LOCAL AND GLOBAL MEASUREMENTS OF DYNAMIC DAMAGE EVOLUTION IN WOVEN COMPOSITE SYSTEMS

James D. Pearson, Mohammed A. Zikry*, Kara J. Peters, Mohanraj Prabhugoud
***Department of Mechanical and Aerospace Engineering, North Carolina State University**
Raleigh, NC, U.S.A., 27695, zikry@ncsu.edu

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Abstract

In this study, measurements from low-impact velocity experiments including embedded and surface mounted optical fiber Bragg grating (FBG) sensors were used to obtain detailed information pertaining to damage progression in two-dimensional woven composites. The woven composites were subjected to multiple strikes at 2m/s until perforation occurred, and the impactor position and acceleration were monitored throughout. From these measurements, we obtained dissipated energies and contact forces. The FBG sensors were embedded and surface mounted at different locations near penetration damaged regions. These sensors were used to obtain residual strains and axial and transverse strains corresponding to matrix cracking and delamination. An analysis of the FBG spectra provided independent feedback on the integrity of the Bragg gratings. A comparison by number of strikes and dissipated energies corresponding to material perforation indicates embedding these sensors did not affect the integrity of the woven system, and that these measurements can provide accurate failure strains.

1 Introduction

Woven and braided composites are being extensively used in military, commercial aerospace and automotive industries as well as bridge and ship construction [1-5]. FBG sensors are being used in conjunction with composites to monitor and measure local strains at critical structural locations. These composites are highly susceptible to instantaneous failure because failure modes can initiate at the subsurface, and hence are not easily detectable [6].

The development of low-loss, high-quality optical fiber for the telecommunications industry in the 1970's has spurred the extensive use of optical fiber Bragg grating (FBG) sensors for the measurement of failure strains in the aerospace and textile industries, with in flight testing scheduled for commercial airliners and the X38/CRV spacecraft [7-9]. Particular attention has been devoted to the application of FBG sensors for monitoring the behavior of fiber-reinforced composites during fabrication [10-13] and in-use service [4-16] due to the sensor's unique advantages over conventional foil strain gauges. These include accurate local strain measurements, high resolution and signal bandwidth [17], small size, light-weight [18], single-fiber multiple-gauge multiplexing ability [4,18] and the ability to withstand high heat and pressure with long term stability [17].

However, one of the major challenges in using these sensors for low-velocity impact, is to be able to relate local measured strains, which would be obtained in terms of bandwidth and Bragg wavelength shift to overall damage initiation and progression in the composite. Furthermore, material damage must be clearly delineated from optical fiber damage, hence material interactions between a host material and an embedded or mounted sensor must be characterized and the placement of sensors at critical locations must be identified a priori.

In this paper, we investigate how damage initiates and evolves at critical locations in laminated 2D woven composite panels that are subjected to low-velocity impact. FBG sensors are both surface mounted and embedded before impact, and the overall mechanical response is combined with local strain measurements and damage characterization to obtain a detailed understanding of how failure evolves at different scales. Based on these measurements, our results indicate that the contact force, as a function of the measured local strain, can be classified into five regimes which correspond to the damage progression of the 2D woven laminated composites. These regimes can provide a guide to determining the local level of damage at critical locations for heterogeneous materials subjected to impact loading conditions. The paper is organized as follows: Firstly, the experimental setup for mounting, impacting and interrogating the sensors is described. Afterwards, the results for the impact tests and strain measurements separated by method of sensor application are presented, and finally, the conclusions are summarized.

2 Experimental Methods and Measurements

2.1 Material Preparation and Sensor Positioning

Composite specimens were fabricated from a twill woven carbon fiber prepreg with thermoset epoxy matrix as seen in Fig. 1. All specimens were approximately 4.16 mm thick and consisted of 24 stacked prepreg lamina squares mutually aligned in the weave direction, and they were consolidated in a 12.7 cm square aluminum mold at 80° C and 1.24 MPa for 3 hours with an additional 30 minutes of pressure during cool down.

