ABSTRACT

PEARSON, JAMES DEON. An Integrated Global-Local System for the Detection and Monitoring of Damage Progression in Heterogeneous Materials (Under the direction of Mohammed A. Zikry.)

In this study, global measurements from low-impact velocity experiments and local strain measurements from embedded and surface mounted optical fiber Bragg grating (FBG) sensors were used to obtain detailed information pertaining to damage progression in two materials, multi-dimensional laminate woven composites and Polymethyl-methacrylate (PMMA) acrylic. The woven composites and PMMA specimens were subjected to multiple strikes at 2m/s until perforation occurred. The impactor position and acceleration were monitored to obtain dissipated energies and contact forces. FBG sensors, which were embedded and mounted on the surface, at different critical locations near regions of penetration-induced damage, were used to obtain local strains. Measurements of initial residual strains and both axial and transverse strains corresponding to matrix cracking, delamination and fiber breakage were obtained for the composites, and impact induced surface deformations were obtained for the PMMA. From the FBG sensor response spectra, optical fiber sensor and host material damage were separated by an analysis based on the signal intensity, the presence of cladding modes, and the behavior of individual Bragg peaks as a function of evolving and repeated impact loads. A comparison by number of strikes and dissipated energies corresponding to composite material perforation indicates that embedding these sensors did not affect the integrity of the woven systems, and that FBG sensor measurements can provide accurate failure strains even after the initial loss of sensor integrity, which generally occurred prior to complete host material failure. The measurements from surface mounted and embedded FBG sensors were used with the global
measurements to develop maps of failure paths for the host woven composite materials, and to determine the accuracy of FBG measurements.

These characteristic maps were obtained by identifying relations between the impact contact force and the local strain fields that corresponded to five distinct regimes of composite and sensor response spanning behavior from initial impact to complete material penetration. The FBG sensors were also used to obtain residual impact relaxation strains, and to uniquely determine the mode of relaxation, a measurement that is not possible with conventional strain gauges. The PMMA specimens were impacted and quasi-statically deformed. The global measurements, for both loading regimes, were used with local measurements from surface mounted FBGs to obtain critical information related to strain-transfer, how the strain evolves from the point of impact, how the sensor debonds, and how catastrophic overall failure can be related to sensor failure. The current experimental approach indicates that local measurements can be used with global measurements to obtain a framework that can be effectively used to monitor damage progression in different host materials, and it can be potentially used to mitigate damage, if it is detected at an early stage of damage progression.
AN INTEGRATED GLOBAL-LOCAL SYSTEM FOR THE DETECTION AND MONITORING OF DAMAGE PROGRESSION IN HETEROGENEOUS MATERIALS

by

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A thesis submitted to the Graduate Faculty of North Carolina State University In partial fulfillment of the requirements for the Degree of Master of Science

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APPROVED BY:

Chair of Advisory Committee
DEDICATION

This work is dedicated to a dedicated God, country, family and considerable number of caring, supporting, and entertaining(!), cast. Without your constant support this project could not have succeeded. Cheers!!!
BIOGRAPHY

James Pearson was born in Greensboro, N.C. April 13th 1981 to Benjamin (Jim) and Debbie Pearson three and ½ years after his sister Jennifer. After moving to Newport News Virginia, he settled in Winston-Salem N.C. and attended middle and high school at Northwest Middle and North Forsyth High respectively.

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Upon high school graduation, he attended North Carolina State University in pursuit of a Bachelors of Science in Mechanical Engineering. James was awarded the Edgar B. Nichols scholarship the same year he was elected to Phi Kappa Phi in 2002. He was later nominated for Golden Key and Tau Beta Phi Honors Societies. He was also nominated for the 2003 College of Engineering Senior Award for Scholarly Achievement. An internship was performed his sophomore year at the Duke Power Catawba Nuclear Station in Rock Hill SC. James performed undergraduate research in the field of ballistic impact on composites for two summers after his sophomore year. During this time, he self taught himself at the piano and performed at the earth day Tree Jam. At graduation, James was valedictorian of
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Upon graduation after four years, he pursued a Masters of Science in Mechanical Engineering at North Carolina State University under the oversight of Professor Mohammed A. Zikry in the experimental field of instrumented low velocity impact upon composites in conjunction with highly local strain measurements from optical strain gauge sensors with funding from the National Science Foundation through grant # CMS 0219690. Six publications, comprising four proceedings, two journal articles and this Masters Thesis, were produced and presented from the work.

After graduation, a PhD was pursued under the guidance of Professor Mohammed A Zikry in the field of nano-tribological wear and friction of nanocomposite metal alloy surface coatings with support from the Air Force Research Lab.
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1. INTRODUCTION

Heterogeneous materials, such as fiber reinforced composites, can be used for military applications, commercial aerospace vehicles, automotive structures, infrastructural systems and marine systems where life-service and reliability are predicated on durable, high strength, and light weight materials that can be tailored for the desired application over a broad spectrum of loading environments and conditions (Baucom and Zikry 2003; Friebele et al. 1999; Melotik et al. 1993; Idriss et al. 1998; Shah Khan and Grabovac 2000). Traditionally, most structural fiber reinforced composites have laminated architectures. However, woven composites, whose design can include either through thickness three-dimensional weaving or two-dimensional laminar weaving, such as fabrics, are increasingly used due to an enhanced ability to suppress interlaminar shear and delamination for loading regimes spanning quasi-static to high strain-rates. (Feraboli and Masini 2004; Baucom and Zikry 2003; Flanagan et al. 1999).

As limits in specific strength and corresponding modulus of fibers and matrix are reached, further advancements in composite performance can be obtained from understanding and tailoring fiber reinforcement architecture to affect and control material behavior (Bocherens et al. 2000; Bayandor et al. 2003). This is critical as failure modes due to both static and dynamic loadings can initiate at the subsurface and lead to instantaneous failure without any prior indications. Hence, it is necessary to accurately predict and understand the initiation and evolution of damage, particularly impact damage, within composites without compromising the material’s integrity or reducing its degree of serviceability over a system’s life-cycle (Shyr and Pan 2003).
Accurate measurements of strains, as failure progresses, are required to understand, predict, and potentially control damage progression. Global measurements of contact force and dissipated energy under impact can be related to fiber breakage and delamination growth. However, these measurements are destructive, and cannot be related to changing material properties in terms of the remaining effective composite life (Kumar and Bhat 1998; Bosia et al. 2003). Predicting damage progression in composites from global measurements has traditionally followed two paths: one is based on determining the damage area from the impact load and another is based on determining the critical force threshold pertaining to damage growth (Güemes et al. 2001).

A principal limitation of these global measurements is the inability to obtain specific local, external or internal measurements of the composites evolving strength at critical locations. Hence, local measurements are needed, as the material is deformed, such that failure can be predicted. The measurement of strain fields, for example, by conventional strain gauges is intractable due to the material’s heterogeneous nature and the local discontinuities in the strain field at transitions between individual rovings and between rovings and the matrix. Furthermore, conventional foil strain gauges are impractical for internal strain measurements due to the ingress/egress of electrical leads as well as the size of the embedded strain gauge.

Recently, fiber Bragg grating (FBG) strain sensors have been used to overcome the limitations of conventional foil strain gauges. These sensors encode strains along a length of optical fiber, which acts as the gauge, into reflectivity of light as a linear function of wavelength. The development of low-loss and high-quality optical fiber for the telecommunications industry spurred the extensive use of optical FBG sensors for the
measurement of failure strains in the aerospace and textile industries, with in flight testing using these gauges scheduled for commercial airliners and the X38/CRV spacecraft (Betz et al. 2003; Ecke et al. 2001). FBG sensors have been used for monitoring the behavior of fiber reinforced composites during fabrication and in-use service (Murukeshan et al. 2000; Leng and Asundi 2002; Doyle et al. 1998; Kuang et al. 2001). These sensors provide accurate local strain measurements with high resolution and signal bandwidth, compact size, light-weight, single optical fiber multiple strain gauge multiplexing ability and the capability to withstand high heat and pressure with long-term stability (Waele et al. 2003; Yang et al. 2004). A significant disadvantage to these sensors is the inherent fragility, affecting survivability and reliability in systems subjected to impact loads. While FBG sensors have been used in impact detection, one of the major challenges in using these sensors under low-velocity impact is to accurately relate the local measured strains, which are obtained in terms of Bragg wavelength shift and spectrum width, to global damage measurements that pertain to damage initiation and progression in composite materials (Bocherens et al. 2000; Bayandor et al. 2003).

Furthermore, the local measured strains, which would be obtained from FBG sensors, need to be related to how overall damage progresses and what the degraded strength of the composite would be. Critical behavior that also needs to be clearly understood and characterized for dynamic applications is how the sensor interacts with the host material, how strain transfer occurs, and how the presence of sensors would affect the composite strength and response. While the FBG’s mode of operation provides a method of separating and identifying composite failure from FBG sensor failure, the technique does not address how strain transduction occurs from the host material to the sensor, the fragility and the failure
inherent to FBG sensors, the effects of residual strains due to sensor mounting and embedding on reliability and survivability, and the sensors ability to accurately measure strain within the composite over the entire serviceable life of the material (Fernando et al. 2002; Measures et al. 1989; Prabhugoud et al. 2004; Bosia et al. 2003).

In this study, we investigate how low-velocity impact and quasi-static perforation damage initiates in two material systems, E-glass and carbon fiber two-dimensional and three-dimensional woven composites and acrylic polymethyl-methacrylate (PMMA). Damage progression is monitored at a local scale by the use of surface mounted and embedded FBGs at critical internal and surface locations. These measurements are then used with global measurements, such as contact forces, dissipated energies, and surface deflections that are obtained from low-velocity impact experiments to develop an integrated methodology to detect and monitor damage progression from initiation to catastrophic failure. The response of PMMA specimens under low-velocity impact and quasi-static loading was also investigated. PMMA was used as a benchmark material for the proposed integrated methodology. This polymer material is widely used in applications due to its high strength and optical transparency, as well as in many studies of the fracture behavior of polymer materials (Gorham et al. 2003). In comparison with woven composites, PMMA exhibits different failure modes such as cracking and shear-crazing depending on loading rate, plate thickness and surface conditions (Ogihara et al. 1998; Wada et al. 1996; Puttick and Yousif 1982). Due to its isotropy, elasticity, and transparency, it is an ideal material, in contrast with the heterogeneous composites, to further understand how locally obtained strains from FBG sensors can be related to global measurements such that damage progression can be accurately characterized and understood.
The measurements from surface mounted and embedded FBG sensors were used with global measurements to develop maps of failure paths for the host woven composite materials, and to determine the accuracy of FBG measurements. These characteristic maps were obtained by relating the impact contact force to the local strain fields corresponding to five distinct regimes of composite and sensor response spanning behavior from initial impact to complete penetration. The FBG sensors were also used to obtain residual impact relaxation strains and to uniquely determine the mode of relaxation, a measurement that is not possible with conventional strain gauges. The PMMA specimens were impacted and quasi-statically deformed. The global measurements for both loading regimes were used with measurements from surface mounted FBGs to obtain critical information related to strain-transfer, how the strain evolves from the point of impact, how the sensor debonds, and how catastrophic overall failure can be related to sensor failure.

