these pictures document, the embedment of relatively thick inclusions as microprocessors, forces the plies above and below the implant to deform, leaving large resin-rich regions. The length of the resin-rich area shown in Figure 3 was observed to be around 6 mm in all the unidirectional samples. More precisely, two resin-rich areas, symmetrically located with respect to the integrated dummy sensor, form along the fiber direction. Orthogonally to the fibers the material around the sensor appears uniformly distributed through the thickness. However, the fibers are spaced farther apart in these regions.

It is also well known that such material inhomogeneities induce high values of localized residual strains during the material fabrication due to the mismatch of the thermal properties between the resin and fibers [22–24]. Their negative effects can influence the matrix/fiber interface strength.

![Photomicrographs of the dummy sensor–matrix interface within a unidirectional sample; view orthogonal to the fiber direction.](image2)

Figure 2

![Photomicrograph, magnification 50×, of the resin pocket area around the embedded dummy sensor: side view, along the fiber direction.](image3)

Figure 3
Of particular interest also is the finding that voids due to the curing process and air eventually trapped within the material during the hand lay-up procedure are generally observed being distributed between two adjacent plies. Very few voids of smaller size were instead found at the sensor-resin matrix interface in some of the samples analyzed. This observation led to assume a good quality of the bond achieved between the composite and the simulated sensor surfaces during the fabrication which assumption was used for the development of our numerical studies.

The total area of the cross section occupied by the voids was estimated around 1.4–1.6% in both samples with and without embedded inclusions through analysis of the images.

Additionally, different samples were cut and polished progressively to show their microstructure at different distances from the implant.

The first image (A) in Figure 4 shows the tip of the resin pocket area at almost 5 mm from the inclusion, while the second image (B) shows the cross section of the material with the integrated device. In this way, the inclusion status after the fabrication as well as the resin pocket region integrity was explored. The observations were repeated on four different coupons.

The same procedure was adopted to identify possible sites of micro-crack initiation into the resin matrix in samples that were a priori subjected to determined stress levels. After a certain load was reached, the samples were unloaded and removed from the grips to be polished and their microstructure analyzed. The results follow in the next section.

4 Test Results and Discussion

The AE technique has been extensively used for assessing micro-changes and damage in materials and structures. Acoustic emissions are stress waves generated by deformation, micro-fracture, and failures within the material that can be sensed by PZT transducers. The signal output of the PZT sensors, then, can be amplified and analyzed to provide important information about the damage onset and growth. Many efforts have been already made to categorize the different sources of damage within composites, such as matrix cracking, fiber–matrix debonding, fiber pull-out, fiber breakage, and interlaminar delamination through signal amplitude and other classical AE parameters or through frequency analysis. First, significant attention has been devoted to the understanding of the damage failure mechanisms identification using the AE technique described in [25–28]. Many other contributions exist that specifically address the study of damage source identification within composite plates.
A recent classification of the acoustic events within glass fiber-reinforced composites is reported in [29]. Additionally, it has been demonstrated that in single-edge-notch laminated composites, the presence of stress concentrators induces a higher number of acoustic events with higher spectrum of frequencies than in un-notched materials [30]. Following these previous works therefore, we present the results obtained comparing the acoustic behavior of samples with and without embedded inclusions. The focus is on the characterization of the initial acoustic events within the material. In this work, we base the identification of the initial acoustic activity on classical AE parametric information supported by the material microstructure observation and analysis.

As mentioned before, two kinds of experiments were conducted. First, five samples of each type (blank [0]₄ and [0]₄ with inclusion) were monotonically loaded in tension until failure, while being monitored by the acoustic transducers. The typical material response and the acoustic events detected during the tests are presented in Figures 5 and 6. The following results refer to two specific experiments. However, an overview of the complete tests is given in Table 2. Good repeatability of the tests and agreement of the results were observed.

The AE system records external information, such as load and displacement, only when an audible event occurs, as clearly shown in Figures 5 and 6.

