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An intensity based optical fiber sensor for low velocity impact detection in unidirectional composites

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Abstract—Prevention of serious damage of composite structures might be achieved by inspecting the structural integrity during exploitation. This paper decribes the design and development of a promising optical fiber sensor system for low velocity impact detection in unidirectional composite that does not have a laminate structure. Obtained results showed that light in multimode fibers embedded in glass-fiber reinforced epoxy unidirectional composites is attenuated during the time of the impact load. Microstructural analysis of the fracture surfaces obtained from mechanically fractured samples was carried out to examine the failure mode of the composite host with embedded optical fibers.

Keywords: Undirectional composites; three-point bending impact; embedded optical fiber; signal attenuation.

1. INTRODUCTION

Understanding and detecting impact damage in composite materials was one of the first applications that motivated the development of fiber optic smart structures. Prevention of serious damage after low velocity impacts of the aerospace, marine and civil applications of fiber reinforced plastics, might be achieved by monitoring the structural integrity of these materials in-service.

The two types of optical fibre sensors are intensity modulated and phase modulated. In intensity based sensors a measurand, such as strain, produces a change in the power of the light propagating in the fibre. A typical intensity modulated optical fiber sensor system consists of a light source, a sensing device, detector to measure the intensity of the transmitted signal and optical fibers to carry light between these

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components. The principal advantage of such a system is that it does not need the complicated instrumentation and signal processing demanded by other classes of optical fiber sensors, which increase their cost and reduce their applicability.

The investigations related to intensity based optical fiber sensors, performed by past researchers differ in the variety of the laminate composite structure, optical fiber coating, and type of testing [1–6]. Many authors have reported observing effects on the optical signals of embedded optical fibers during a low velocity impact. Measures *et al*. [7, 8] showed that threshold impact energy for the fracture of the embedded optical fibers in composites could be made close to that for the damage of the composite material. In the work recently reported by Doyle *et al*. [9], the light transmission through the optical fibers integrated into the glass-fiber-reinforced epoxy filament-wound tubes was determined before and after the impact. The system proposed by Doyle and Fernando [10] was based on a simple intensity-based optical fiber vibration sensor and a neural network, for impact damage detection in carbon fiber reinforced epoxy composites. Malki *et al*. [11] have reported a method for sensing vibrations and locating impacts by splicing two multimode fibers. From a structural health monitoring point of view, it is necessary to investigate the distribution of damage through the thickness of the composite. By embedding an optical fiber intensity based sensor array [12], damage growth mapping could be obtained with sufficient accuracy.

However, the low velocity impact on the unidirectional composite laminates has not been studied systematically. In a review of optical fiber–composite, interaction mechanics, Sirkis and Dasgupta [13] pointed the need of concentrated effort in investigation of host microarchitectures other than laminated composites. The purpose of this analysis is to clarify the response of unidirectional composite with embedded optical fiber that does not have a laminate structure under low velocity impact, which is the subject of interest for engineering and design for industrial application. In most previous investigations, the light transmission through the optical fibers was determined before and after the impact. The system proposed in this paper enables continuous in-service monitoring of impact events. Microstructural analysis of the fracture surfaces was carried out to examine the failure mode of the composite host and embedded optical fibers.

2. EXPERIMENTAL

The fiber reinforcement was woven roving E-glass (Tehnotex-Sombor), with a silane sizing. Unidirectional plies were obtained by removing all weft yarns from the woven roving plies. The matrix material was based on a diglycidyl ether of bisphenol A together with an aromatic amine hardener (Araldite CY 223/HT972, Ciba-Geigy). The epoxy–amine mixtures were prepared by heating the resin in an oil bath to 70°C and adding the curing agent with continuous stirring until a clear homogeneous solution was obtained. Alternate layers of liquid resin and six longitudinal fiber plies were placed inside a dam on a flat mould plate.

Four optical fibers with core/cladding/coating diameter equal to 62.5/125/250 μm were introduced by hand during sample lay-up. Two of them (acrylate coated and uncoated designated as COF1 and BOF1, respectively) were placed between the third and fourth layer along the glass fiber direction and separated by 10 mm, the other two (coated and uncoated designated as COF2 and BOF2, respectively) were between the fifth and sixth layer.

At the end of the lay-up procedure, a plate with applied pressure was placed on the top of the composite to ensure uniform thickness. The specimens were cured during 48 h at room temperature, followed by 5 h at 90°C, and final slow cooling. An internal lubricant was used for mold release. Fiber volume fraction for each specimen was approximately 50%.