This paper is organized as follows: In Chapter 2, the experimental procedures for measuring local strains and global behavior for the low-velocity impact and quasi-static deformation of the woven composites and PMMA specimens are presented along with the fabrication methodologies; in Chapter 3 results for PMMA specimens are presented and discussed; in Chapter 4, results for monitoring damage progression for two-dimensional and three-dimensional composites are presented; and future research recommendations are outlined in Chapter 5.
2. EXPERIMENTAL METHODS AND SPECIMEN FABRICATION

An instrumented drop tower was used to impact PMMA and two- and three-dimensional woven composites at low velocities. An Instron 4400R universal testing machine was used for the quasi-static perforation experiments involving the PMMA specimens. Optical Fiber Bragg grating (FBG) strain sensors were surface mounted and embedded to obtain residual impact and quasi-static strain measurements. A tunable laser unit was used to interrogate the FBG sensors that were impacted by the drop tower and statically loaded with the Instron machine. The resulting strain measurements, pertaining to the FBG’s wavelength shift and spectrum bandwidth, were combined with the dissipated energy, impact contact force profiles, and the force-displacement curves to obtain a detailed understanding of how damage progresses in PMMA and woven composite systems.

2.1 DROP TOWER IMPACT

The instrumented drop weight impactor consists of a 19 mm diameter hemispherical hardened steel indentor mounted to an adjustable mass aluminum crosshead capable of delivering between 1-500 Joules per impact (Figure 2.1). Multiple strikes at the same location on each sample were conducted at 2 m/s and a nominal incident kinetic energy of 11 Joules. The experiments were stopped when complete perforation of the composite panel occurred. For the PMMA specimens, failure occurred due to shear crazing or catastrophic fracture. Specimens were securely clamped and supported from above and underneath on two 76.2 mm inner- and 152 mm outer-diameter steel rings with a thin neoprene mat on the upper and lower surface to protect the optical fiber at rough edges and transitions (Figure
2.2). The rebound of the crosshead is manually arrested to prevent rebound impacts during a single strike event. Specimens were generally impacted at the center of the specimens (Figure 2.3).

A piezoelectric accelerometer was used to continuously monitor the acceleration of the crosshead during impact. A non-contacting magnetorestrictive sensor was used to record the position and velocity of the indentor for each strike. Using an oscilloscope, the acceleration, position and velocity of the crosshead were recorded and provided dynamic measurements of contact force, surface deformation and dissipated energy for each strike.

Contact force was derived from the crossheads acceleration. Assuming the impactor to be rigid, the force transferred through the indentor can be expressed as

\[ F_{\text{Contact}}(t) = m_{\text{Crosshead}}a_{\text{Crosshead}}(t), \]  

where the mass of the crosshead used in all experiments was kept constant at 5.5 kg. Typical contact force histories for one strike for composite and PMMA materials are shown in Figure 2.4. As can be seen, the contact trace from the composite impact produces a high degree of oscillation compared with the impact of PMMA materials. This oscillation is attributable to the heterogeneous material composition of composite materials.

To compare contact force histories for different impacts of the same sample, three measurements were made from the contact force history to provide single comparable values across multiple impacts. The first, duration of contact, was calculated to be the time from the initial rise in contact force, indicating first contact, to the final fall off of contact force indicating rebound. The second, peak unfiltered force, was measured from the maximum
transient contact force recorded during the duration of contact. The third measurement, peak filtered contact force, was measured from the maximum averaged force recorded during the contact time. It was found that peak unfiltered contact force is not a highly reliable measurement due to the wide variance imparted by the oscillations. Therefore, to avoid these variations in peak unfiltered contact force, and to more reliably compare the samples stiffness across multiple impacts, the unfiltered contact force history was filtered using a 0.46 millisecond moving average. Averaging the unfiltered signal reduced the degree of oscillation, while maintaining the original form of the contact force profile (Figure 2.5).

The dissipated energy can be expressed in terms of the change in velocity of the crosshead during impact by balancing the translational kinetic energy of the impactor from before impact and immediately after. The energy given up by the impactor and dissipated by the sample, neglecting other sources of minimal energy dissipation including friction and sound, can be expressed by

\[
\Delta E_{\text{Crosshead}} = E_{\text{Dissipated}} = KE_{\text{Initial}} - KE_{\text{Final}},
\]

\[
E_{\text{Dissipated}} = \frac{1}{2} m_{\text{Crosshead}} (V_{\text{Initial}}^2 - V_{\text{Final}}^2),
\]

where the velocities of the impactor are determined through the position sensor from the inbound and rebound portions of the signal. Dissipated energy is measured for each strike as well as the total amount of energy dissipated over all strikes required to perforate the sample.

The position sensor was also used to monitor the deformation of the point of impact during loading and the residual indentation of the impact point in the unloaded position. Deformation during impact was calculated from the difference between the initial surface
height of the sample’s top surface and the minimum height reached by the impactor during contact with the sample’s top surface under impact. Residual indentation was measured after each impact as the difference between the initial height of the sample’s top surface before impacting and the height of the surface immediately after impact. These height measurements were recorded by resting the crosshead on the surface without impacting and measuring the position signal.

2.2 INSTRON QUASI-STATIC

The quasi-static experiments for the PMMA panels were carried out using a screw driven, rate adjustable Instron 4400R universal testing machine with a displacement controlled loading rate of $0.254 \text{ mm/minute}$. Support setup, with the exception of exchanging simple support along the boundary edges instead of a rigidly clamped support (Figure 2.2 without top clamp and spacer plate), and loading were similar to the impact experiments with a 19 mm hemispherical hardened steel indentor applying transverse load to the center of the specimens. The indentor was centered with respect to the support ring (Figure 2.3 (b)). Compressive loads generated by the indentor were measured continuously with a 10 kip load cell. Force and displacement measurements were recorded with a personal computer. Simple support at the boundaries allowed rotations at the support ring perimeter.

Two types of loading experiments were conducted until fracture, a constant loading and an incremental load and release pattern. For the constant loading case, the specimen was loaded until fracture, pausing at 440-newton increments to obtain a static strain measurement before loading to the next increment. In the incremental load and release case, at every successive 440-newton increment the loading was stopped to take strain measurements
before releasing the specimen at the same loading strain rate until strain free, where an additional strain measurement was taken in the unloaded condition. The specimen was again then loaded to the next 440-newton highest increment.

In both loading cases, after sensor failure the specimen was continuously loaded until fracture without pause. During pauses in the loading, which were required to obtain static strain measurements, there were load drops. This was caused by the load level falling an amount corresponding to a smaller displacement of the specimen than is detectable by the Instron thus providing for a constant, displacement even though the load varies while the Instron was paused.

2.3 FIBER BRAGG GRATIGN SENSOR MOUNTING AND INTERROGATION

Interrogation of surface mounted and embedded FBGs was carried out after each strike using either a Tunics tunable laser unit or a Micron Optics Si720 spectrum analyzer. All measurements were made in the transmission mode before optical fiber failure. Afterward, the reflection mode was used in which reflected light from the FBG was separated through a three-way circulator to a photo detector. Spectrums were stored in terms of transmission or reflection intensity and wavelength for each impact event.

The Tunics unit when used had a wavelength resolution of 0.005 nm or 4.4 µε at a Bragg wavelength of 1500 nm and scan step size of 0.01 nm when calculated using the common method of calculating axial strain in a Bragg grating as

$$
e_{Axial} = \left( \frac{1}{0.78} \right) \frac{\Delta \lambda_B}{\lambda_B},$$  

(3)
where $\lambda_B$ is the baseline Bragg wavelength from the FBG after surface mounting or embedding, and $\Delta\lambda_B$ is the shift in Bragg wavelength after loading.

LabView software was used as the data acquisition system, and 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 for the Tunics unit, thus precluding obtaining dynamic strain measurements where the total signal time length, measured as the contact duration between impactor and specimen, was approximately 10 ms.

The Micron Optics interrogation unit was used to continuously probe the FBG strain gauge at 5 Hz frequency. Recorded spectra were displayed in real time on a CRT screen. A digital video recorder was used to capture the displayed spectra, and the video of the spectrum was later converted to still frames before being digitized into terms of intensity and wavelength spectrums. This method lowered the strain resolution to approximately 90 $\mu$ε at 1500 nm.

From the transmission or reflection spectrums, which are interchangeable, the Bragg wavelength used in determining the axial strain was taken as the geometric centroid of the transmission or reflection spectrum’s Bragg peak. A representative Bragg reflection peak as well as peaks exhibiting transverse strains, non-uniform axial strains, and damage are shown in Figure 2.6. Bandwidth measurements of all spectra were determined from the width of the Bragg peak or spectrum at 10% of the peak reflection intensity or 90% of the peak transmission intensity.

Prior to surface mounting or embedding, approximately 25.4 mm of optical fiber anterior, along the length of and posterior to the FBG were chemically stripped to remove the
protective, acrylate surface coating and increase the effectiveness of strain transfer into the grating. The fiber was cleaned with denatured alcohol, and then it was surface mounted or embedded. MBond 200 strain gauge adhesive was used for mounting the optical fibers containing FBGs to the surfaces of both the composite and PMMA material systems. Before the sensors were mounted to the surface, the surfaces were cleaned with denatured alcohol and dried.

Adhesive was applied in a continuous bead along 76 mm of optical fiber surrounding the gauge when mounted to composite specimens. For the PMMA specimens, adhesive was applied sparingly and by passing the optical fiber first through an adhesive reservoir before underneath a doctor blade to uniformly distribute the bonding agent. The sensing part of the fiber was then positioned in the desired location along the length of the panel.

All sensors that were used had 8 mm gauge lengths and were positioned on the rear face of specimens. Sensors were mounted on the surface at 3 different locations and 2 different axial orientations for the PMMA materials as discussed later in Chapter 2.4.1. For the composite materials, all sensors were either mounted on the surface or embedded at approximately 14.3 mm from the point of impact. The embedded FBGs were placed in the center of the panel at the thickness mid-plane approximately 14.3 mm from the point of impact. The entry and exit points of the optical fiber into the composite were left unadulterated. The axial orientation of the FBGs, for the embedded and surface mounted composites, was aligned collinear with and between the principal exterior surface rovings as seen in Figure 2.7.
2.4 SPECIMEN FABRICATION

Two different heterogeneous composite systems and a homogenous PMMA acrylic material were impacted to monitor damage evolution within the host material and sensor separately. Composite specimens were obtained from different vendors or fabricated onsite, such that FBGs could be embedded. The PMMA specimens were all fabricated on site.

2.4.1 PMMA SPECIMEN FABRICATION

PMMA specimens were cut from a single 12.5 mm thick stock sheet. All PMMA specimens were fashioned in 12.7 cm square coupons, and they were fabricated to the dimensions shown in Figure 2.8. The sensors were surface mounted and oriented according to the markers #1-6. A 2.54 cm hole was drilled through the thickness, and the impact point was positioned 2.17 cm away from the hole’s center along a radial line. The highly smooth surface finish of stock acrylic reduced the efficacy of FBG surface bonding. While sanding or surface roughening is recommended to achieve a better bond, this was avoided as scratches and abrasions added to the specimen surface would affect the failure of the material by introducing surface flaws from which fracture initiates, particularly for surfaces undergoing large tensile strains.

2.4.2 COMPOSITE SPECIMEN FABRICATION

Three-dimensional woven composites were obtained prefabricated offsite from a composite manufacturer, 3TEX. These composites were orthogonal laminas of E-glass fiber woven together through the thickness by Z-crimp rovings and embedded in a vinyl-ester matrix. Two-dimensional 2x2 twill woven carbon fiber prepreg with thermoset matrix was
obtained from the Advanced Composite Group. Architectures of both composite types are seen in Figure 2.9.

All finished composite panels, including the 3D woven, were 12.7 cm square and either 4.16 mm thick for the prepreg or 7.2 mm thick for the 3D woven specimens. Two-dimensional prepreg composites were fabricated to allow for embedding. All 2D woven specimens consisted of 24 stacked prepreg lamina squares mutually aligned in the principal weave directions. They were consolidated in a 12.7 cm square aluminum mold at 80°C and at 1.24 Mpa for 3 hours with an additional 30 minutes of pressure during cool down. This technique produced highly reliable lamination and low void concentration as seen in Figures 2.10 and 2.11.

