Optimization studies of self-sensing composites

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ABSTRACT

The demand for real-time or *in situ* structural health monitoring has stimulated efforts to integrate self and environmental sensing capabilities into structural composite materials. Essential to the application of smart composites is the issue of the mechanical coupling of the sensor to the host material. In this study various methods of embedding sensors within the host composite material are examined. Quasi-static three-point bending (short beam) and fatigue three-point bending (short beam) tests are conducted in order to characterize the effects of introducing the sensors or suitable simulated sensors. The sensors that are examined include simulated sensors in the form of chip resistors with the original packaging geometry and thin film sensors (PVDF). The sensors are integrated into the composite either by placement between the layers of prepreg or by placement within precision punched cut-outs of the prepreg material. Thus, through these tests we determine the technique that optimizes the mechanical properties of the host composite material.

Keywords: Composite materials, smart composites, three-point bending, fatigue, short beam shear

1. BACKGROUND

In smart applications, it is essential to integrate sensors, actuators, and devices in a structure. The primary modes of integration include surface mounting and embedding the sensors within the host structure. In many applications, surface mounting is not feasible, and embedding is the only realistic way to introduce a sensor to the host structure. Embedding the sensors allows for protection from adverse environmental conditions. It is also the only means suitable for creating an autonomous structure with a smooth surface finish.

Previous efforts to integrate sensors and MEMS devices into fiber-reinforced composites have often required that such a device be placed between the fiber layers of a composite as it is being fabricated. As a result, the device is usually surrounded by the matrix phase, typically a polymer, which is generally the weaker phase within the composite. Interlaminar stresses arise at or near the inclusions and could result in delamination, which in turn reduces load carrying capability and further reduces the ability of an embedded sensor to detect its surrounding environment[5]. Therefore, it is necessary to characterize the effects of embedding sensors on the mechanical properties of the host structural composite material.

In this study, the characterization consisted of both quasi-static and fatigue three-point bending (short beam) tests. It is the interlaminar shear strength that often in the critical parameter. In most fibrous composites, the interlaminar shear strength is considerably lower than that of the longitudinal tensile strength. It follows that with laminated composite structures, the delamination failure mode has the potential for being the major life-limiting failure process.

2. INTRODUCTION

In this study, 0-degree unidirectional laminates made from S2/BT250E-1LV glass-epoxy prepreg were tested in both quasi-static and fatigue three-point bending (short-beam) tests. The tests were conducted on blank specimens, specimens that contained two 0805 chip resistors to simulate microsensors placed at the mid-plane between layers of prepreg (hereafter referred to as **embedded sensor specimen**), specimens that contained two 0805 chip resistors placed at the midplane within precision punched prepreg (hereafter referred to as **punched sensor specimen**), and specimens that

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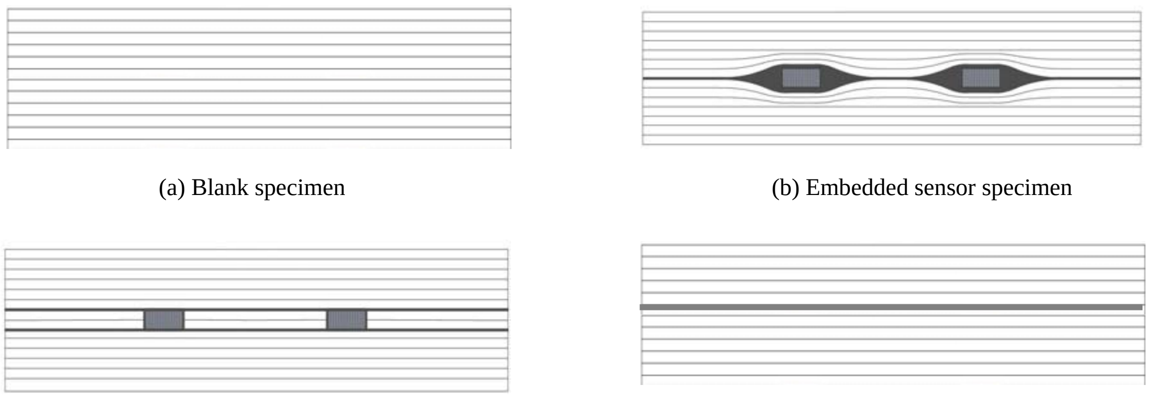
contained a polyvinylidene fluoride (PVDF) sensor placed at the midplane between the layers of prepreg. The various configurations are depicted in Figure 1.

