SMART COMPOSITE USING OPTIC FIBER SENSOR EMBEDDED IN THREE DIMENSIONAL WOVEN PREFORM

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ABSTRACT

Unexpected failure in structures such as airplanes, bridges, and dams can have catastrophic effects. Structural health monitoring (SHM) is a way to monitor the integrity of such structures, so that any critical deformation can be detected and acted upon immediately. Compared to most current SHM systems, which are applied to a structure's exterior, this research aims to introduce a system that is an integral part of the construction material. Optic fibers are well suited to be incorporated in textiles. During composite fabrication, a polymeric optic fiber (POF) can be woven directly alongside yarns in the 3D orthogonal woven preform, creating a smart composite. This allows access to interior locations where other sensing methods may not be able to detect. Testing of this system mimics accidental impacts that can occur during the structure's lifespan by exposing the smart composite samples to multiple low energy impacts at a localized site. The composite sensor system efficacy is then evaluated by establishing a relationship between the sensor's location, composite damage, and the resulting POF signal. This is used to determine the best location for optic fiber sensors to be placed within the composite, so that they can accurately predict structural damage before failure occurs.

1. INTRODUCTION

Man-made materials are continuously evolving. With the popularity of the internet of things, everyday structures can be connected to world, gathering usage metrics, and alerting the user to potential structural danger. Structural health monitoring (SHM) involves an intelligent system which incorporates sensors, data transmission, computational power, and processing ability for real time monitoring of structural conditions. Safety and prevention of structural failure are strong motivators for implementing SHM systems. Structures are often complex and expected to be fully functional under sever environmental conditions such as high winds, storms, and earthquakes. These incidents present extreme loading that may compromise the integrity of the structure and lead to total failure that results in casualties, social, and economic problems.

A successful SHM system will ultimately increase the safety of the structure, increase the structure's longevity, reduce the cost of maintenance, and be reliable and accurate at predicting failure within the structure [1, 2]. Compared to most current SHM systems, which are applied to a structure's exterior, this research aims to introduce and examine a system that is an integral part of the construction material. This system is based on a polymeric optic fiber (POF) sensor embedded in a 3D orthogonal woven (3DOW) textile composite. The relationship between signal loss in optic fibers, as measured by optical time domain reflectometry (OTDR), and the reduction

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in compressive strength relative to impact induced damage serves as the basis to interpret the structure's current health.

1.1 Optic fiber

The term optic fiber indicates a special form of optical waveguide with a circular cross-section, which is flexible, and can be produced at great lengths [3]. They are most well-known for their use in communication to transmit light over longer distances and with higher data rates than other forms of communication. Today, optic fiber sensors have been established as a measurement technology in several fields such as material science, civil engineering, light-weight structures, and geotechnical areas [4]. All optic fibers are composed of a core, a cladding, and sometimes another outer protective layer [5]. In order to transmit a light signal effectively through the core of the fiber, the core and cladding are composed of two optically dissimilar materials. Light waves are trapped and carried within the core by reflection at the interface between the core and cladding [3, 6, 7].

Many of the characteristics of optic fibers are determined by their materials. There are two main material categories when dealing with optic fibers for use in sensing applications. The first and most widely used are silica optic fibers also known as glass optic fiber (GOF). GOFs benefit from having a high strength, small size, and low attenuation. They however also come with a low tensile strain and a tendency to be brittle. These optic fibers cannot handle bending and require protective layers such as a polymer layer to reduce abrasion and a protective outer jack to protect the core in situations where bending may be present [8]. Such protections can result in inconsistencies between the fiber strain and structural strain [9]. Polymeric optic fibers on the other hand exhibit high fracture resistance and flexibility in bending, which are highly advantageous qualities when embedding in a material [5]. In the past, POF have been plagued by high attenuation associated with PMMA, PC, PS cores, which limited the use to short distances. One of the main reasons behind the high attenuation is the C-H bond vibration absorption, which can be reduced by replacing hydrogen atoms with heavier atoms such as fluorine, chlorine and deuterium. These polymers decrease the attenuation to <50 dB/km at the visible region of the spectrum, which is five times lower when compared to a PMMA optic fiber [10, 11].