MBond 200 strain gauge adhesive was used for surface mounting the FBGs on two separate composite specimens, which will be referred to as C1 and C2. Before use, the optical fiber's acrylate coating in the vicinity of the Bragg grating gauge was chemically stripped with acetone to increase the sensitivity and transfer of strain to the sensitive fiber core region [16,19]. After aligning the fibers with the direction of the top lamina's weave, the optical fiber was tensioned slightly to be straight, and it was adhered to the rear face of the composite specimen approximately 1.43 cm from the chosen point of impact on the front face.

A single FBG was embedded for specimen C3 with the optical fiber positioned at the center of the mid plane and aligned with the weave direction similar to C1 and C2. All FBG sensors were written in Corning SMF-28 optical fibers. The fabrication of C3 was different from C1 and C2 to allow for embedding, and it was performed in three stages, however the same number of prepreg layers was used for all specimens. In the first stages two 11-layer panels were prefabricated with the mold, and in the final stage an FBG was oriented between two additional square prepreg laminas and this arrangement then sandwiched between both 11-layer panels sans mold before final pressing. This technique made use of the thermoset polymer's integrity under additional heating in the third stage to retain the 12.7 cm square shape.

2.2 Instrumented Drop Tower for Low-Velocity Impact

The instrumented drop tower consists of a 19 mm diameter hemispherical hardened steel indentor mounted to an adjustable 5.5 kg aluminum crosshead capable of delivering between 1-500 Joule impacts. All impacts were conducted at 2 m/s and a nominal incident kinetic energy of 11 Joules. Specimens were securely clamped and supported from underneath on a three inch steel ring with a thin neoprene mat on the surface to protect the optical fiber at rough edges and transitions. Specimens C3 and C2 were tested with the impactor's line of action aligned through the center of the support ring. Specimen C1 was tested differently with a support ring eccentric to the impactor thus effecting an apparent increase in support and number of strikes to penetration by bringing the point of impact and steel support ring closer.

The experiment was stopped when complete perforation of the composite panel occurred. Using an oscilloscope, contact force and dissipated energy for each strike were obtained through both the crosshead's acceleration during impact and the entry and exit velocities of the impactor. Contact force data was filtered using a 0.46 millisecond moving average to remove the characteristic oscillations in contact force with damage growth during impact [20-22].

2.3 Data Acquisition Systems

The FBG interrogation was carried out after each strike using a Tunics tunable laser unit with a wavelength resolution of 0.005 nm and scan step size of 0.01 nm. The axial strain in a Bragg grating is determined by

$$\varepsilon_{Axial} = \Delta\lambda_B / \lambda_B (1 - p_e) \qquad (1)$$

where λ_B is the Bragg wavelength, $\Delta\lambda_B$ is the shift in Bragg wavelength, and p_e is a constant ≅0.26. Therefore the resolution of the system was 4.4 με at a Bragg wavelength of 1500 nm. The Bragg wavelength used in determining the axial strain was the geometric centroid of the transmission or reflection spectrum's Bragg peak. However, when spectrum distortion, unwanted optical modes and/or multiple Bragg peaks appeared in the signal due to fiber damage, the Bragg wavelength was obtained as discussed later. The FBGs had a length of 8mm.

A photodetector was used to convert the optical signal from the FBG into an analog signal. LabView software was used for data collection and the measured spectrum in terms of transmission intensity and wavelength was stored for each impact event. The time required to complete one interrogation of the FBG was determined by the speed of tuning the laser through the scan range at the input incremental step size. This was approximately 15 seconds, thus precluding obtaining strain measurements where the total signal time length, measured as the contact duration between impactor and specimen, was greater than approximately 10 ms.