Comparing the two cases, some major differences can be pointed out. First, the AE events were sensed at ~320 MPa, defined in this work as \( \sigma_{Fae-B} \), i.e., the axial stress at which acoustic events begin in all blank samples. The detected amplitude of the initial events was in a range between 35–60db. In samples with embedded dummy microprocessors, instead, significant but isolated acoustic emissions were acquired at a stress, \( \sigma_{Fae-E} \), that is 25–33% of \( \sigma_{Fae-B} \) for almost all the tests. The amplitude of the early emissions generally falls into a range of 50–75db. Additionally, the distribution of the events was observed to be quite different, which can be attributed to a different failure process (Figure 7).

Another important result emphasized by these experiments is that, in cases with embedded dummy sensors, the starting events were at the sensor location, Figure 8(b), in agreement with the observed overall sample response; see Figure 7. On the other hand, the behavior generally observed for the material without implants is similar to the one given in Figure 8(a), which shows a uniform distribution of events likely due to the progressive growth of flaws within the composite. The locations of the AE sources were determined based on the first threshold crossing time of the signals acquired by the sensors.

Figure 5  Typical material response and acoustic behavior under tensile load of sample 4 without integrated inclusion.
In order to correlate the acoustic results with specific physical events, four [0]_s samples with embedded simulated sensors were subjected to increasing tensile loads until the first events were detected. The samples were then removed and cut orthogonally to the fibers, a few millimeters away from the implant, and polished for micrographic inspection. The photos in Figure 9 show the state of the material surrounding the implant in one of the samples that had been loaded up to 400 MPa. Even though acoustic events were captured at rather low stress levels, the samples chosen for optical microscopy were subjected to higher stresses to render the damage visible.

The left image in Figure 9 shows the cross section at the sensor location of a virgin sample, while the right image presents the cross section of a loaded sample. To see the resin matrix-resistor interface more clearly, we used the scanning electron microscope (SEM) (Figure 10).

**Table 2** Material without and with embedded inclusions: tensile strength and acoustic behavior.

<table>
<thead>
<tr>
<th>TEST n^a</th>
<th>Average (MPa)</th>
<th>DS^b</th>
<th>CV %^b</th>
<th>Strength (MPa)</th>
<th>Average (MPa)</th>
<th>DS</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 4</td>
<td>321</td>
<td>319.6</td>
<td>20.07</td>
<td>6.15</td>
<td>1771</td>
<td>1729.4</td>
<td>40</td>
</tr>
<tr>
<td>Sample 5</td>
<td>325</td>
<td></td>
<td></td>
<td></td>
<td>1717</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 6</td>
<td>306</td>
<td></td>
<td></td>
<td></td>
<td>1722</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sample 10</td>
<td>354</td>
<td></td>
<td></td>
<td></td>
<td>1765</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 13</td>
<td>292</td>
<td></td>
<td></td>
<td></td>
<td>1672</td>
<td></td>
<td></td>
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<tr>
<td>Samples with integrated device</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sample R1</td>
<td>106</td>
<td>89.7</td>
<td>22.18</td>
<td>24.7</td>
<td>1713</td>
<td>1685</td>
<td>39.9</td>
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<tr>
<td>Sample R2</td>
<td>106</td>
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<td></td>
<td></td>
<td>1683</td>
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<tr>
<td>Sample R4</td>
<td>88</td>
<td></td>
<td></td>
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<td>1630</td>
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<tr>
<td>Sample R5</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
<td>1716</td>
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<tr>
<td>Sample R6</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td>1644</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Results</td>
<td>(\sigma_{\text{AE}}/\sigma_{\text{IB}})</td>
<td>97.42%</td>
<td></td>
<td>(\sigma_{\text{FAE-B}}/\sigma_{\text{FAE-E}})</td>
<td></td>
<td></td>
<td>3.56</td>
</tr>
</tbody>
</table>

^a\(\sigma_{\text{AE}}\) tensile strength of the material with embedded inclusions; \(\sigma_{\text{IB}}\) tensile strength of blank material; \(\sigma_{\text{FAE-B}}\) stress at which the acoustic events start in blank samples and \(\sigma_{\text{FAE-E}}\) stress at which the events begin in sample with integrated device.

^bDS = standard deviation; CV = coefficient of variation; definitions according to ASTM 3039M.
Figure 7  Failure by progressive edge delamination in blank samples (a); initiation of the failure of the device-composite interface in sample with integrated inclusion (b); propagation of the initial cracks followed by a sudden catastrophic failure in cases with implant (c).