1.2 3DOW smart composite

Due to their flexible, yarn-like structure optic fibers are well suited to be incorporated in textile structures, such as the preform component of a fiber reinforced composite. High strength textile composites are an excellent candidate for infrastructure applications due to their light weight, ease of fabrication, long life, and low maintenance requirements. These types of composites have been used in numerous applications including aircraft, automotive, and wind turbines. During composite fabrication, a POF can be woven directly alongside the yarns in the fiber preform. Research by Zhou and Sim confirms that embedded optic fiber sensors perform in the same way as non-embedded sensors [7]. In order to prevent movement of the fibers within a composite, the fiber optic sensors can be woven into the structure either by 2D, 3D, or 3D orthogonal weave (3DOW) structure. In this setting, 3DOW has advantages over the others because of its structure. Optic fibers exhibit high attenuation when subject to bending. With 2D weaving an optic fiber would be incorporated as a warp or weft yarn and therefore would experience micro bending in the form of crimp as part of the weave type. With 3DOW, the warp and weft yarns are on straight planes in the x or y direction and woven together with a third z-yarn. The POF can be incorporated as part of the x or y layer and therefore avoid unnecessary bending. One concern with the use of composites in infrastructure is that they are susceptible to damage, mainly delamination in the z direction between layers. Interior delamination significantly affects performance by degrading stiffness and reducing load bearing capability of the structure [7]. An additional benefit of 3D orthogonal weave is that it adds reinforcement in the thickness direction and prevents delamination. Two of the goals of SHM are to increase the longevity of the structure and reduce maintenance time and cost. This orientation of fibers helps meet the goals of SHM by providing added reinforcement and preventing one type of common damage from occurring.

2. EXPERIMENTATION

All load-bearing structures will experience some level of damage during their lifespan. Using a parameter to evaluate the effect of damage on the structural performance, such as in SHM, can be fully achieved only when the nature of damage is understood and characterized [7]. The basic steps of SHM in the case of damage monitoring are that the damage is detected by a sensor, the damage is located and identified, and the severity of the damage is determined. After this the damage is reported and the necessary steps are taken, such as sending out a warning or making repairs. The first three steps were investigated in this work. First the smart composite was fabricated then a series of destructive impact tests were performed. A signal from the optic fiber was obtained using OTDR after each impact event to detect and locate the damage and lastly severity of the damage was determined by evaluating the residual compressive strength after exposure to an impact event.

2.1 Materials

The POF (GigaPOF-62LD) sensor that was used in this study was a low attenuation, multi-mode, IR-transparent POF with a high bandwidth graded index, acquired from Chromis Fiberoptics, Inc. The core and cladding of the POF were made of a perfluorinated polymer (PF) (Polyperfluoro-butenyvinyleether). The core diameter was 62.5 μm, which is a common diameter for multi-mode optic fibers. Bending radius is an important parameter to consider in order to minimize attenuation loss due to bending when embedding an optic fiber in a material. Seyam and Hamouda determined that the critical bending radius, minimum bending radius at which the optic fiber exhibits no signal loss, for this optic fiber to be 19 mm [12]. The sensor functions as a distributed sensor based on Rayleigh scattering.

Fiber glass (E-glass), supplied by PPG Industries was used as the reinforcement material. Glass fibers have a high tensile strength, high heat resistance, high chemical resistance, and a low cost compared to other high performance fibers. These properties allow glass fibers to be used in a variety of fiber reinforced composite applications. Three different linear densities, 735 (g/km or tex), 2400 (g/km or tex), and 276 (g/km or tex), were acquired for the x, y, and z yarns.

The resin system used to form the 3DOW composites was the Epoxy 2000 and 2120 hardener combination, distributed by Fibre Glast Developments Corporation. This resin system was mixed in a 100:27 weight ratio and had a pot life of two hours at room temperature. It was selected for its high tensile strength (67 Mpa) [13], high modulus (2.8 Gpa) [13], and harmless effect on the POF and its sensing abilities [14]. It is critical that the resin not interact with the POF material to ensure the performance of the sensor in the composite.

2.2 Smart Composite Formation

The smart composites were formed using a two-step process: first preforms were woven with embedded POFs and second the preforms were infused with the resin system and allowed to cure. The samples were woven on the 3D weaving machine donated by 3TEX, Inc. available at the Wilson College of Textiles, NC State University. The weave structure for every preform was plain weave with four y-yarn layers and five x-yarn layers. The y-yarns were drawn through the reed so that there was one yarn per layer in a reed dent. X-yarns were inserted simultaneously between y-yarn layers with a double insertion per shed and a density of 4.72 pick/cm/layer (12 pick/in/layer). Z-yarns bind these layers together with the plain weave design and there was one z-yarn per reed dent so that they were positioned evenly between y-yarns.

During weaving, the POF was manually inserted into the preform in the x-direction. Three test groups were set up to compare POF structural position, represented in figure 1. The pick density and number of layers remained constant while the POF was inserted in either the top (between 1st and 2nd y-layer), middle (between 2nd and 3rd y-layer), or bottom (between 3rd and 4th y-layer) layers. The POF are located approximately 2 mm (top), 3 mm (middle), 4 mm (bottom) from the surface of the composite.