The 2D woven specimens used for the surface mounted sensors were fabricated in a one step process where 24 lamina were stacked, vacuum bagged and then consolidated while in vacuum during a single pressing through the hot press. Specimens with embedded optical fibers were fabricated in a three-step process. In the first stages, two 11-layer panels were prefabricated exactly as in the previous one step process with use of the mold at 80°C and 1.24 MPa for 3 hours. In the final stage, an optical fiber or FBG sensor was oriented between two fresh square prepreg laminas in the desired location and orientation. This arrangement was then sandwiched between both 11-layer panels, sans mold and vacuum bag, before final pressing. This technique utilized the thermoset polymer’s integrity under additional heating in the third stage to maintain the 12.7 cm square shape. Resin overflow was minimal in this stage, and the optical fiber can be easily positioned at desired locations in the composite as seen in Figure 4.30.
2.5 FIGURES

(Chapter 2)
Figure 2.1: Instrumented drop tower facility. Data from the accelerometer and position sensor continuously recorded via oscilloscope.
Figure 2.2: Clamping used for drop-weight impacts. Quarter inch nuts tightened to 50 in-lbs torque.
Figure 2.3: Eccentric impact test for 2D woven specimen #1 (a). All other specimens tested as shown in (b) with indentor centered with respect to the support ring.
Figure 2.4: Unfiltered contact force history during one 2m/s impact for (a) acrylic material and (b) 2D woven composite material.
Figure 2.5: Unfiltered in blue and resulting filtered contact force history in bolded red and the foreground during one 2m/s impact for (a) acrylic material and (b) 2D woven composite material. Note the unfiltered data is taken from Figure 2.4.
Figure 2.6: FBG reflection spectrum from (a) normal unloaded conditions, (b) uniform axial load, (c) uniform load transverse to the grating length (diametrical compression), (d) distortion from complicated non-uniform loadings and (e) damage to the optical fiber and grating.
Figure 2.7: Surface mounted FBG showing bond length, surface texture, and axial direction of FBG aligned with the principal weave directions.
Figure 2.8: Acrylic specimen schematic showing geometry, impact point and sensor positions and orientations marked by circled numbers on the rear face. All dimensions in mm.
Figure 2.9: Composite architectures (a) 3D woven and (b) 2x2 twill woven laminate. All impacts along the ‘3’ direction. Note that (b) depicts a single 2x2 twill woven lamina with 0° and 90° rovings. Prepreg specimens were constructed by consolidation in the ‘3’ direction of 24 of the single laminas depicted in (b).
Figure 2.10: Optical microscopy of a 2D woven composite before impact testing showing low resin buildup between lamina and low void concentration within the matrix. Regions banded by red lines are individual lamina with rovings at $90^\circ$ and $0^\circ$ as indicated in Figure 2.11.
Figure 2.11: 2D weave schematic for the composite cross-section of Figure 2.10 in the red boxed region. Oval rovings are oriented out of the page at 90°.
3. DAMAGE DETECTION IN PMMA MATERIAL SYSTEMS

The PMMA specimens were fabricated, and the fiber Bragg gratings were mounted on the surface to monitor damage progression due to quasi-static and impact loading conditions. The FBG sensors were used to obtain the residual impact strain field, and to resolve the effects of surface bonding and debonding failure on strain transfer to the sensor. These local measurements were used with the low-velocity impact measurements of contact forces and dissipated energies and the quasi-static measurements of force and displacement to obtain a detailed understanding of how damage progresses in PMMA. PMMA was chosen, since it is an isotropic, transparent, and elastic material that can be used as a benchmark material to understand how the surface mounted sensor can be used with global measurements to track damage evolution. 1) PMMA is optically transparent and allows for visual inspection of damage to both the sensor and material and, 2) the brittle, isotropic behavior and smooth surface finish provides a benchmark to further understand how FBG sensors can be used to monitor damage progression in heterogeneous materials.

3.1 LOW VELOCITY IMPACT

Seven PMMA specimens were impact tested as shown in Table 3.1 at different low impact velocities and FBG sensor positions. The dominant PMMA failure mode under impact is shown for each specimen in Figures 3.1-3.6. In the figures, the impact point on the front face is denoted by the intersection of blue orthogonal lines, the diameter and the location of the support ring is indicated by a blue circle, and the sensor location and axial direction are indicated by a box along the optical fiber. Since PMMA is a brittle material, it
would fail by cracking or shear-crazing, and this is clearly seen in Figures 3.1-3.6. While local micro-cracking under the point of impact was clearly evident, the predominant through thickness cracking and catastrophic failure, as seen in Figures 3.1-3.6, occurred at the final strike.

The catastrophic failure of the PMMA specimens during the final strike was also evident based on the global measurements. In general, the dissipated energy per strike remains constant for each strike until the final strike, which dissipates slightly higher energy than the prior strikes (Table 3.1, Figure 3.13). Furthermore, the total amount of dissipated energy in fracturing each sample varied greatly for each specimen as seen in Table 3.1. This stems directly from the variance in number of strikes to failure, which is caused by the brittle nature of the material, the imperfections between samples, and the minor variances in the point of impact between strikes.

The contact forces corresponding to failure varied for all the tested specimens. In Table 3.1, the average peak filtered and average peak unfiltered contact force values for all the strikes were fairly similar, except for the final strikes. This indicates that since fracture occurs instantaneously and randomly, the contact force is not a function of the dissipated energy for this high strength material. Furthermore, the actual contact force profile during impact for each specimen also did not yield an indication of imminent material fracture, in that the contact force did not gradually decrease prior to catastrophic fracture. In Figure 3.7, the contact force profile for the last strike of specimen #4 is shown with an image of the catastrophic damage. There was no observed specimen damage for all the previous strikes.

When the averaged peak contact force profiles for each strike are ranked by maximum force recorded during impact, the resulting order of impacts is random and not
sequential in order of successive strikes as seen in the inset of Figure 3.7. This indicates that the peak contact force attained during successive impacts cannot be used as an indication or precursor of material failure, unlike composite materials which with accumulated damage exhibit decreasing stiffness and contact force as reported by Baucom and Zikry 2005. The small difference between the averaged and original unfiltered data in (a) shows that little detectable damage occurred during the first fifteen strikes, but at the 16th strike, dominant damage occurs as seen in Figure 3.7. Also as seen from this figure, are the oscillations in the contact force when fracture occurs.

Point of impact deflection measurements during impact, as measured by the displacement of the drop tower crosshead, also did not provide detailed information on when catastrophic failure would occur. All deflections at the point of impact were fairly constant (Figure 3.8), until the final strike, when the displacements at the point of contact were usually slightly higher.

To gain a more detailed understanding of how failure evolves before the final stage, FBG sensors were used to map the residual impact strain field before specimen fracture. These impact experiments were also used to test the survivability of the surface mounted sensors. In most cases, with the exception of specimen #4, the Bragg grating survived the impact event with minimal debonding. When debonding occurred, it was repaired by rebonding it to the surface, and the impact experiments were resumed. Optical fiber fracture usually occurred near the sensor at the later stages just prior to the failure of the PMMA specimen. However, strain measurements were still obtainable up to the end of the experiment through the reflection mode. At the conclusion of the experiment, when the catastrophic failure occurred, the sensor was completely debonded from the surface.
The residual impact strain measurements for specimens #1-6 are shown in Figure 3.9 for each impact event until fracture of the specimen or, as in the case of specimen #4, the complete failure of the optical fiber surrounding the sensor occurred. As can be seen from this figure, the residual strains are all compressive, even though the sensors were still attached to the rear face of the specimen, where the strains should be tensile due to the bending of the specimen. As discussed later, in the results pertaining to the quasi-static experiments, these tensile strains are due to the frictional effects associated with the bonding agent and the partial debonding of the sensor.

From Figure 3.9, it is also apparent that the residual strains after each impact are not constant between successive impacts, but fluctuate throughout the experiment much the same as the global measurements. Specifically, there is a lack of characteristic progression to catastrophic failure; specimen failure occurs instantaneously. Furthermore, the magnitude of residual strain fluctuations between successive impacts increases with the magnitude of residual strain. The FBG sensors provided valuable information pertaining to PMMA unloading and failure of the bonding agent. In general, the sensors attained a peak residual compressive strain before gauge debonding had occurred. This local minimum strain relates to the failure strength of the bonding agent. As apparent, sensors in the near field, where the largest strains occur, failed earlier and detected larger strains than the sensors in the intermediate and far fields. Hence, this is an indication that sensor placement at critical locations can be used to detect strains related to failure.

More insight can be obtained from the residual impact strain field by examining the maximum and minimum compressive strains measured by each sensor over the duration of the experiment. In Figure 3.10, the maximum and the minimum strains recorded for each
sensor position, indicated by the bolded data markers in Figure 3.9, are plotted as a function of the radial distance from the point of impact for different sensor orientations with respect to the point of impact. The residual strains should attain the highest values at the point of impact, and then decrease to zero at the fixed boundary. For sensors oriented at 45°, underneath the point of impact the highest magnitude strain recorded was -769 µε. Sensors positioned at 12.7 cm and 25.4 cm radially from the point of impact recorded strains that decreased with radial distance. The sensor at 12.7 cm had a strain of -241 µε, and the sensor at 25.4 cm had a strain of -96 µε. This mapping of the sensors approximately corresponds to near field (at the point of impact), intermediate (12.7 cm), and far-field (25.4 cm) measurements of how the strains are varying at this orientation of 45°. This mapping provides direct strain measurements of how the strain decreases inversely with radial direction away from the point of impact.

Sensors were also oriented at 90° from the point of impact along the same radial locations as the 45° oriented sensors. For this orientation, at the same locations, there were larger residual strains in the near and intermediate fields, while sensors oriented at 45° had the largest values of strain in the far-field, as seen in Figure 3.10. These differences in strain are due to how the failure surface forms. As seen from the figures, pertaining to catastrophic failure (Figure 3.1-3.6), the failure surfaces form transverse to 90° from the point of impact, and then the surface progresses toward the high stress concentration region at the drilled hole. This orientation of fracture surface intersects with the sensors that are oriented at 90° in the near and intermediate fields from the point of impact. This is one of the reasons why the strains in the near and intermediate fields are higher for this orientation in comparison with the 45° oriented sensors. Another reason is that under compressive loadings in brittle
materials, cracks can form in normal directions to the loading axis as noted by Horii and Nemat-Nasser 1986. At the far field, cracking extends through both sensor positions instead of only the 90° orientation as at the other locations.

One specimen was also tested at a lower velocity with a sensor in the near field at 90° underneath the point of impact to understand whether compressive residual impact strains are affected by impact velocity. Specimen #7 was impacted at 1.5 m/s for only 20 strikes as failure could not be induced at this impact velocity. There were lower magnitudes of strains in comparison with the strains obtained at the impact velocity of 2 m/s. The residual strains after each strike for specimen #7 are shown in Figure 3.11. It can be concluded that strains in the near field decrease as the impact velocity is decreased.

In all cases, the FBG spectrum after each strike retained a uniform width and shape indicating that non-uniform surface deformations did not occur, and that the fiber cross section remained circular after impact. The residual strains measured after the final impact for all specimens were stable with the passage of time over a period of days after the final strike.