Span length between the supports, width and thickness of the specimen were 80, 40 and 2.3 mm, respectively. We used a light emitting diodes centered at 840 nm (Siemens SFH 401). The optical signals derived from the fiber ends were detected (Phototransistor based Photodetector LPT 100 A) and amplified for further signal processing. The strain gauge was bonded to the tension side of the specimen to monitor the bending strain.

Scanning electron microscopy (SEM-JEOL JSM 5300) was performed on the fracture surfaces of the mechanically failed specimens to study the failure mode of the composite and embedded optical fiber. The fracture surfaces were vapour-coated with a thin layer of gold to enhance the image.

3. RESULTS AND DISCUSSION

Samples were impacted at energies ranging from 1 J up to 2.5 J by using a simple drop-weight impactor. The projectile used for the tests had a mass of 500 g, and was cylindrical in shape with a rounded 20 mm diameter nose. All the specimens were struck at the centre of the span. Transmission is normalized by the output intensity measured before the specimen is impacted. The results of the optical fiber light transmission are plotted on the same graph as those obtained from the electrical resistance strain gages, for direct comparison of the values acquired from each sensor.

The responses of the optical fibers and the resistance strain gage on the impacted coupon are reported in Figs 1–3. Presented results showed that light in multimode fibers embedded in unidirectional composite specimens is attenuated during the time of the impact load. This can be explained from the increased microbend losses during the loading.

Transmitted light intensity is lost in response to microbending. This loss occurs most frequently when the highest-order guided mode in the fiber core is coupled to the first cladding (radiation) mode, which then is rapidly attenuated. Environmental effects, such as temperature, pressure, impact, or acoustic waves, which produce structural strain, can induce the coupling. The microbending curvatures are very

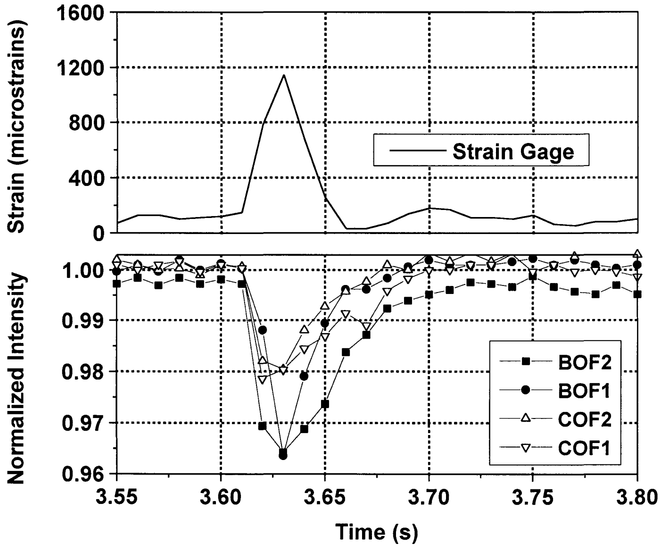

Figure 1. Optical fiber loss and strain gage response for impact energy of 1.0 J.

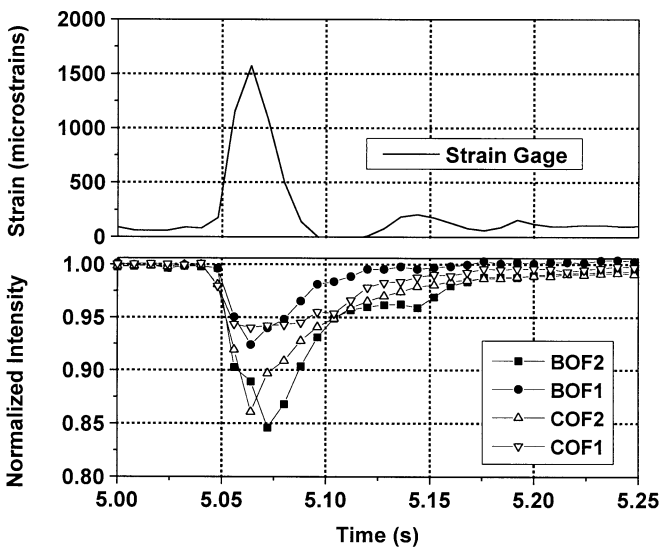

Figure 2. Optical fiber loss and strain gage response for impact energy of 2.0 J.

small, and very abrupt, in this way differing from the more familiar phenomenon, macrobending [14, 15].