Figure 8  ae hits amplitude (db) vs position (position is set in inches by default in the AE software) typically observed in sample without (a) and with embedded simulated sensors (b). The schematic shows where the acoustic sensors where positioned on the surface of the sample, at equal distance from the center of overall length of the sample.
A considerable number of small cracks, oriented along the interface boundary, and enlarged voids were found in this area.

On the other hand, as shown in Figure 11, the resin pocket tip region of the same sample loaded up to 400 MPa, remained undamaged, demonstrating that the damage initiation within the studied material appears at the implant-composite interface, and not at the root of the resin pocket region.

Past research has suggested that the frequency content in an AE signal can be related to the damage mode. A summary of the results obtained for carbon-fiber laminated composites compared with other works on glass and carbon-fiber composites based on parametric information of AE data is presented in [31]. From the optical investigations conducted on tested samples, it appears that the first acoustic events detected in blank samples may be attributed to flaws growth, fiber pullout, and matrix cracking phenomena. We saw also that these first events are characterized by low amplitude events with frequencies of 150–180 kHz. Moreover, the distribution of the damage seems to be uniform through the length of the sample.

On the other hand, in samples with integrated devices, the observed acoustic events are more likely due to the presence of stress concentration induced by geometrical and material discontinuities at the sensor-resin interface which then produces fiber–matrix debonding at this interface.
and matrix failure with consequent debonding of the implant from the surrounding material. In fact, from the observation of the microstructure, localized cracks and debonding are mostly seen at the sensor-resin interface. The corresponding events acquired through the AE system are associated with low and medium amplitude signals with frequencies in the range of 150–300 kHz.

The frequencies of the events acquired during the tests reported in Figures 5 and 6 are compared in Figure 12. In this plot we have superposed the acoustic results obtained from the two samples in terms of frequency distribution versus the stress applied. It is evident that events involving matrix phenomena start at low stress levels in samples with inclusions. In this specific case, at very low stress level, some events are characterized by high-peak frequency. After the appearance of these events the following ones show the same characteristic acoustic signature as general resin matrix events and, in fact, they are found to be very similar to those obtained from the characterization of the sample without integrated inclusion. In conclusion, the summarized results of this comparison are presented in Tables 2 and 3. The high value of the coefficient of variation computed for the stress at which the first AE events are acquired in samples with integrated implant is probably due to the orientation and position of the implant inside the material as well as the local resin volume content. During the fabrication process in fact, the hand lay-up and the flow of the resin during the curing cycle may induce the device to move from the assigned position, which consists in aligning the

\[ \text{Figure 12} \quad \text{Signal frequencies detected in samples with (rectangular dots) and without integrated dummy sensors (triangular dots).} \]

\[ \text{Table 3} \quad \text{Material with and without embedded inclusions: stress at which matrix events start to occur and events classification.} \]

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Stress range (MPa)</th>
<th>Events amplitude range (db)</th>
<th>Peak frequency (kHz)</th>
<th>Event type classification based on micrographic inspections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank samples</td>
<td>320–400</td>
<td>35–60</td>
<td>100–190</td>
<td>Matrix micro-cracking, fiber pull-out</td>
</tr>
<tr>
<td>Sample with dummy sensor</td>
<td>89–106</td>
<td>50–77</td>
<td>150–300</td>
<td>Matrix micro-cracking at the sensor interface, debonding events</td>
</tr>
</tbody>
</table>

and matrix failure with consequent debonding of the implant from the surrounding material. In fact, from the observation of the microstructure, localized cracks and debonding are mostly seen at the sensor-resin interface. The corresponding events acquired through the AE system are associated with low and medium amplitude signals with frequencies in the range of 150–300 kHz.