3.2 QUASI-STATIC INDENTATION

Quasi-static tests were conducted to understand strain-rate effects on failure, how strain transfers from the host acrylic to FBG sensor, and why the residual strains on the PMMA’s rear face are compressive. An Instron machine was used to indent the PMMA specimens as summarized in Table 3.2. For specimens #8 and #9, the FBG sensors fractured and debonded from the surface, thus eliminating the possibility of further measurements in the reflection mode.
For specimen #8, tensile strains occurred on the rear face (Figure 3.12) during indentation, as they did for the specimens subjected to the impact loads. The FBG spectrums at different loadings during the experiment indicate damage occurring within the grating. In Figure 3.14, at high loading points the expanded bandwidth of the FBG spectrums from an initial 0.5 nm bandwidth in the unloaded condition is most likely due to damage to the grating, as seen by the decreased reflection intensity at higher loads. It is not attributable to non-uniform axial strains since the spectrum broadening is not uniform and the spectrum has oscillations. As also seen from this spectrum, the Bragg peak in each spectrum at higher loadings has the original 0.5 nm bandwidth, and it does not oscillate. This indicates that the expanded spectrum width in the shorter wavelengths is due to waveguide damage.

Specimen #9 yielded additional insight into the strain transfer between the PMMA host material and the FBG sensor. At the initial loading stage, there are tensile axial strains on the rear face, which is similar to the tensile strains in the specimens that were impacted. However, upon unloading, there are compressive residual axial strains (Figure 3.15). When unloaded, the rear face of the acrylic is in a strain free state as measured by the lack of residual crosshead displacement in the load deflection curve. The compressive unloaded strains have a lower magnitude than the measured tensile straining preceding unloading. Furthermore, these compressive strains increase with increasing tensile strain. It is then likely that the compressive strains measured are due to the gradual debonding of the sensor from the host PMMA.

This is demonstrated in Figure 3.16, which shows the compressive strains generated due to the unloading from a previously tensile strained state. As seen in this figure, the bonding agent adhered to the optical fiber in small discrete regions, and it was not a
continuous uniform coating over the fiber. The localized regions of adherence were small and uniformly distributed along the bonded length of the fiber. Specifically, under high tensile loading, bonding regions of poor quality and areas under the greatest stress broke down prior to the failure of the host PMMA material. Subsequently, upon unloading, these slipped regions do not unload to zero, but were pinned down by regions of fiber still adhering to the surface. They were held in place by the friction between the contacting fracture surfaces of glue. This process is irreversible. Compressive loads, which cause the bonding breakdown, will not induce tensile residual strains when unloaded due to buckling of the fiber from the surface.

3.3 CONCLUSIONS

Low-velocity and quasi-static experiments were used in conjunction with local surface measurements from FBG sensors to characterize failure at different velocity regimes. For the low-velocity impact experiments, the FBG sensors were used to monitor the residual strain field at different distances and orientations from the point of impact on the rear face of PMMA specimens. For low-velocity impact, specimen failure was difficult to identify due to the brittle nature of the material and the catastrophic breakdown in strain transfer from host material to the sensor. The FBG sensors were able to detect higher residual strains in regions which had the highest deformation. Therefore, these sensors can provide valuable information pertaining to specimen failure.

Quasi-static experiments were used to further understand the host-sensor interaction in a controlled environment. These experiments indicated that the strain transfer to the sensor is strongly influenced by the bonding conditions at the surface. Due to the debonding
of the sensor and the frictional effects associated with the bonding agent, compressive strains occurred on the rear-surface, as they did in the low-velocity impact experiments. These range of experiments provide a detailed understanding of when the sensor fails at different loading rates, and how this sensor failure is related to the catastrophic failure of the PMMA host material. Furthermore, for the impact experiments, sensors placed at different orientations and locations from the point of impact, provide a distinct mapping of the strains that clearly show the strains decreasing radially, from high values near the point of impact to far-field values, which are significantly lower than the near-field values. Sensors located in critical locations upon total specimen failure had the highest residual strains prior to PMMA fracture. Hence, a detailed understanding of how strain evolves and how catastrophic fracture occurs can be obtained, which can then be potentially used to mitigate damage.
3.4 TABLES AND FIGURES

(Chapter 3)
Table 3.1: Acrylic specimens impact tested identified by specimen number. All distances measured in mm, forces in kN, and dissipated energies in Joules. Distance indicates shortest radial length from impact point to gauge, angle refers to FBG axial orientation. Specimen #7 could not be fractured with 1.5 m/s, 6 Joule impacts and was only subjected to 20 strikes.

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>FBG Position (Figure 2.8)</th>
<th>Angle</th>
<th>Distance</th>
<th>Strikes to Failure</th>
<th>Peak Raw Force</th>
<th>Average Peak Raw Force</th>
<th>Peak Filtered Force</th>
<th>Average Peak Filtered Force</th>
<th>Average Dissipated Energy per Strike</th>
<th>Total Dissipated Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 90º Near Field</td>
<td>90º</td>
<td>0.0</td>
<td>4</td>
<td>12.2</td>
<td>11.6</td>
<td>11.7</td>
<td>11.2</td>
<td>6.0</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>2 90º Intermediate Field</td>
<td>90º</td>
<td>12.7</td>
<td>4</td>
<td>14.2</td>
<td>13.9</td>
<td>12.0</td>
<td>11.9</td>
<td>6.1</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>3 90º Far Field</td>
<td>90º</td>
<td>25.4</td>
<td>36</td>
<td>15.8</td>
<td>12.6</td>
<td>12.7</td>
<td>11.7</td>
<td>4.5</td>
<td>143</td>
</tr>
<tr>
<td>4</td>
<td>4 45º Near Field</td>
<td>45º</td>
<td>0.0</td>
<td>16</td>
<td>15.4</td>
<td>14.2</td>
<td>12.7</td>
<td>12.1</td>
<td>5.8</td>
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<td>5 45º Intermediate Field</td>
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<td>14.7</td>
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<tr>
<td>6</td>
<td>6 45º Far Field</td>
<td>45º</td>
<td>25.4</td>
<td>19</td>
<td>15.0</td>
<td>13.2</td>
<td>12.0</td>
<td>11.6</td>
<td>5.8</td>
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<td>14.6</td>
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<td>11.5</td>
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<td></td>
<td>Standard Deviation:</td>
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<tr>
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<td>1 90º 1.5 m/s Near Field</td>
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<td>10.8</td>
<td>9.2</td>
<td>9.0</td>
<td>3.02</td>
<td>60</td>
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Table 3.2: Acrylic specimens tested under quasi-static indentation identified by specimen number. All displacements measured in mm, loads in kN, and strains in \( \mu \varepsilon \). Distance indicates shortest radial length from impact point to gauge, angle refers to FBG axial orientation.

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>FBG Position (Figure 2.8)</th>
<th>FBG Position Angle</th>
<th>Distance</th>
<th>Failure Load</th>
<th>Failure Displacement</th>
<th>Gauge Failure Load Increment</th>
<th>Strain Prior to Gauge Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>90° Near Field</td>
<td>90°</td>
<td>0.0</td>
<td>14,781</td>
<td>7.4486</td>
<td>4,448</td>
<td>10322</td>
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<tr>
<td>9</td>
<td>90° Near Field</td>
<td>90°</td>
<td>0.0</td>
<td>12,766</td>
<td>4.9995</td>
<td>4,893</td>
<td>11286</td>
</tr>
</tbody>
</table>
Figure 3.1: Acrylic specimen #1 with FBG gauge mounted under the point of impact at 90° after fracturing from 4 strikes at 2m/s shown with specimen’s rear face facing out of the page. Note the fracture extends to the clamping perimeter before terminating.
Figure 3.2: Acrylic specimen #2 with FBG gauge mounted in the intermediate zone from the point of impact at 90° after fracturing from 4 strikes at 2m/s shown with specimen’s rear face facing out of the page. Note the fracture is not the typical radial cracking seen in all other specimens.
Figure 3.3: Acrylic specimen #3 with FBG gauge mounted in the far field zone from the point of impact at 90° after fracturing from 36 strikes at 2m/s shown with specimen’s rear face facing out of the page. Note the fracture extends to the clamping perimeter before terminating. Gauge location indicated by box along optical fiber and axial direction indicated by blue line.
Figure 3.4: Acrylic specimen #4 with FBG gauge mounted under the point of impact at 45° after fracturing from 16 strikes at 2m/s shown with specimen’s rear face facing out of the page. Note the fracture extends to the clamping perimeter before terminating.
Figure 3.5: Acrylic specimen #5 with FBG gauge mounted in the intermediate zone from the point of impact at 45º after fracturing from 27 strikes at 2m/s shown with specimen’s rear face facing out of the page. Note the fracture extends to the clamping perimeter before terminating.
Figure 3.6: Acrylic specimen #6 with FBG gauge mounted in the far field from the point of impact at 45° after fracturing from 19 strikes at 2m/s shown with specimen’s rear face facing out of the page. Note the fracture extends to the clamping perimeter before terminating.
Figure 3.7: Contact force profiles versus time for all strikes (1-15) preceding failure (a) and including the final strike (1-16) (b) for acrylic specimen #4. Data in black are the raw contact force profiles and data in white and the foreground are the filtered values.
Figure 3.8: Maximum deflection of the point of impact during each strike of (a) specimen #3 with FBG mounted at 90° far from the point of impact and (b) specimen #4 with FBG mounted at 45° under the point of impact.
Figure 3.9: Residual impact strain recorded after each strike of acrylic specimens (a) #1 and #4, (b) #2 and #5 and (c) #3 and #6. Bold values in each plot mark the largest residual compressive strain amongst all strikes for each specimen. Bold and italics values denote the smallest residual compressive strain recorded amongst all strikes for each specimen.
Figure 3.10: Maximum (a) and minimum (b) strain recorded among all strikes of specimens #1-3 in red and specimens #4-6 in blue versus distance from the point of impact. Dashed lines show the expected form of exponential strain decay, \( \gamma_1 = 300 \), \( \gamma_2 = 50 \), \( r_0 = 38.1 \) mm. White diamond markers indicate strains for specimen #7 impacted at 1.5 m/s with gauge at 90° under the point of impact.
Figure 3.11: Residual impact strain (µε) in the 90° near field position recorded after each 1.5 m/s strike of specimen #7 until the experiment was stopped at strike 20. Single bolded data marker denotes strike with the largest magnitude compressive residual strain.
Figure 3.12: Strain measurements (blue data points, secondary rightmost ordinate) and applied load (red line, primary leftmost ordinate) for quasi-static testing of specimen #8 versus indentation of the loading point for (a) the linear response of the material before FBG gauge failure and (b) the total experiment until fracture of the specimen.
Figure 3.13: Dissipated energy per strike (a) specimen #3 with FBG mounted at 90° far from the point of impact and (b) specimen #4 with FBG mounted at 45° under the point of impact.
Figure 3.14: FBG reflection spectrums for four different loadings of specimen #8. Indicated above each separate FBG spectrum’s Bragg peak is the applied loading and resulting strain represented by the displayed spectrum. Notice the bandwidth of the main Bragg peak whose width is indicated by identical arrows does not deviate from the baseline width under load.
Figure 3.15: Tensile strain at applied load (blue diamond data points/labels) and compressive strain after unloading (red circular data points/labels) for specimen #9. Red data points were all measured at zero applied load and should therefore be grouped together at the origin but are instead shown distributed along the x-axis underneath the blue data point from which the specimen was unloaded.
**Figure 3.16:** Method of strain transfer between acrylic and FBG sensor when loaded in tension and subsequently unloaded. Beginning at left in the strain free and unloaded state, a tensile load is applied similar to the experimental conditions causing localized regions of bonding failure in the center image. After unloading, a residual compressive strain develops due to the constraint applied by the adhered regions of fiber and friction between the fracture surfaces in the regions of failed and slipped adhesive.
4. DAMAGE DETECTION IN COMPOSITE MATERIALS

The proposed failure detection methodology was used to investigate damage progression in two types of continuous fiber reinforced composites: a two-dimensional woven laminate prepreg and a three-dimensional woven laminate. Schematics of these two material systems are shown in Figure 4.1. The FBG sensors were both surface mounted and embedded at different surface and subsurface locations. A framework for determining the composite host damage and sensor integrity based on local FBG sensor measurements, global measurements of contact force, and dissipated energy pertaining to drop tower impact, visual observations of failure, and post-mortem characterization of surface strain relaxation is proposed. The global measurements are used to determine material degradation due to low-velocity impact. The FBG sensor strain measurements and signal outputs are used to determine local measurements of damage and residual strains at critical locations. Both these interrelated local and global measurements are then used to provide a damage map for both the host composite material and the sensor.