Notice, from data presented in Figs 2 and 3, that the magnitude of the transmitted light in optical fibers located at the centre of the specimen is much smaller than that of the ones embedded between the fifth and sixth ply. This observation may be explained by the fact that in flexural testing the mechanical response is controlled by the loading span to specimen thickness ratio. At relatively high ratios, the

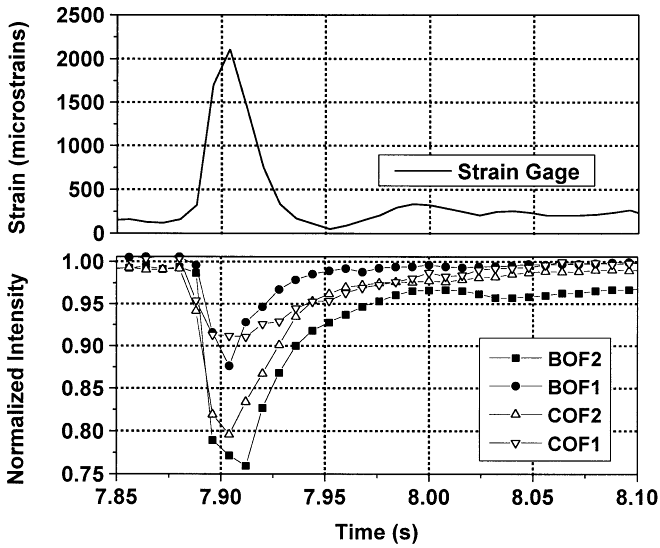

Figure 3. Optical fiber loss and strain gage response for impact energy of 2.5 J.

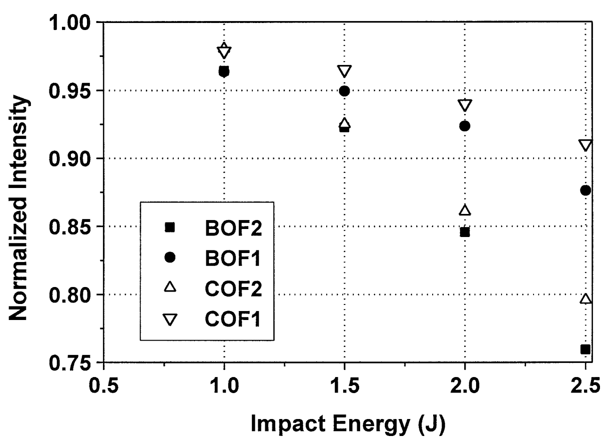

Figure 4. Minimal detector output for various impact energies.

outermost layers, located at the maximum distances from the neutral plane in the two directions, are subjected to maximum tensile/compression strains, and their properties dominate the behaviour [16].

Comparison of maximal signal attenuation of embedded optical fibers for various impact energies is presented in Fig. 4. Presented results demonstrate that a relationship exists between the applied impact energy and the resulting light output intensity. Results recorded in Fig. 1 and Fig. 4 shows that BOF1 exhibits greater loss than COF2, which is not the case in higher energy impacts. We suppose that this could be the consequence of the higher microbending sensitivity of the bare optical fiber. Generally, the polymer coating of the fiber protects the silica from

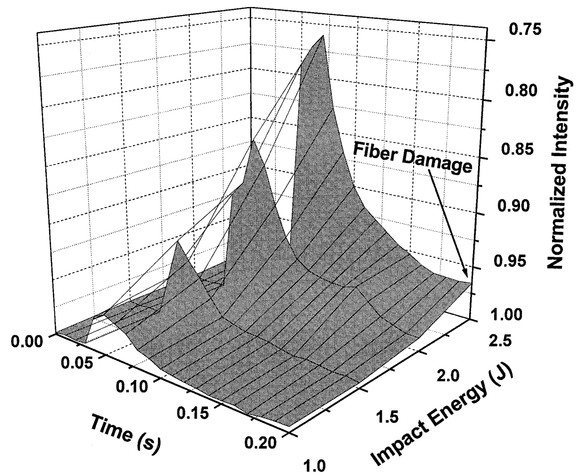

Figure 5. Response plot of BOF2 optical fiber for various impact energies.

microbending by shielding it from perturbations in the surrounding matrix [17]. In the tests were the higher impact energies were achieved (Figs. 2 and 3), the coated fibers responded with less sensitivity than the uncoated (i.e. bare silica cladding) when placed in the same depth. For higher impact energies, the depth at which the optical fibers have been embedded plays a more significant role in their effectiveness than the coating presence in the sensing region.