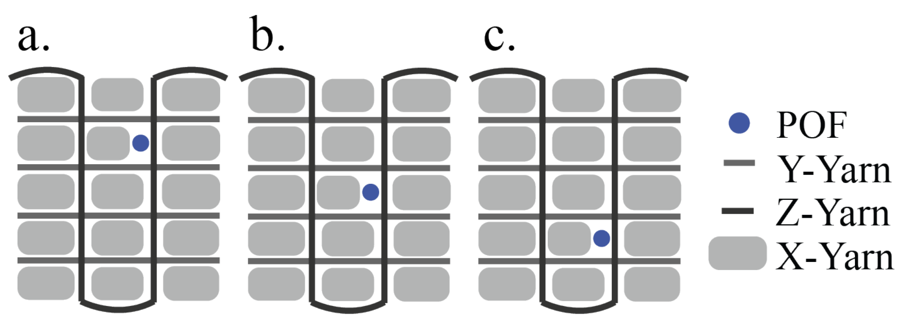

Figure 1. Representation of POF structural position a) POF located in the top layer b) POF located in the middle layer and c) POF located in the bottom layer

The optic fiber was inserted in 5 m segments with approximately 1.5 m embedded in the preform. About 1.75 meters of POF protruded from each side of the preform to account for reflection at the fiber input and output during OTDR. The POF are very fragile and undergo a lot of handling during the composite fabrication. The portion of POF outside of the preform was threaded into a 2 mm furcation tube to provide extra protection during weaving, infusion, and testing. A distance of 3.8 cm, shown in figure 2, was kept between the POF insertions to accommodate the bending radius at both selvedges of the 3D orthogonal woven preform.

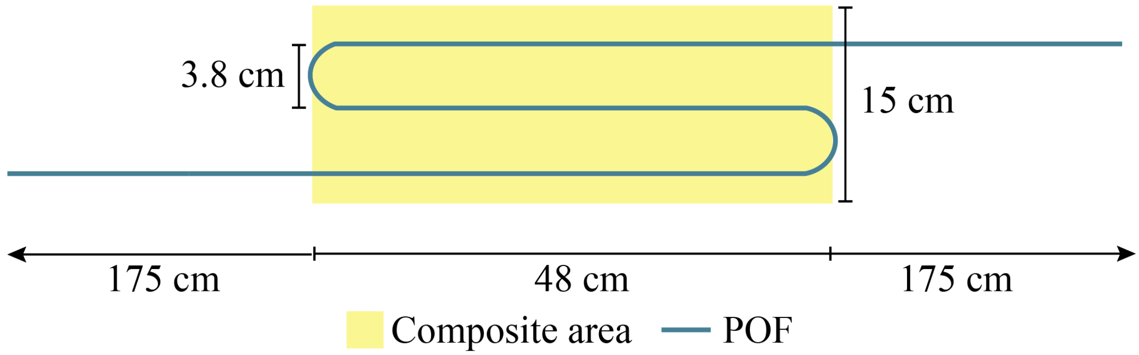

Figure 2. Schematic of POF embedded in the smart composite

3DOW preforms were treated with the resin system using vacuum assisted resin transfer molding (VARTM). The furcation tubes were placed on top of sticky tape and an additional small piece of sticky tape was placed on top to prevent any air leakage during the resin treatment process. This also prevented excess resin from curing on the ends of the POF which needed to be connected to the OTDR. A vacuum pressure of 100 kPa was applied for all samples. The prepared resin mixture was placed in a vacuum desiccator for degassing for 20-30 minutes to remove the air bubbles created during stirring and thus decrease the potential for voids within the composite. The panel was left on the table to cure at room temperature. After the panel was cured, the panel was cut into specimens with dimension 48 cm x 15 cm, figures 2 and 3. The thickness of the composite panels was 6.5 ± 0.3 mm.