4.1 SPECIMENS WITH SURFACE MOUNTED SENSORS

A single FBG sensor was surface mounted near the point of impact on the rear face of both material systems. All the specimens were impacted at a velocity of 2m/s until the composite panel was punctured.
4.1.1 GLOBAL IMPACT MEASUREMENTS

Four specimens of the two-dimensional architecture were impacted. These specimens are hereby designated as specimens # 1-4. Specimen #1 required 105 strikes before being punctured, and it dissipated 113 Joules of total energy before the impactor punctured it. As shown in Figures 4.2 through 4.5, it took 61 strikes and 131 Joules of dissipated energy for the penetration of specimen #2, it took 20 strikes and 139 joules for the puncturing of specimen #3, and it took 23 strikes and 162 Joules for the penetration of specimen #4. The greater number of strikes required to penetrate specimens #1 and #2 were most likely due to that they were manufactured earlier than specimens #3 and #4. These specimens may have suffered from the expiration of prepreg matrix material while in storage. Furthermore, as noted there is an inherent variance to all impact testing and composite fabrication (Belingardi and Vadori 2002; Kang and Kim 2004). However, despite the difference in number of repeated strikes, the total dissipated energy required for puncturing these panels was approximately the same with an average dissipated energy of 136.3 Joules. The 3D woven composite, specimen #5, was not penetrated even after more than 1000 strikes and 5500 Joules of total dissipated energy. This resistance to impact is due to its inherent woven architecture (Flanagan et al. 1999).

The total dissipated energy can be used in conjunction with the energy dissipated per strike, or damage degree, to estimate the composite specimens remaining life, decrease in stiffness under load, and delamination damage size (Kumar and Bhat 1998; Bosia et al. 2003). The dissipated energy per strike of different composite specimens is shown in Figure 4.6. It is apparent that as the energy dissipated per strike for both prepreg and 3D woven composites exceeded 8-10 Joules for an 11 Joule incident impact, penetration failure by fiber
breakage occurred. While matrix cracking occurs before fiber breakage under impact, specimen penetration is more dependent on fiber breakage than matrix failure (Baucom and Zikry, 2005). As seen from Figure 4.6, the 3D woven’s dissipated energy never exceeded 6 Joules, which indicates why this material was never punctured by the impactor.

In Figure 4.7 the peak filtered contact force for each strike expended in perforating the woven composite specimens is shown for specimens #3 and 4 (two-dimensional woven composites) and #5 (three-dimensional woven composite). As can be seen, at the initial stages, the contact force is high indicating a stiff, integrated structure with little impact damage. As the number of strikes increase and damage accumulates, the 2D woven composite’s stiffness decreases as seen by the drop in contact force to one seventh of the undamaged value. In Figure 4.8 the filtered contact force evolution during each strike of a 2D woven composite benchmark, similar to specimens #1-4, is shown to illustrate how the stiffness decreases until complete perforation is obtained.

In Figure 4.7, the contact force plotted in green for the 3D woven is approximately constant as the number of strikes increases indicating the composite’s ability to dissipate impact energy without significant damage accumulation. Furthermore, the unfiltered contact force trace did not contain oscillations characteristic of fiber breakage indicating that this failure mode would not likely occur. The inability to penetrate specimen #5 is attributable to the increased thickness, the tough reinforcement fiberglass, and the 3D weave which suppresses delamination (Davies and Zhang 1994; Flanagan et al. 1999).

The peak contact force evolution and the energy dissipated per strike are shown in Figures 4.2 through 4.5 for specimens #1-4. As these results indicate, there are five distinct regimes which correlate principally to FBG measurements but also relate to global
measurements as is also shown in Table 4.1. Furthermore, in Figures 4.9, 4.10, 4.11, 4.12 and 4.13 the plot of representative strike’s contact force histories from these regimes are shown. In general, the five regimes correspond to different rates of force unloading. The first regime corresponds to the largest decrease in filtered contact force before a force plateau is attained in the second regime with a decreasing rate of change in contact force. Steady rates of force decrease occurred in the final third, fourth and fifth regimes. In these regimes, the dissipated energy per strike begins to exceed 8-10 Joules indicating imminent material failure due to material penetration.

Global measurements also included point of impact surface deflection as a measure of both the residual permanent indentation at the surface after impact and the deflection induced during impact. These measurements are shown for two-dimensional specimens #3, #4 and #6 in (a) of Figure 4.14. These surface displacements increase significantly with each impact event. The indentations approach 5 mm at the penetration stage for the 2D woven composites. These panels were originally 4.16 mm thick, thus indicating extensive deformation near the region of impact. For the 7.2 mm thick 3D woven specimen, the static displacement attained a maximum of 1 mm, which is far below that reached for the 2D woven specimens, which indicates that damage accumulates for this architecture at a fairly insignificant rate. This conclusion is further supported in (b) of Figure 4.14 as the displacements during impact for the initial strikes are identical to the displacement during the final strikes. As noted earlier, the inherently thinner 2D woven specimen architecture, in comparison with the 3D woven specimen, resulted in complete penetration by the successive 11 Joule impacts. Post-mortem images of damage modes fiber breakage, delamination, and matrix cracking can be seen at the rear surface (Figures 4.1, 4.15 and 4.35).
4.1.2  LOCAL FBG STRAIN MEASUREMENTS

The FBGs sensors were surface mounted to the two-dimensional woven composite specimens (#1-4). The sensors fractured due to impact before complete penetration of the composite, as shown in Table 4.1. However, they continued to provide viable strain measurements via the reflection mode up to specimen penetration. The optical gauges were able to survive at least half of the composite’s impact lifetime before an initial fracture, and after the initial fracture, strain measurements were still obtainable for the duration of the experiment through the reflection mode. As seen in Figure 4.1, the sensors debonded near the impact region. The sensor attached to the 3D woven composite did not fracture due to the inherent strength of this architecture. This further underscores that sensor debonding is not affected by the impact event, but it may be more significantly affected by the damage progression and strength of the host material system.

The surface mounted FBG sensor impact response can also be classified into five distinct regimes during the impact history for the two-dimensional specimens. These five regimes are primarily based on local measurements that account for Bragg peak spectrum shape, wavelength shift, transmission intensity, fiber integrity, and visible appearance. A description of each regime is given in Table 4.2 for different strikes and transmission modes. The effectiveness of sensor measurements are assessed for each regime, and they are summarized in Table 4.1.

Results for the two-dimensional woven specimens are summarized in Table 4.2. In the table, force values reported for each individual regime are the representative mean value of all strikes within each regime. Visible surface damage images depict the point of impact’s approximate location on the opposite face marked by the intersecting orthogonal lines in the
left side of each image, as well as the FBG gauge and optical fiber bonded near the point of impact in the right of each image for different strikes of specimen #3. FBG reflection spectrums, all plotted on identical scales, are displayed in terms of reflection as a function of wavelength. The primary Bragg peak and surrounding wavelengths are shown for specimen #2 in this figure.

Local FBG measurements from regimes 1 through 3 provide reliable composite surface strain measurements, while measurements from regimes 4 and 5 are not accurate and deviate from the global response. With increasing number of impacts, the FBG reflection spectra from Table 4.2 in regimes 1 through 3 show increasing residual post impact strain, as seen by the shift of the Bragg peak into longer wavelengths, as well as an increasing non-uniformity of the axial strain along the gauge length of the FBG, as seen by the increase in Bragg peak width. This growing non-uniform axial tension may arise from local strain gradients at the matrix-roving interface and between the adjacent woven rovings of which the gauge traverses approximately 4 mm within the 8 mm gauge length as seen in Figure 4.1. These gradients would continue to increase as the damage progresses near the interface of the sensor.

As noted earlier, the contact force in regime 1 is high indicating a stiff structure with little damage. At the onset of non-uniform strains in regimes 2 and 3, the contact force exhibits a dramatic drop from regime 1 indicating that the material’s strength is degrading with increasing accumulated damage. This drop in contact force also corresponds to a tensile residual strain of 2000 µε (Figure 4.16).

All the surface mounted sensors fractured in either regime 4 or 5 as summarized in Tables 4.2 and 4.1. The partial debonding of the optical fiber along the 7.6 cm bonded length
and bond adhesive failure also occur as seen in Figure 4.1. The inset picture in Table 4.2, regime 4, shows the optical fiber fracture near the gauge and directly atop a region of carbon fiber breakage emanating from the impact point for specimen #3. The FBG reflection spectrum from regime 5 appears identical to regime 1 (Table 4.2) indicating that the strain gauge is debonded and approximately strain free. When damage is visibly apparent on the rear surface in regimes 4 and 5, the FBG gauge no longer provides reliable measurements because of the sensor debonding from the host material. However, the global measurements of decreasing contact force and increasing dissipated energy still indicate that even though the specimen is degrading with successive impact loads, the specimen has not completely been penetrated. Figures 4.17, 4.18 and 4.19 provide a visual progression of the damage to the rear face of specimen #3 after every impact up until complete penetration. Damage not at first apparent is still detected by the FBG sensor.

The recorded residual axial strain and the spectrum bandwidth after each impact up until penetration of the specimen are displayed in Figures 4.16 and 4.20 with color-coding by regime as described in Tables 4.1 and 4.2. As can been seen in Figure 4.16, the residual surface strains recorded during the experiment increased gradually in regimes 1-2, and then attained a peak value of approximately 2500 to 3500 µε in regime 3. In regimes 4 and 5, there are fluctuating compressive strains, which is a clear indication that the sensor is no longer reliable. Specimens #3 and 4 exhibited multiple strain peaks in a single FBG spectrum. For these specimens the Bragg sub-peak indicating the highest magnitude strain, whether compressive or tensile, is plotted.

In Figure 4.20, the recorded spectrum width after each impact is shown. The growth is indicative of increases in the strain field’s non-uniformity. The bandwidth increases to a
maximum of 4.615 nm in regime 3 from an original average bandwidth of approximately 1.154 nm in regime 1. Specimens #3 and #4, which exhibited multiple strain peaks in a single FBG spectrum due to waveguide damage, debonding, and applied strain field, do not exhibit as large an increase in spectrum width. This is attributable to the division of the spectrum into separate peaks. For each strike of specimens #3 and #4 in (c) and (d) of Figure 4.20, both the bandwidth of the individual Bragg sub-peak indicating the highest magnitude strain is plotted by regime and the cumulative bandwidth is plotted in gray cross hatching. The original Bragg peak bandwidth after mounting but before impacting is in white and the maximum bandwidth and the maximum cumulative bandwidth are measured in nm.