However, from Fig. 3, it is also apparent that BOF2 did not recover the optical transmissivity after the 2.5 J impact. Data from the embedded optical fiber indicated a reduction in optical transmissivity of 4% after the 2.5 J impact event. Comparing data from Fig. 3 we conclude that the critical design strain for optical fiber embedded in this material configuration is 2000 microstrains.

The translucence of the material was useful for finding the location of the BOF2 fiber damage pointed in Fig. 5, by the bleeding of red He-Ne laser light launched from the fiber ends. Figure 6 shows laser light bleeding from fractured embedded optical fiber after 2.5 J impact. For clarity, the laser light path was converted from red to white, after scanning the original colour filmed photograph. In the case of thick, inaccessible components or wherever opaque materials are employed, it is not feasible to look for bleeding light as an indicator for damage. Instead, location of failure point of the optical fiber could be detected with sufficient accuracy by using an optical time domain reflectometer (OTDR).

By applying high pressure at the end of the lay up procedure, glass fiber layers penetrated into one another obtaining a composite that does not have a laminate structure. Fractographic analysis presented in Figs 7 and 8, revealed that the dominant fiber-related failure mechanism is separation along the glass fiber/matrix interface. Fiber debonding seemed to be the dominant mechanism of energy dissipation (Fig. 7). However, when the impact energy exceeds the critical value, crack propagates through the thickness of the specimen breaking the reinforced

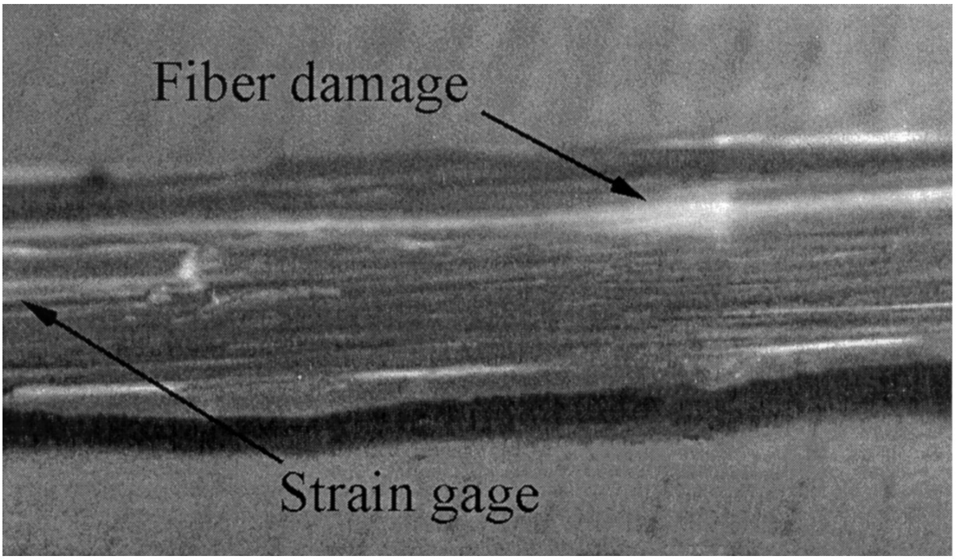

Figure 6. Bleeding light emanating from the damaged optical fiber after impact.