The three-point bending (short beam) specimens were 20-ply specimens, measuring 8.76 mm (0.3450 in) wide, 25.4 mm (1.0 in) long, and 4.36 mm (0.1715in) thick in accordance with ASTM D 2344. The quasi-static three-point bending tests were conducted to characterize the short beam shear strength as well as to characterize the subsequent effects of the various embedments and their embedding configurations. The fatigue three-point bending (short beam) tests were conducted in order to characterize the effect the various embedments and embedding methods had upon the fatigue life of the specimen



(a) Blank specimen

(b) Embedded sensor specimen

(c) Punched sensor specimen

(d) PVDF specimen

Figure 1: Specimen configurations

3. MATERIALS

The S2/BT250E-1LV unidirectional glass-epoxy was supplied as 305 mm (12 in) wide prepreg tape by Bryte Technologies, Inc (Bryte). The S2 glass fiber density was 2.49 g/cm^2, and the fiber aerial weight was 284 g/m^2. The uncured resin content was 35% by weight. On average, a 305mm by 305mm panel had a total thickness variation of 0.076mm (0.003 in). Specimens were 20-ply laminates with dimensions 8.76mm wide, 25.4mm long and 4.36mm thick in accordance with ASTM D 2344. The average fiber volume fraction as determined by ASTM D 2584-02 was 51%. Further details of the fabrication procedure may be found in a related publication[4].

4. SPECIMEN PREPARATION

The unidirectional test specimens were cut using a computer numerical control (CNC) 3-axis milling machine. The 0805 chip resistors and PVDF sensors were targeted and marked. The unidirectional composite panel was then clamped to an aluminum plate mounted in a vise. The panel was flooded or submerged in water in order to contain the harmful dust created by cutting the material. The specimens were cut out by side milling with a 3.175 mm (0.125 in) diameter titanium nitride coated carbide four flute cutter. The cutter speed was 1200 rpm, with a feed of 203 mm per minute for rough cuts and 101.5 mm per minute for finish cuts. All cuts were done at full depth, the thickness of the composite panel. Finally, the specimens were deburred, rinsed with water, and thoroughly dried.

5. EXPERIMENTS

5.1 Testing equipment and test configurations

The quasi-static and fatigue three-point bending (short beam) tests were performed using a MTS model 309.20 load frame with a MTS model 490.05B load unit controller. The load frame was equipped with a 22.2 kN (5000 lb) load cell.

The load frame was equipped with a three-point bending fixture shown in Figure 2 that consisted of individual upper and lower supports kept in proper alignment through two linear bearings. The loading nose cylinder had a 6.00 mm (0.250 in) diameter, while the support cylinders maintain a 3.00 mm (0.125 in) diameter. All cylinders were free to rotate. The three-point bending (short-beam) tests were performed with a bottom span length of 17.42 mm (0.686 in), with a span-to-thickness ratio of 4.0, all in accordance with ASTM D 2344.

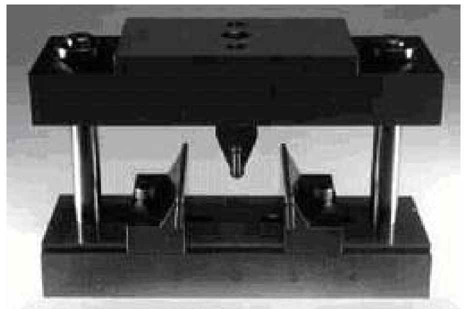


Figure 2: Three-point bending (short-beam) test fixture

5.2 Test procedure

The quasi-static three-point bending (short beam) tests were performed in displacement control, at ambient laboratory conditions. The crosshead movement was at a rate of 1.25 mm/min (0.05 in/min). The specimens were centrally aligned on the supports. The test proceeded until one of the following events occurred: a load drop-off of 30%, two-piece specimen failure, or the loading head travel exceeded the nominal specimen thickness. Six specimens of each configuration were tested.

The short beam shear strength was determined using the following equation, as given in ASTM D 2344:

$$F_{SBS} = \frac{0.75 P_m}{bh}$$

where F_{SBS} (MPa) is the short-beam shear strength, P_m (N) is the maximum load observed during test, b (mm) is the measured specimen width, and h (mm) is the measured specimen thickness.

Further testing, namely three-point bending (short beam) fatigue tests have been conducted in order to more wholly understand the in-service effects of the embedded elements on the mechanical properties of the host structural composite material. Twelve of each of the specimens from the aforementioned configurations were tested. The tests were performed in the same MTS universal testing machine as the quasi-static tests, under load control and at ambient laboratory conditions. The specimens were centrally aligned on the supports. The specimens were cyclically loaded between 222 N and 2224 N using a sinusoidal input wave function at a frequency of 10 Hz. The cyclic loads correspond to 6% and 60% of the short beam shear strength of the specimens, respectively. Thus, the stress ratio was equal to 0.1. The specimens were centrally aligned on the supports and such that the unidirectional fibers were oriented along the length of the fixture. The tests proceeded until the modulus of the specimen decreased to the point that specimen triggered displacement interlocks at 2.54 mm.