Bandwidths measured in regime 3 fluctuated for all specimens and maximum bandwidths do not correspond with maximum axial strains. In general, the bandwidth decreased after regime 3 due to the gradual debonding of the sensor with successive impacts. The debonding of the fiber from the surface can be clearly seen in Figure 4.16 for regimes 3 through 5, where the reductions of strain are not in agreement with the indicated increase in surface displacements that were obtained from the global measurements.

The global measurements of the contact force and the total dissipated energy can be combined with the local strain measurements for each regime such that a damage map can be obtained as shown in Figure 4.21 for one of the two-dimensional woven composite specimens. This damage map tracks the evolution of the contact force as a function of residual impact strain. Similar plots were also obtained for the remaining two-dimensional woven composites as shown in Figure 4.22. As noted earlier, the global measurements of contact force and dissipated energy provide a reliable prediction of the composite impact lifetime over the entire experiment, while FBG measurements can be used to identify initial
damage that would not be detectable with global measurements or visual observations. In these figures, the large circular data points color-coded by regime indicate selected strikes in each regime.

FBG measurements, under certain surface bonding and traction conditions, such as debonding or a rapidly changing deformation gradient over the gauge length, can contain multiple strain values represented as separate Bragg sub-peaks encoded into a single FBG spectrum. Instead of a central Bragg peak shown in (a) of Figure 2.6, which indicates an average strain over the grating length, regions of the gauge under highly varying axial strain may be separated into individual Bragg sub-peaks. The onset of these sub-peak events generally preceded the complete fracture of the optical fiber.

These peaks are not attributable to noise in the spectrum because of the demonstrated repeatability and shift, or evolution, in response to additional impacts (Figure 4.23 and 4.24). Also, these peaks occurred before optical fiber fracture, thus discounting any effect of waveguide failure. Furthermore, the separate peaks are not attributable to radiation or cladding modes due to both the lack of any periodic nature in the wavelengths surrounding the main Bragg spectrum and the high relative intensity compared to the background noise (Erdogan 1997; Prabhugoud et al. 2004).

Multiple strain peaks in a single FBG spectrum are shown for specimen #3 and #4 in Figures 4.25 and 4.26 respectively. These peaks complicate strain evaluation due to multiple values, all of which are missed when analyzing the signal through the centroid method, the result of which is shown with a star in the figures. Reporting all strain values and peaks present in the spectrum after impact, instead of only the single largest magnitude strain as plotted in (b) and (c) of Figure 4.16 for specimens #3 and #4 changes Figure 4.16 (b) and (c)
into Figure 4.23 for specimen #3 and Figure 4.24 for specimen #4. Once the spectra split into multiple peaks, the spectrum continued to exhibit multiple strain values until complete sample perforation. In these figures, triangular data markers indicate measurements made before optical fiber fracture. After fracture and transmission loss, solid boxes represent End 1 measurements and open circles indicate End 2 measurements in reflection.

Optical fiber fracture occurred for sample #3 within the gauge after strike 11 and sample #4 outside of the gauge length after strike 16. The through grating fracture for specimen #3 effectively separated the FBG into two separate sensors, one at each end of the fiber. Both of the effectively separate gauges measured multiple strain values, and both had similar strains in regimes 4 and 5. As seen after strike 11 in Figure 4.23, for low axial strains, parts of both effective gauges were debonded, and hence these strains do not correspond to the composite strains.

While the FBG mounted to specimen #4 did not fracture into two gratings, measurements were possible through the reflection mode from one end of the sensor. As with specimen #3, regions of the grating debonded both prior to and preceding the fracture as indicated in Figure 4.24 for strike 14. These strikes are in regime 4, which corresponds to the onset of sensor debonding and failure.

FBG sensors were used to measure residual surface strain relaxation after impact for specimens #1 and #2 in real time with the Micron Optics Si720 spectrum analyzer. The relaxation of permanent post-impact residual strain indicates an additional form of impact energy storage and dissipation through internal friction between delaminated plies. As can be seen in Table 4.3, relaxation was found to occur in two forms from the spectra, Bragg peak bandwidth reduction and Bragg peak center wavelength shift. In general, these
relaxation forms relate to a reduction of the non-uniform axial strain gradient over the grating length and a reduction of the mean axial strain field.

Strain relaxation can be due to post impact equilibration, and it’s occurrence is found in regimes 1 and 2, before the failure of the bonding agent. This relaxation might underestimate the actual steady state strain values after each impact. This can be significant considering that at the peak, the measured strain relaxation between strikes is approximately 1000 $\mu\varepsilon$, which is one-third of the measured residual surface strain.

Figure 4.27 illustrates the quantified relaxation rates. As seen, they are very comparable between specimens #3 and #4 when separated by regime. Based on the total lack of bandwidth change in regime 1, the form of strain relaxation is tensile. The largest rates of bandwidth change, or relief in the non-uniformity of surface strains, are found in regimes 3 and 4 where the global measurements indicated the highest rate of delamination growth, thus further indicating that energy storage and dissipation through strain relaxation is occurring through frictional sliding between the delaminated plies.

Bandwidth change in general is not uniform around the center Bragg wavelength leading to an apparent increase in surface strain in regime 5 for both prepreg specimens. This effect is clearly seen after strikes 34, 44, and 66 for specimen #1 in Table 4.3. In this table, the FBG reflection spectra, all plotted on identical scales, after one strike from each regime for specimen #1 are displayed in terms of reflection intensity versus wavelength. The Bragg peak after impact is shown in the upper row of images, and after the passage of the allotted relaxation time in the lower row. Shaded and boxed areas on the spectrums from strikes 34, 44, and 66 compare the uniformity of bandwidth relaxation at identical wavelengths before and after the progression of the relaxation time. The resulting relaxation
measurements from these spectra are shown in bold and italics. After strike 34, the spectrum recorded after the relaxation time narrowed predominately in the longer wavelengths when compared to the spectrum recorded immediately after impact. This shifted the Bragg peak center wavelength toward the shorter wavelengths, which indicates a decrease in axial strain tension. However after strike 66, the spectrum narrowed for wavelengths below the Bragg peak thus moving the spectrum’s centroid and the Bragg center wavelength into longer wavelengths leading to increasing strain. Strike 44 indicates a uniform bandwidth reduction about the center wavelength without an accompanying shift in the Bragg peak or a change in the indicated mean axial strain over the relaxation time.

4.2 EMBEDDED SENSORS

Specimens with embedded fibers were fabricated using the layup method developed for embedding optical fibers. The difference in final composite sample fabrication was minimal. In Figure 4.7, the contact forces for 2D woven carbon fiber specimens fabricated in stages using the layup method developed for optical fiber embedment are shown in red and samples fabricated from a monolithic 24 laminas used for the surface mounted sensors are shown in blue for different repeated strikes. As seen, the two separate fabrication methods produce identical results in terms of contact force and number of strikes to puncture. The difference in number of strikes required to puncture each sample ranged from 15 to 23 joules, and it is due to the natural variances between fabricated specimens. In Figure 4.6 and (a) of Figure 4.14 specimen #6 with an embedded gauge is compared with specimens #3 and #4 with the surface mounted sensors. Both specimen fabrication techniques yield nearly identical values of dynamic surface deformation during the early strikes and very similar
results for the final strike. With fabrication techniques seen to yield similar results, we used
the drop tower measurements to determine the degradation of the material with increasing
accumulated impact damage. We then used the embedded FBG measurements and optical
microscopy characterization to understand how damage progresses at critical specimen
locations.

4.2.1 GLOBAL IMPACT MEASUREMENTS

The impact measurements for the embedded two-dimensional specimen (hereby
designated as #6) were very similar to specimens #1-4 tested with surface mounted sensors.
Specimen #6 dissipated 166.9 Joules of energy after being punctured by 20 strikes,
comparing very well to the surface mounted specimens.

The peak contact force and dissipated energy for each strike are shown in Figure 4.28.
Figure 4.29 shows the displacement of the point of impact after and during each strike. The
trends are the same as noted earlier, with a plateau in contact force after the large initial drop
following the first strikes and an increase in the dissipated energy indicating delamination in
the final strikes preceding sample failure. The initial stiffness is very comparable to
specimens #1-4 as measured by the peak contact force during strike 1 without impact
damage. The residual indentation of the point of impact on the composites surface
approached the depth of the mid-plane where the FBG is embedded on strike 11, and it
exceeded the samples initial thickness in the strikes before final perforation.
4.2.2 LOCAL STRAIN MEASUREMENTS

Embedded strain measurements from specimen #6 indicated that debonding and multiple strain peaks were not the major limitations of sensor function as with the surface mounted sensors in regimes 4 and 5. During the embedding process, the optical fiber fractured from the transverse pressure and lateral flowing of the flexible prepreg into the mold. While the fiber fractured during fabrication, strain measurements were still possible in reflection from one fiber end seen in Figure 4.30. Examining the FBG spectrum after processing indicated large transverse strains and a degraded ability of the waveguide to transmit light.

A characteristic of the embedding technique along with the common resin eye formed for all inclusions in composites is seen in the matrix rich zone immediately surrounding the laminas above and below the optical fiber inclusion in Figure 4.31. Thermoset epoxy had already cured in the panels above and below the fiber and thus could not flow into and combine with the epoxy from the final two plies used to embed the FBG. In Figure 4.31, one can see the resin eye, the large diametrical compression of the fiber into an elliptical shape and the thickness of the two middle single woven plies used for embedding the optical fiber gauge.

Under diametrical loading, the single Bragg peak splits into two identical smaller Bragg peaks centered on either side of the original peak wavelength (Zhang et al. 2003; Wagreich et al. 1996; Bosia et al. 2003; Matos et al. 2001). This effect is present in the embedded FBG spectrum owing to the compression during fabrication of the sample as can be seen in Figures 4.31, 4.32 and 4.33.
Fiber damage from fabrication is most evident in comparing the FBG reflection spectrum from before and after consolidation. In Figure 4.32 (a) the original light guiding ability of the fiber, as measured by intensity, had dramatically degraded and was almost eliminated after fabrication. This effect was circumvented by normalizing the spectrum’s peak intensity to unity. Normalization in Figure 4.32 (b) clearly indicates large diametrical compression from the Bragg peak splitting in addition to moderate axial compressive strain from the split peak’s shift into shorter wavelengths as compared to before fabrication. Axial strains from fabrication are approximately -249 με, and were not completely relieved until strike 4.

Through thickness compression at the mid-plane was completely relieved on the sensor after strike 7 as seen in Figure 4.33 by the gradual transformation of the split peak into a single coherent Bragg peak. As also seen in Figure 4.33, the uniform spectral shift into longer wavelengths indicates growing axial tension with increasing strikes. Spectrum bandwidth did not appear to correlate with strain evolution and no increase or decrease was noted with successive impacts in sharp contrast to surface mounted sensors. The transition from tensile to compressive residual axial strain, as the number of strikes increased, indicates that matrix cracking and delamination had interacted with the FBG. At the onset of compressive strains, occurring with increasing strikes and damage progression, the permanent indentation of the point of impact was approximately half the thickness of the panel. At the point of optical fiber fracture during strike 15, where strain measurements were no longer possible owing to the loss of one end of the fiber due to mishandling, the indented deflections approached the composite panel thickness.
As with surface mounted sensors, there are distinct regimes associated with the embedded sensor. As shown in Figure 4.36, there is regime 1 where tensile strain is seen to increase with a uniform axial strain field applied to the sensor. The lack of spectrum broadening in Figure 4.34 and non-uniform strains in regimes 2 and 4 may be due to the relaxation of any non-uniform axial strains through the resin eye. Furthermore, the optical fiber is surrounded by plies and constrained at all points; hence a non-uniform axial strain would not develop. As with the surface mounted sensors, Regime 5 corresponds to sensor failure.