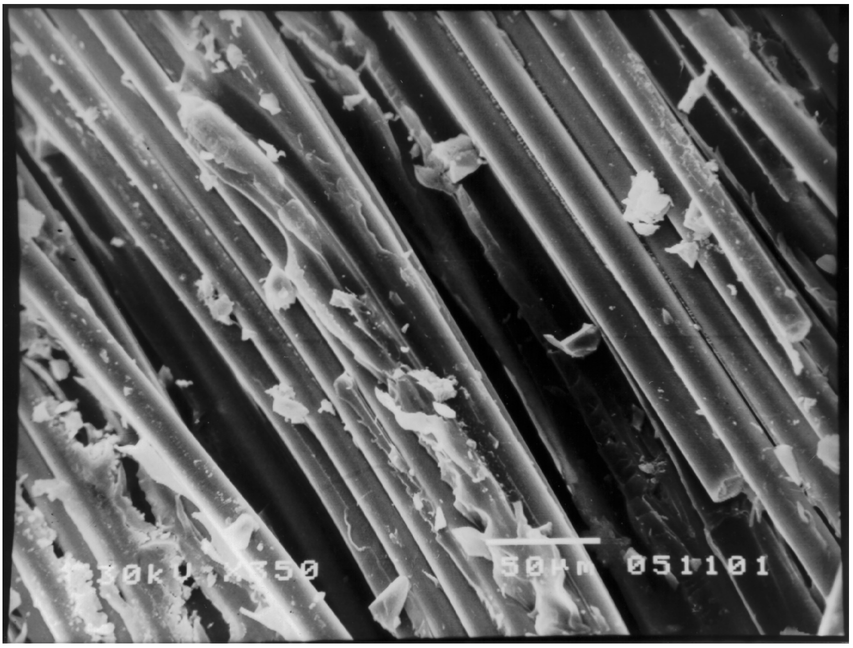

Figure 7. Fracture surface micrograph of the impacted specimen (×350).

glass fibers leading to failure of the coupon (Fig. 8). This figure also shows a fiber bundle, which has been partially broken away and bent toward the compression side of the specimen. This photograph is oriented such that the area, which was nearest to the tension side of the impact specimen, is at the right of the photograph.

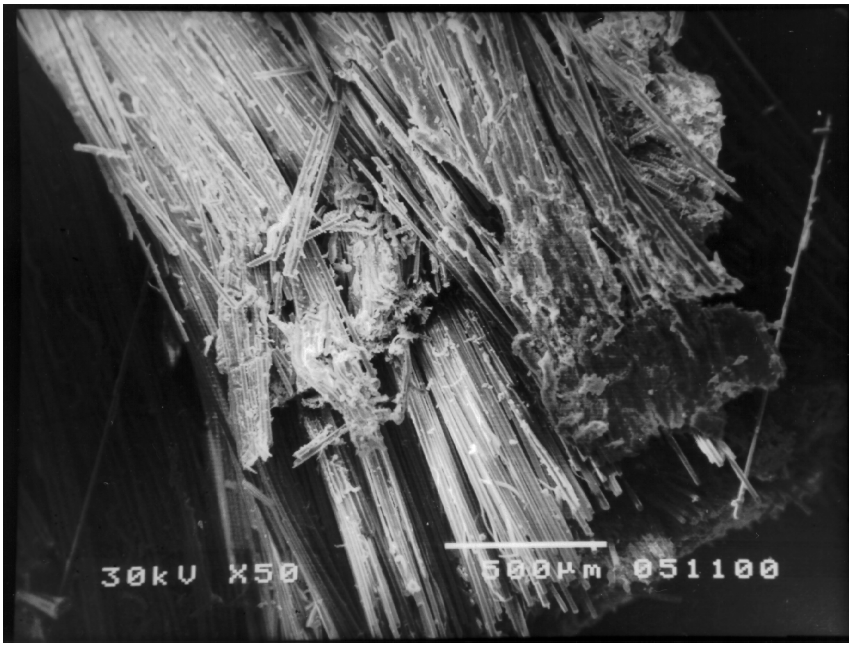

Figure 8. Fracture surface micrograph of the impacted specimen (×50).

For the case of impacted composites composed of unidirectional plies, three possible mechanisms of optical fiber failure during impact are proposed by Measures *et al*. [7]. The first failure mechanism is that of delamination-induced shear failure. Because delaminations were never seen to occur between collinear plies, despite the inclusion of the optical fibers, this mechanism is thought to be less important than the others. Another proposed mechanism is through-the-thickness cracking. Cracks propagating through the matrix parallel to the reinforcing material fiber direction fracture optical fibers they encounter. The optical fibers lying parallel to the material fibers will not normally intersect matrix cracks. In the third mechanism, flexurally induced tension, the impact-induced bending causes tension on the rear surface, inducing strain in the matrix and the optical fiber embedded at that location. When the strain in the flexed plate exceeds the ultimate strain of the optical fiber, it will fracture. There was no externally visible damage evident after the 2.5 J impact. Damage of BOF2 was due to exceeding the critical strain of the optical fiber. Embedded optical fiber with stripped coating fails prior to the composite specimen. Removal of the coating and chemical treatment of the fibre is required to reduce the strength of glass fiber if detection of barely visible impact damage is required. This would permit the development of a strain threshold detector. Additional evidence in support of this flexurally induced tension is provided by the larger impact energy required for fracture when the optical fibers are positioned further from the rear surface, which suffers the maximum flexure.