6. RESULTS AND DISCUSSION

The results of the three-point bending tests concluded that the average short beam shear strength of blank samples was 72.96 MPa with a sample standard deviation of 0.52%. The embedded sensor specimens generated an average short beam shear strength of 71.45 MPa with a sample standard deviation of 1.03% while the punched sensor specimens yielded an average short beam shear strength of 73.69 MPa with a sample standard deviation of 1.18%. Finally, the PVDF specimens had an average short beam shear strength of 66.44 MPa with a sample standard deviation of 5.09%

The results of the fatigue three-point bending tests concluded that the blank specimens generated an average fatigue life of 1.71×10^6 cycles with a standard deviation of 80.19%. The embedded sensor specimens generated an average fatigue life of 0.528×10^6 cycles with a standard deviation of 51.30%., while the punched sensor specimens yielded an average fatigue life of 1.44×10^6 cycles with a standard deviation of 56.89%. Finally the PVDF specimens had a fatigue life of only 0.05×10^6 cycles with a standard deviation of 59.09%. Therefore, the fatigue three-point bending tests concluded that the introduction of the embedded elements had a very profound influence upon the fatigue life of the specimens. Furthermore, the results are highly indicative of the fact that the method in which the sensor is integrated into the host composite material has a profound effect on the fatigue life. Photographic results of the fatigue three-point bending tests can be seen in Figures 3-6.

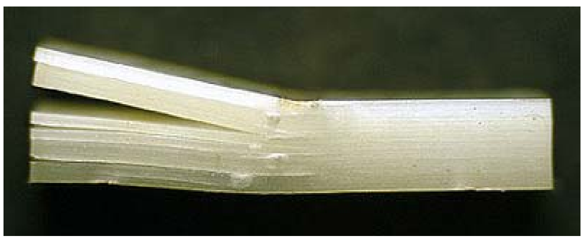


Figure 3: Blank fatigue specimen.

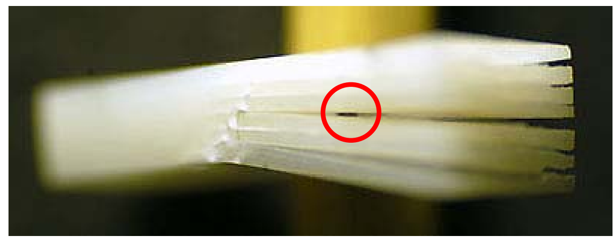


Figure 4: Embedded sensor specimen

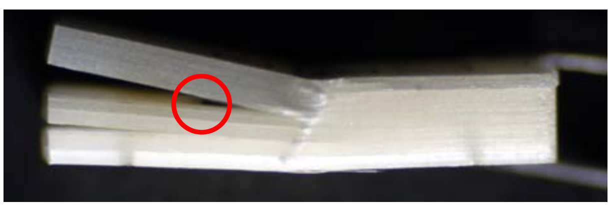


Figure5: Punched sensor specimen

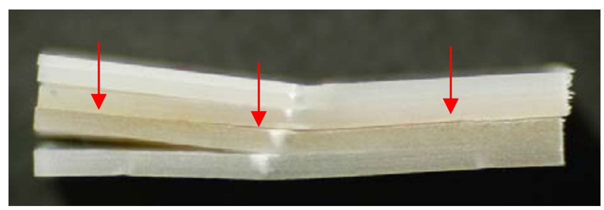


Figure 6: PVDF specimen

7. CONCLUSIONS

The results of the quasi-static tension tests provide valuable baseline values of the characteristic properties of the host composite material. The preliminary results indicate that the introduction of the microsensor or suitable simulated microsensor (0805 chip resistor) had a negligible effect upon the ultimate tensile strength of the composite material, yet the introduction of the PVDF sensor had a noticeable effect.

The fatigue three-point bending (short beam) tests, which more accurately simulate real world or in-service loading conditions, indicate that the introduction of the embedded elements, either in the form of embedded microsensors placed either between layers of prepreg or within precision punched cut-outs of prepreg or in the form of PVDF thin film sensors, decreases the fatigue life. Furthermore, the results of the fatigue testing indicate that the method in which the microsensors are integrated into the host composite material has a profound effect on the fatigue life. Through the use of precision punched prepreg in the punched sensor specimens versus simply placing the microsensors between the layers of prepreg as done in the embedded sensor specimen the fatigue life was greatly increased. In fact, the punched sensor specimens had a fatigue life that was 85% the life of the blank specimens. Whereas the embedded sensor specimens had a fatigue life that was only 31% the life of the blank specimens. Thus, the use of precision punched prepreg with the microsensors increased the fatigue life nearly three-fold.

While the results of the experimental work to date are promising, further investigation is indeed necessary. Currently, quasi-static and fatigue three-point bending (short beam) testing is being conducted on specimens that contain a sandwich PVDF structure. Future work will also focus on optimizing the actual geometry of the microsensor. The current simulated microsensor has relatively sharp corners. In the sensor packaging industry, all sensor packaging tends to be angular. These sharp corners can be beveled through a tumbling process in an effort to minimize the stress concentrations. The direction of future work focuses on integrating microsensors into the host composite material in a way that minimizes any adverse effects on integrity of the host composite material. The primary goal of this research is to ultimately extend the functionality of the composite material beyond that of simply load bearing. This work seeks to enable *in situ* sensing, without compromising the structural integrity of the host composite material.

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