These results are further corroborated by the maximum tensile and compressive residual impact strains obtained from the embedded sensor, which were an order lower in magnitude, ranging from 320 to -700 $\mu \varepsilon$, than the peak surface mounted strains of approximately 3000 to -4000 $\mu \varepsilon$. The normal strains at the mid-plane and geometric center of the composite are expected to be lower than the strains at the free surface farthest from the center because of bending. Spectrum broadening in this case, due to the constraint on the optical fiber embedded near the mid-plane, is less when compared to embedding the sensor at the specimen’s free surface.
4.3 CONCLUSIONS

A study of two-dimensional and three-dimensional woven composite response to low-velocity impact and perforation was completed utilizing local measurements of post impact residual strain from surface mounted and embedded optical FBG strain sensors and global measurements of contact force, dissipated energy, and point of impact displacements. A summary of the salient findings is:

- There are five distinct regimes, which are classified based on progressive damage to the composite and sensor, global contact and local strain measurements (Table 4.1);
- Taken separately, local and global measurements may not indicate the onset and progression of damage, but when these measurements are combined, the integrity of the composite as well as that of the sensor can be accurately monitored. These interrelated global-local measurements were also used to obtain damage maps that can be used to delineate the host material damage progression and FBG sensor integrity;
- *Local measurements* are best suited to capturing the onset and evolution of damage in regimes 1 through 3 with the FBG unable to report accurate, true strain values after regime 3;
- In regimes 3 through 5, there is a significant decrease in FBG effectiveness due to sensor fiber fracture and debonding, and visual observations and global measurements have to be used;
- *Global measurements* provide a continuous, albeit destructive, ability for monitoring a specimens integrity through regimes 1 though 5;
• Damage to the fiber and fiber bonding in regimes 4 and 5 can be separated from that of the host composite structure by analyzing the transmission integrity of the fiber, the FBG transmission/reflection intensity and the Bragg peak bandwidth/distortion.

• The initiation of non-uniform axial strains along the composite surface, which can be detected in regime 2, is due to the local discontinuity between individual woven fiber rovings and the penetration of fiber breakage and matrix cracking damage into the sensor detection zone, as delamination was not prevalent at this stage;

• For the 3D composite, where there was no specimen penetration due to the impact loads, the increase of residual surface strain from local measurements indicates that subsurface damage accumulation is occurring, and it is most likely related to matrix cracking. This is a further indication that local measurements are needed for accurate prediction of damage progression;

• FBG sensors fail prior to the failure of the host composite material, but can still provide accurate strain measurements throughout the entire composite impact lifetime using the reflection mode;

• After FBG sensor failure, there is an inherent decrease in the sensor’s ability to accurately monitor the true composite strain due to optical fiber debonding and fracture;

• The primary limitations of surface mounted FBG’s are debonding and the interpretation of distorted, non-uniform FBG spectra developed under exposure to high strain gradients between adjacent surface rovings;

• Multiple strain values encoded into spectrums from surface mounted FBGs were found with growing damage to the impacted 2D woven composite, and they are due
to debonded regions of the gauge under low strain and damage from matrix cracking and fiber breakage;

- The major limitations of embedded FBG’s stem from the large diametrical strains on the fiber from the fabrication process, and the associated damage to the wave guiding ability of the fiber including fracture and decreased transmission coefficient;

- Transverse and to a lesser degree axial compressive residual strains generated during fabrication are relieved at the mid-plane with successive impacts;

- The relief of transverse compressive strains and onset of axial compressive strains at the mid-plane are associated with increasing proximity between the FBG and extensive matrix cracking and delamination;

- The bandwidth of the embedded sensor does not change significantly with impacts indicating a lack of non-uniform strain development within the composite interior over successive impacts;

- Permanent residual impact strains measured along the interior mid-plane were an order of magnitude lower than strains measured at the free surface;

A measurement of residual impact strain relaxation was also obtained and correlated with each regime. A summary of the findings for the effects of strain relaxations are

- Large relaxations in the non-uniformity of the strain field and in the mean axial strain value were found to occur after each impact indicating an additional form of energy storage through frictional sliding friction between delaminated plies;
• Impact strain relaxation occurred in two forms: one is a global relaxation of the average strain over the grating seen by uniform Bragg peak shifts, and the second is a reduction in the strain fields non-uniformity over the grating length as indicated by the non-uniform reductions in the peak bandwidth around the Bragg wavelength;

• Residual impact strain relaxation was measured, and it approaches a maximum of one-third the peak residual impact strains recorded;

• The magnitudes of bandwidth and axial strain relaxation were greatest in regime 3, where the largest axial and non-uniform strains were measured;

• The largest rates of bandwidth change are found in regimes 3 and 4, where global measurements indicate the highest rate of delamination growth occurs, thus further indicating that internal energy storage and dissipation via strain relaxation occurs through frictional sliding between delaminated plies;

• Due to strain relaxation, the amount of time between impact events allows time for sample equilibration, which has an effect on the composites’ response to additional impacts.
4.4 TABLES AND FIGURES

(Chapter 4)
Table 4.1: Measurement effectiveness and regime breakdown of each strike for 2D woven specimens #1-4. Coloring convention used in Table 4.2 and Figures 4.16 and 4.20 indicated below each regime. For specimens #3 and #4, multiple strain values from a single FBG spectra were recorded for the first time and after every subsequent impact beginning with the indicated strike.

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<th>Strikes in Regime 2</th>
<th>Strike in Regime 3</th>
<th>Strikes in Regime 4</th>
<th>Strikes in Regime 5</th>
<th>Strike of Initial FBG Failure, Transmission Loss</th>
<th>Total Number of Strikes Dissipated before puncture</th>
<th>Strike of Multiple Strain Values</th>
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<th>Local Measurement</th>
<th>Visual Observation</th>
<th>Interpretation of Composite and Sensor Damage from Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highest contact force • Large oscillations in contact force indicate fiber breakage • Largest decrease in contact force</td>
<td>Growing uniform axial strain</td>
<td>Single visible fractured roving</td>
<td>Composite develops damage with first strike consisting of: o Matrix cracking o Fiber breakage on rear face. • FBG sensor is intact, capable of reliable true composite strain measurements</td>
</tr>
<tr>
<td>2</td>
<td>Plateau at 5.5 kN + stabilizing contact force decrease • Large oscillations in contact force decrease</td>
<td>Increasing axial surface strain at maximum rate • Onset + growth in nonuniformity of surface strains</td>
<td>No visible damage growth</td>
<td>Composite has reached damage level required for non-uniform surface strains • FBG sensor is intact, significant damage has spread into the FBG’s detection zone</td>
</tr>
<tr>
<td>3</td>
<td>Start of steady decline in contact force</td>
<td>Peak permanent residual tensile strain</td>
<td>Slightly visible damage • Apparent start of through thickness perforation</td>
<td>Composite has reached a state of slowing damage growth with additional impacts • FBG sensor is beginning to lose reliability</td>
</tr>
<tr>
<td>4</td>
<td>Steady decline in contact force • Growth in dissipated energy per strike • Accelerated growth of residual and dynamic point of impact deflection</td>
<td>Decrease in non-uniformity of axial strain field • Average axial strain shifts into compression</td>
<td>Visible damage • Cracking along rear face extends along weave directions away from impact point and past FBG sensor</td>
<td>Composite is approaching end of impact lifetime, rapid increase in delaminations • FBG sensor is likely damaged through: o Fracture o Debonding • FBG cannot provide reliable measurements</td>
</tr>
<tr>
<td>5</td>
<td>Steady decline in contact force • Highest values of dissipated energy per strike</td>
<td>Fluctuation of uniform compressive axial strains</td>
<td>Heavy visible perforation damage • Large wing cracks • Cone of permanent deformation</td>
<td>Perforation of the composite is imminent. • FBG measurements are unreliable and gauge damage is present in the forms: o Fracture o Debonding</td>
</tr>
</tbody>
</table>
Table 4.2: Description and interpretation of regimes.

<table>
<thead>
<tr>
<th>Deformation Regime</th>
<th>Color (Fig 4.16)</th>
<th>FBG Signal Response</th>
<th>Strain Response</th>
<th>Contact Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Light Blue</td>
<td>Bragg peak shift, uniform bandwidth</td>
<td>Gradual buildup in axial tension</td>
<td>8.3 kN</td>
</tr>
<tr>
<td>2</td>
<td>Dark Blue</td>
<td>Spectrum bandwidth increase, Tensile shift in Bragg peak</td>
<td>Growth of axial tension and non-uniformity of axial tension over grating length</td>
<td>5.5 kN</td>
</tr>
<tr>
<td>3</td>
<td>White</td>
<td>Maximum Bragg peak shift</td>
<td>Maximum axial tension</td>
<td>5.0 kN</td>
</tr>
<tr>
<td>4</td>
<td>Gray</td>
<td>Compressive shift in Bragg peak, Bandwidth fluctuates</td>
<td>Axial strain reverses into compression of varying uniformity over the grating length</td>
<td>4.1 kN</td>
</tr>
<tr>
<td>5</td>
<td>Black</td>
<td>Fluctuating peak shift, Small drop in bandwidth</td>
<td>Fluctuations in magnitude of uniform compressive axial strain over gauge length</td>
<td>2.4 kN</td>
</tr>
</tbody>
</table>

**Rear Surface Visible Damage**

<table>
<thead>
<tr>
<th>REGIME 1</th>
<th>REGIME 2</th>
<th>REGIME 3</th>
<th>REGIME 4</th>
<th>REGIME 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**FBG Reflection Spectrum**

<table>
<thead>
<tr>
<th>REGIME 1</th>
<th>REGIME 2</th>
<th>REGIME 3</th>
<th>REGIME 4</th>
<th>REGIME 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Table 4.3: Residual surface strain relaxation measurements after one representative strike from each regime for prepreg specimen #1, displayed in bold and left hand columns, and #2, displayed in the right hand columns by normal, non-bolded text. Relaxation time refers to the duration over which the measured strain relaxation, center shift of the Bragg peak, and bandwidth change were recorded.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Strike #</th>
<th>Δ Relaxation Time (s)</th>
<th>Δε Relaxation (µε)</th>
<th>Center λ&lt;sub&gt;b&lt;/sub&gt; Shift (nm)</th>
<th>Δ Bandwidth (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>8</td>
<td>15</td>
<td>10</td>
<td>-61 -147 -0.07 -0.169 0.0</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>15</td>
<td>40</td>
<td>10</td>
<td>-87 0 -0.1 0 -0.769 -0.25</td>
</tr>
<tr>
<td>3</td>
<td>34</td>
<td>17</td>
<td>25</td>
<td>10</td>
<td>-521 -868 -0.6 -1.0 -1.2 -1.15</td>
</tr>
<tr>
<td>4</td>
<td>44</td>
<td>20</td>
<td>15</td>
<td>22</td>
<td>0 -451 0.0 -0.52 -1.25 -1.11</td>
</tr>
<tr>
<td>5</td>
<td>66</td>
<td>23</td>
<td>20</td>
<td>10</td>
<td>503 304 0.6 0.35 -0.833 0.0</td>
</tr>
</tbody>
</table>

Immediately After Impact

<table>
<thead>
<tr>
<th>Δ Relaxation Time After Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRIKE 12</td>
</tr>
</tbody>
</table>