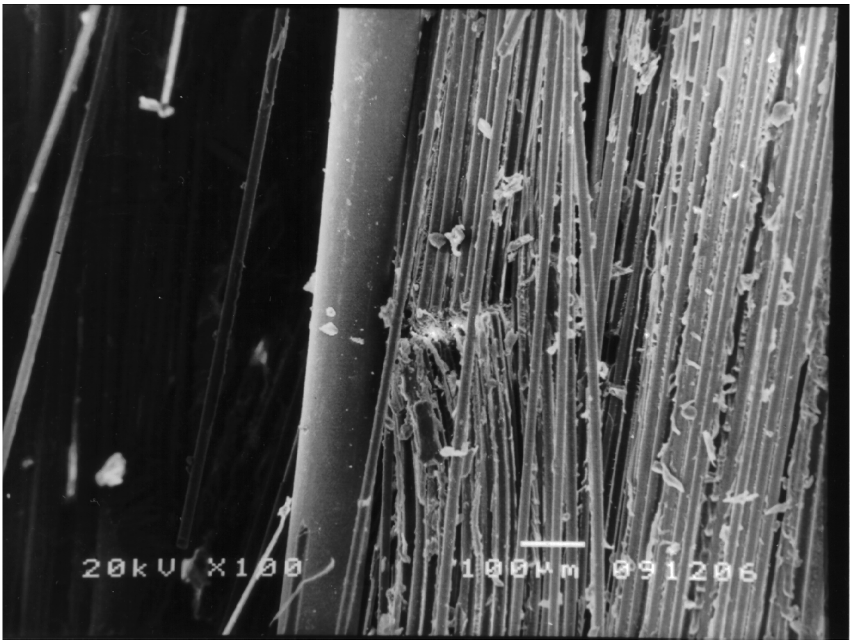

Figure 9. Fracture surface micrograph showing breakage of glass fibers near the BOF2 ($\times$100).

In the case of composite materials, it is important to consider the orientation of the fiber in the part as well as the overall size of the optical fiber and its coating. Despite the fact that the optical fibers placed perpendicular to the adjacent reinforcing material fibers would encounter many more matrix cracks than those placed parallel, running the optical fiber parallel to the strength-member fibers of the composite material minimizes potential strength degradation of the part. By observing the postimpact micrograph in Fig. 9, it is obvious that the crack from glass fiber breakage did not affect the surface of the embedded bare optical fiber. It is possible that the damage of glass fibers evident from the picture has been initiated by stress concentrations near the interface between optical fiber and the host material, which is considered as the ideal case of embedding. Complex stress states are produced in the host structure in the vicinity of the optical fiber and in the optical fiber as well. The stresses in the optical fiber may cause the optical fiber sensor to fail, or they may alter the interpretation of the embedded sensor signal. It is clearly from the literature that premature fracture of completely embedded optical fiber with compliant coating is not common and that optical fiber sensors generally survive loadings that are far in excess of the loads need to cause failure in the host material system [13, 18]. Stresses that are developed in the optical fiber due to low energy impact event mainly influence the interpretation of the sensor signal.

Despite the fact that the sensor is sensing strain, not damage, if the ultimate strain of the optical fiber coincides with the ultimate strain of the examined composite then this type of measurement can be used to asses damage and warn of weakening in the structure. If the optical fibers are acting as damage sensors through their fracture above certain critical loads, then the optimum sensitivity arises when the optical fibers are embedded as close to the surface of maximum tensile strain.

4. CONCLUSIONS

Real-time detection of actual impacts requires continuous monitoring of the structure, an approach that can be expensive in terms of both the sensor system and the processing required. We have made the measurements of the threshold impact energy for the fracture of the embedded optical fibers in unidirectional composite that does not have a laminate structure. It is apparent from presented results that the embedded optical fibers were capable of detecting a 1 J impact and above. We have demonstrated that a relationship exists between the applied impact energy and the resulting light output intensity. In thin composite structures, the best location for impact detection and damage extent assessment is in the tensile region. For higher impact energies, it has also been found that the depth, at which the optical fibers have been embedded, plays a more significant role in their effectiveness than the coating presence in the sensing region. Fractographic analysis revealed that the dominant fiber-related failure mechanism is separation along the glass fiber/matrix interface.

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