The frequencies of the events acquired during the tests reported in Figures 5 and 6 are compared in Figure 12. In this plot we have superposed the acoustic results obtained from the two samples in terms of frequency distribution versus the stress applied. It is evident that events involving matrix phenomena start at low stress levels in samples with inclusions. In this specific case, at very low stress level, some events are characterized by high-peak frequency. After the appearance of these events the following ones show the same characteristic acoustic signature as general resin matrix events and, in fact, they are found to be very similar to those obtained from the characterization of the sample without integrated inclusion. In conclusion, the summarized results of this comparison are presented in Tables 2 and 3. The high value of the coefficient of variation computed for the stress at which the first AE events are acquired in samples with integrated implant is probably due to the orientation and position of the implant inside the material as well as the local resin volume content. During the fabrication process in fact, the hand lay-up and the flow of the resin during the curing cycle may induce the device to move from the assigned position, which consists in aligning the
length of the device with the fibers direction. Moreover, less resin content with consequent higher fiber volume fraction in the cross section containing the implant was sometimes observed due to the external pressure and the vacuum applied for fabricating the material.

Further investigation on the failure initiation within anisotropic media with inclusions is necessary and would greatly improve the understanding of the effects of integrated electronics on the structural integrity of layered composites.

5 Concluding Remarks and Discussion

The integrity and mechanical behavior of unidirectional fiber glass/epoxy composites with integrated simulated SHM sensors were investigated in this work. Particularly, the damage initiation within the material and its identification were sought. To achieve this aim, monotonic tensile tests were performed on samples while continuously monitoring their AE behavior. A series of micrographic inspections were also conducted. Our major experimental observations can be summarized as follows:

- The material properties and the tensile strength of [0]_n laminates with inclusions are substantially the same of those characterizing the material without integrated dummy sensors.
- The embedment process causes material and geometrical discontinuities within the composite laminate creating large interlaminar eye-shaped resin pockets around the implant. Nonuniform fiber spacing is observed around these regions. Sharp geometrical discontinuities and material inhomogeneities are responsible for localized high values of the stress concentrations, which affect the initiation of the failure and the development of the damage.
- Early acoustic events are detected at the sensor location at \( \frac{1}{4} \) of the stress that is observed to induce acoustic activity in the material without implants. Moreover, the amplitude of the events acquired is usually at least 10 db higher than those noticed in samples without inclusions.
- The frequency of the early events in samples without inclusions is within a 150–180 kHz range and is mainly attributed to the growth of flaws and fiber pull-out, while those detected in samples with dummy sensors fall within a higher range of 150–300 kHz, which are classified as matrix cracking and debonding phenomena. A series of micrographic inspections was conducted to support these observations.
- Unlike the Shivakumar and Emmanwori observations, the experiments show that the failure initiates at the implant-composite resin interface by interface debonding and micro-cracks around the sensor due to the high values of interlaminar stress. The results are documented by micrographic inspections. Large flaws at the implant-composite resin interface that were not generally observed in samples inspected prior to testing, indicate that high stresses were likely responsible for the interface failure. Moreover, no sign of damage at this stress levels was observed at the tip of the resin pocket.

In conclusions, this article describes the results obtained on the impact of integrated devices on the local material integrity of laminated composites. These results are similar to those of some works present in the literature, but add fundamental details on the initiation of the failure at the interface implant-composite resin matrix. Discontinuities into anisotropic media provoke an inevitable impact on the material, however the local effects on its integrity depend on the implanted device geometry and the properties of the system analyzed.

In this article and its companion manuscript [17], the term sensor is often used as generalized definition of implant, integrated device, or simulated microprocessor. The aim of this work has been in fact the integration of electronics together with sensors into laminated composites. The implants embedded are either signal conditioning devices (chip resistors) or microprocessors. Notwithstanding the remarkable improvements achieved in the sensors technology so that miniaturized, thin, highly deformable, and resin compatible transducers are commercially available, electronic devices still represent rigid thick inclusions to the host material. Therefore, attempting
to embed electronics in order to create a biologically inspired material with a fully integrated sensing network requires some attention. For this reason, the problem of stress concentration in composite media due to the presence of integrated notches and discontinuities has been emphasized. The integration of SHM sensors networks into advanced materials requires a careful design approach due to the fact that debonding, peak of stress concentration leading to localized cracks at the interface cannot be visibly inspected. Besides this, the analysis and quantification of the stress concentration and the interaction implant-composite can contribute to the development of new electronic devices and sensors stimulating new fabrication techniques and procedures to minimize the impact of the implant on the specific material chosen.

The development of smart, multifunctional composite materials is possible and can be successful if a proper design and investigations of the material limits are considered.

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