Immediately After Impact
Figure 4.1: 2D woven specimens numbered (a) #1, (b) #2, (c) #3, (d) #4, 3D woven composite (e) #5 (rear face) and 2D woven specimen (f) #6 (front face, embedded gauge). The support ring’s 7.62 cm diameter is visible in (c)-(f) from the circular markings and the matrix cracking’s circular discoloration.
Figure 4.2: Peak contact force (a) and dissipated energy (b) per strike for each strike of 2D woven specimen #1. Colors indicate regime as follows: light blue-regime 1, dark blue-regime 2, white-regime 3, gray-regime 4, dark gray-regime 5, and hatched-regime 5 but after FBG fracture has occurred. Strikes not explicitly shown have values similar to the nearest preceding displayed strike.
Figure 4.3: Peak contact force (a) and dissipated energy (b) per strike for each strike of 2D woven specimen #2. Colors indicate regime as follows: light blue-regime 1, dark blue-regime 2, white-regime 3, gray-regime 4, dark gray-regime 5, and hatched-regime 5 but after FBG fracture has occurred.
Figure 4.4: Peak contact force (a) and dissipated energy (b) per strike for each strike of 2D woven specimen #3. Colors indicate regime as follows: light blue—regime 1, dark blue—regime 2, white—regime 3 and hatched—regime 4 and 5 where FBG fracture has occurred on the first strike of regime 4.
Figure 4.5: Peak contact force (a) and dissipated energy (b) per strike for each strike of 2D woven specimen #4. Colors indicate regime as follows: light blue-regime 1, dark blue-regime 2, white-regime 3, light gray regime 4 and hatched-end of regime 4 and all of regime 5.
Figure 4.6: Dissipated energy per strike for 2D woven specimens #3 (red), #4 (light yellow), and #6 (embedded gauge, blue) plotted against bottom x-axis and 3D woven sample #5 (foreground and transparent green) plotted against top x-axis.
Figure 4.7: Peak filtered contact force recorded during each strike of all prepreg specimens (with the exception of #1 and #2) tested at 2 m/s, 11 Joules in red and blue and 3D woven composite specimen #5 shown in dashed green and plotted according to secondary x-axis at top of graph.
Figure 4.8: Filtered contact force profiles for first 30 of 60 total strikes at 2 m/s on a 2D woven benchmark composite, comparable to specimens #1-4. Successive strikes reach a lower peak force, require more time to reach the peak force, and contact the specimen for longer time, all indicative of decreased stiffness.
Figure 4.9: Unfiltered contact force (N) history over impact time (ms) for strike 1 in red and strike 2 in blue of specimen #4. Black lines indicate the resulting filtered contact force trace after averaging. Progression of fiber failure initiated and generated from the first impact does not occur during strike 2 until the loading exceeds the maximum loading imparted in strike 1 as explained in the inset (inset scale ordinate in N and abscissa in ms).
Regime 2

Figure 4.10: Unfiltered contact force (N) history over impact time (ms) for strike 5 in red and corresponding filtered contact force in black of specimen #4. As in the previous impacts shown in Figure 4.9, fiber breakage does not occur during the initial contact from 3 to 5 ms until the force exceeds the required level, at which point oscillations in the force appear.
Figure 4.11: Raw, unfiltered contact force (N) history over impact time (ms) for strike 6 in red and the filtered contact force in black of specimen #4. The analysis for this strike is very similar to strike 5 in Figure 4.10.
Figure 4.12: Unfiltered contact force (N) history over impact time (ms) for strike 10 in red, strike 15 in blue and strike 20 in green of specimen #4. Black lines indicate the resulting contact force trace after filtering. The degree of oscillation in the contact force has decreased indicating the rate of damage accumulation due to fiber breakage has slowed in this regime. In the inset, yellow trace is unfiltered contact force data from strike 1 and is provided for comparison to strikes 10, 15 and 20.
Figure 4.13: Unfiltered contact force (N) history over impact time (ms) for the final strike, number 23, causing perforation of specimen #4. Black line indicates the resulting contact force trace after filtering. Note the almost insignificant contact force/resistance generated by the composite when compared to the first strikes in the undamaged state of Figure 4.9.
Figure 4.14: Point of impact (P.O.I) displacement (mm) for (a) 2D woven specimens #3 (red), #4 (light yellow), and #6 (embedded gauge, blue) and (b) 3D woven specimen #5 in green plotted on identical scales. Dynamic deflection during impact displayed as solid line, residual permanent surface indentation after impact displayed as solid circular data points.
Figure 4.15: Comparison of uniform composite interior bonding as manufactured and before impacting in (a) to indentation induced damage at rear surface including delamination, matrix cracking, and fiber breakage in (b).
Figure 4.16: Post impact residual surface strain after each strike for 2D woven composite specimens (a) #1, (b) #2, (c) #3, (d) #4 and (e) 3D woven specimen #5. Strikes not displayed have values similar to the nearest displayed preceding strike. Indicated in each plot is the maximum-recorded tensile and compressive strain in $\mu \varepsilon$. 
Figure 4.17: 2D woven prepreg specimen #3 rear surface appearance after strike (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, and (f) 6. The first impact in (a) produces a fractured roving verifying the global measurement. The damage does not grow visibly through strike 6 while the global measurement of contact force experiences the largest drop in value for these strikes.
Figure 4.18: 2D woven prepreg specimen #3 rear surface appearance after strike (g) 7, (h) 8, (i) 9, (j) 10, (k) 11 and (m) 12. Strike 11 in (k) shows little deformation when compared to the following strike 12 in (m) where residual surface indentation has reached $\frac{1}{2}$ the thickness of the panel.
Figure 4.19: 2D woven prepreg specimen #3 rear surface appearance after strike (n) 13, (o) 14, (p) 15, (q) 16, (r) 17 and (s) 20. Cracking visibly reaches the FBG sensor after strike 15 at which point the erroneous increase in compressive strain abates. The final strike produces the most deformation and strain at the rear surface while the FBG sensor exhibits little change in response.
Figure 4.20: Post impact residual FBG reflection spectrum bandwidth after each strike for 2D woven composite specimens (a) #1, (b) #2, (c) #3, (d) #4 and (e) 3D woven specimen #5. Strikes not displayed have values similar to the nearest displayed preceding strike.
Figure 4.21: Peak filtered contact force during impact versus measured residual axial strain after previous impact for each strike of 2D woven specimen #3. In regime 1 through 3 the fraction of dissipated to incident energy for all strikes is relatively constant at 50% before growing to 75% and 100% in regimes 4 and 5 respectively. Over half the total energy dissipated is expended in regime 4 alone.
Figure 4.22: Peak contact force during impact versus residual axial strain after impact for each strike of 2D woven specimen (a) #1, (b) #2 and (c) #4. Large circular data points color-coded by regime indicate first strike from regime 1, single strike from regime 3, final strike from regime 5 and selected strikes from regimes 2 and 4. Vertical bars explained in Figure 4.20.
Figure 4.23: Specimen #3 measured multiple strain values within a single FBG spectrum interrogation after each strike. Bold data labels at each strike indicate strain peak with largest magnitude used to construct Figure 4.16 for specimen #3. End 2 measurements at strike 18 are marked with solid red fill and correspond to the spectrum shown in Figure 4.25.
Figure 4.24: Specimen #4 measured multiple strain values within a single FBG spectrum interrogation after each strike. Bold data labels at each strike indicate strain peak with largest magnitude used to construct Figure 4.16 for specimen #4. End 2 measurements at strike 21 are marked with solid fill and correspond to the spectrum shown in Figure 4.26.
Figure 4.25: Specimen #3 FBG spectrum after strike 18 as measured from End 2 of the fractured optical fiber in reflection. Three separate, repeatable peaks are identified as well as the indicated strain. The baseline Bragg wavelength after mounting but before impacting is shown by vertical dashed line.

- All 3 identified Bragg peak intensities are significantly greater than noise levels
- Lack of cladding and radiation modes at shorter wavelengths

Normalized Reflection Intensity

Wavelength (nm)

0.0
0.2
0.4
0.6
0.8
1.0
1.2

1524 1525 1526 1527 1528 1529 1530 1531 1532 1533 1534

18 µε
459 µε
1077 µε
Figure 4.26: Specimen #4 FBG spectrum after strike 21 as measured from End 2 of the fractured optical fiber in reflection. Two separate, repeatable peaks are identified as well as the indicated strain. The baseline Bragg wavelength after mounting but before impacting is shown by vertical dashed line.
Figure 4.27: Relaxation rates and forms separated by regime for specimen #3 in blue and specimen #4 in red. From each regime, one representative strike from Table 4.3 is plotted to show the comparison between specimens. Bandwidth change measured in nanometers and average axial strain relaxation in με.
Figure 4.28: Peak contact force (a) and dissipated energy (b) per strike for each strike of 2D woven specimen #6 with embedded gauge.
Figure 4.29: Point of impact deflection during impact in blue and residual point of impact indentation in red after each impact of specimen #6 with embedded gauge. Data labels above alternating strikes mark the residual indentation of the point of impact.
Figure 4.30: Embedded optical fiber at the thickness mid-plane with Fiber Bragg grating extending out of composite panel #6 towards interrogator. Embedded fiber offset (along dotted line) from the impact point at the center of the specimen marked by a solid line. The circular marking denotes the periphery of clamping.
Figure 4.31: View of embedded FBG in specimen #6 well away from impact damage showing 0° & 90° orientation of 2D woven rovings. Black zones in resin adjacent to fiber and missing regions of the circular fiber cladding have been removed during polishing. Pressure during fabrication applied from the top and bottom of the image as arrows indicate at left of image.
Figure 4.32: Reflection FBG spectrums for specimen #6 with embedded gauge from before and after fabrication displayed in (a) original intensity (in dB) and (b) normalized intensity. The after fabrication Bragg peak in red is almost indistinguishable with peak intensity of 0.0293 dB versus 1.228 dB from before fabrication in (a). Wavelength in nm.
**Figure 4.33**: Normalized FBG reflection spectrums for specimen #6 with embedded gauge after strikes 1 through 7. The white arrow indicates the initial peak splitting from through thickness compression, which is gradually relieved with successive impacts.
Figure 4.34: Post impact residual FBG reflection spectrum bandwidth after each strike for 2D woven composite specimen #6 with embedded gauge. Indicated in plot is the original Bragg peak bandwidth after mounting but before impacting displayed in white and printed above strike zero in the upper left hand corner and the max bandwidth recorded during the experiment in nm.
Figure 4.35: Impact damage mechanisms inherent to 2D woven prepreg specimens #1-4 (a) void in matrix developed after impact, (b) voids in the resin rich layers for specimens with embedded fibers, (c) matrix crack traveling along an interlaminar boundary indicating delamination, and (d) large matrix crack completely fracturing a roving before terminating.
Figure 4.36: Post impact residual surface strain after each strike of 2D woven specimen #6 with embedded gauge. Indicated in plot is the maximum recorded tensile and compressive strain in $\mu\varepsilon$. Plot adjusted so that residual strains from embedding are removed and experiment begins with zero measured strain before the first impact.
5. FUTURE RESEARCH RECOMMENDATIONS

Based on the current results and the experimental methodology that integrates local and global measurements for the identification and monitoring of damage progression in composites, future research should address the following objectives:

1. To extend the applicability of the experimental damage identification methodology to higher impact velocities and strain-rates, to different penetrator and support geometries and the effects of multi-axial states of deformation due to oblique and normal impact loadings;

2. The application of the methodology to non-woven angle ply, short fiber/chopped strand and foam core composites;

3. The incorporation of experimental measurements, such as relaxation and residual strains into micromechanical FEM models, such that reliable predictive tools can be used in conjunction with detailed experimental measurements;

4. To develop accurate optimization schemes for sensor data fusion; to develop schemes to determine how many sensors are optimal, what are the most suitable placement and orientation for both sensor survivability and damage detection;

5. To develop actuation schemes for in-situ damage control and mitigation.
6. LIST OF REFERENCES