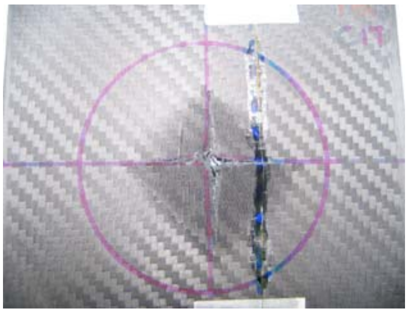
3 Results and Discussion

3.1 Surface Mounted FBG

Specimens C1 (eccentrically impacted) and C2 (centered impacts) are shown with surface mounted gauges after penetration in Fig. 1. As seen from this figure, the gauge was oriented so that axial strains in the optical fiber were recorded in the direction of the prepreg weave. Under impact, sample C1 required 105 strikes and sample C2 required 20 strikes for complete penetration. Despite the difference in number of strikes, which was due to an eccentric support and impactor for C1, the total dissipated energy in puncturing both panels was approximately the same. Specimen C1 had a dissipated energy of 112.9 Joules, and specimen C2 had a dissipated energy of 139.3. These values compare very well to the average dissipated energy calculated for puncturing a batch of identical composite samples at 139.4 Joules.

Surface mounted FBGs fractured well before complete penetration of the composite. For specimen C1, this occurred during strike 82, and for specimen C2 this occurred during strike 11 at which point both specimens had localized debonding near the impact point. After the optical fiber initially fractured, strain interrogation was still possible from the FBGs by probing the Bragg wavelength in the reflection mode instead of the transmission mode for specimen C2.

(a)



(b)

Fig. 1. Perforated composite panels (a) C1 and (b) C2 at the conclusion of the experiment. The 8 mm long gauge length of the FBG is centered in the optical fiber along the horizontal line in (b) with similar location in (a). Adhesive and localized fiber debonding and fracture occurred near the point of impact penetration

The sensor response can be classified into five regimes based on the Bragg peak wavelength shift and spectrum shape. The regimes are:

1. gradual increase in axial tension (the FBG peak shifts with a uniform bandwidth)
2. increase in non-uniformity of axial tension (the FBG spectrum bandwidth increases along with a shift)
3. maximum axial tension (the FBG reaches maximum peak shift)
4. axial strain decreases into compression (the FBG peak shifts to lower wavelengths)
5. compressive axial strain fluctuations (the FBG peak shift fluctuates with a small drop in bandwidth)

These measurements, except from regimes 4 and 5, relate to local composite strains and not to optical fiber failure. Furthermore, once fracture of the optical fiber occurred, the strain measurement was performed over a reduced length of the FBG ($<$ 8mm), although the exact length is not known. A sudden increase in axial strain of the FBG in specimen C1 at strike 80 was most likely due to crimping of the fiber just before failure.

Video analysis indicated a time dependence of the residual impact strains, and measurable relaxation of tensile strains in the tens of seconds immediately following impact indicated an additional form of storing and dissipating impact energy though internal friction between delaminated plies. A relaxation of strain occurred both in axial shifts and in the spectrum bandwidth of axial strains in each regime. In regime 5 the strain appears to increase when it should be relaxing because of the competing effect between decreasing spectra width and tensile Bragg peak center shift.

4 Conclusions

Surface mounted and embedded FBG sensors were used to monitor the development of post impact residual strains in woven prepreg composite systems. For specimens with surface mounted sensors, there were five distinct regimes of response with the final two regimes pertaining to the localized debonding and fiber fracture of the FBG. The onset of non-uniform axial strains, which was due to the local discontinuity between individual woven carbon fiber rovings, was detected in regime 2. Continuous post impact interrogation indicated large relaxations in the residual strains occurring over tens of seconds suggesting an additional mode of energy dissipation and storage through internal friction and sliding between delaminated plies. Strain relaxation was found to occur in two modes, a decrease in total axial tension and a relaxation of the axial strain field's non-uniformity.

Embedded FBGs fractured upon prepreg pressing and consolidation. However, strain measurements could still be obtained in the reflection spectrum. While heat had little effect on sensor integrity, pressure during fabrication further damaged the waveguide by severely degrading the intensity of light guided within the core until the Bragg peak was almost indiscernible from background noise. This will be alleviated in future studies through the use of a polyimide-coated optical fiber.

Embedded strain measurements indicate a reduction in through thickness compression from fabrication with successive impacts, as well as the onset of axial compression at the midplane, which may be associated with increasing proximity between the FBG and extensive matrix cracking. Permanent residual strains measured at the midplane were an order of magnitude lower than strains measured at the free surface.

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