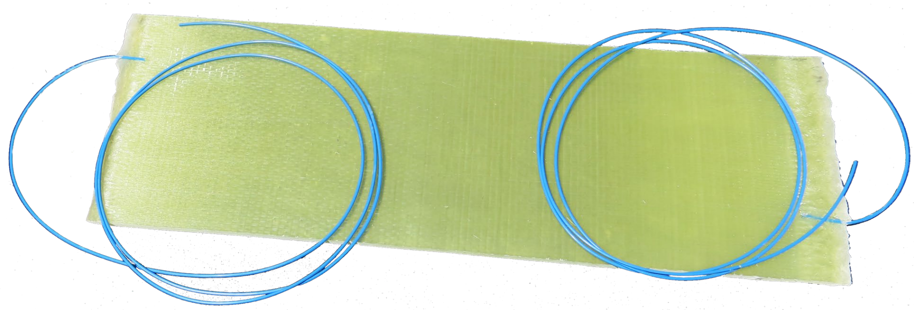

Figure 3. Example of a composite specimen after weaving and resin infusion

2.3 Testing

2.3.1 Attenuation

In OTDR based on Rayleigh, signal is measured through the backscattering of light. Short light pulses are coupled at one end of the optic fiber. The light is propelled through the fiber and undergoes Rayleigh scattering along the fiber length [3]. When light hits fiber particles the light will scatter and be redirected in different directions, which causes signal attenuation and backscattering. Different types of defects affect the light backscattering in different ways and the reflected pulse is detected at the input [15, 16]. The total time duration for the light to travel from the input to reflect to the input again is also measured [17]. From this backscattering measurement, statements about the attenuation curve and local disturbance can be made.

A typical backscattering output signal, characterized in figure 4, consists of a main slope which represents the signal attenuation according to Rayleigh backscattering and a reflection spike according to Fresnel reflection. Fresnel reflection occurs when a sudden change happens to fiber refractive index (i.e. change from fiber material to air) and causes the light to reflect back on the fiber. This Fresnel reflection appears as a spike on OTDR waveform, usually associated with the ends of the optic fiber [18]. Rayleigh backscattering is used to calculate the level of attenuation in the optic fiber as a function of distance, which is shown by a straight slope in an OTDR waveform signature, as the slope decreases attenuation becomes higher [18]. Dynamic range is the distance between the initial backscatter and the noise level. The higher the dynamic range, the higher the signal to noise ratio and the clearer the events will appear.

The backscattered light is recorded as a function of time. The speed of the light, the time for light to launch and be backscattered to the input can be converted into distance corresponding to a position along the fiber and is used to pinpoint damage to the fiber [16, 19]. A reflection or excess loss is observed in the spectra when there are defects, disturbances, or discontinuities in the fiber [16, 19].

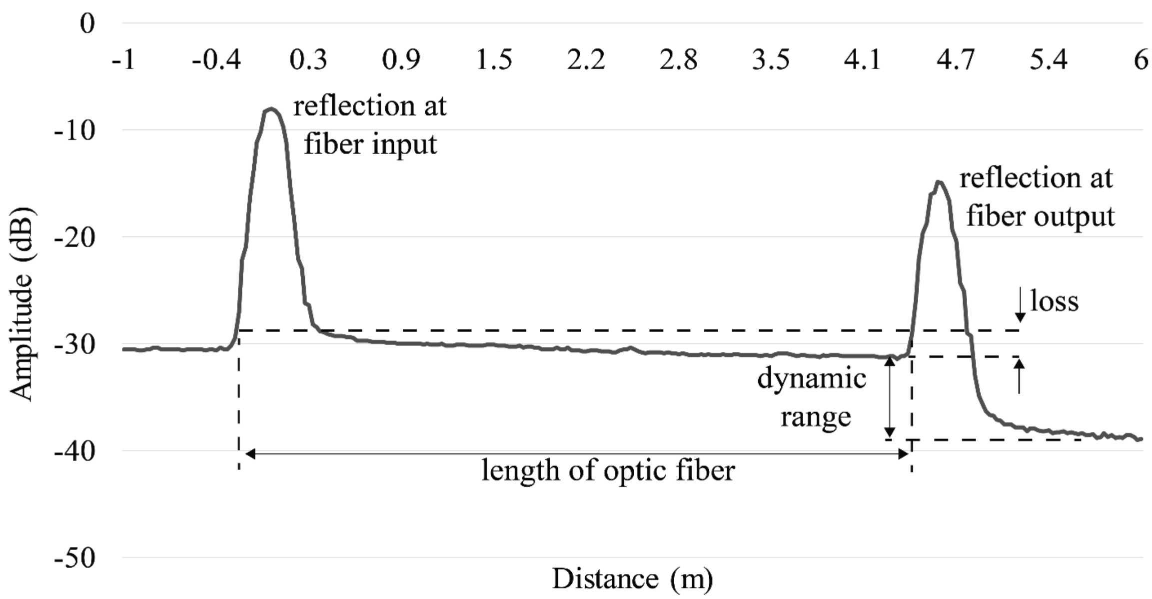

Figure 4. Characterization of a typical POF signal obtained from OTDR

The LOR-220 from Luciol Instruments, a portable high resolution scanning photon-counting OTDR was used to measure the integrity of the POF signal. The OTDR was configured to emit a wavelength of 670 nm, with a time step resolution of 1.25 ns and signal pulse width of 1 ns. The optical pulse width on this technology is 1 ns which is optimized for short range fiber testing. Short dead zones (10 cm event dead zone and 40 cm attenuation dead zone) allow for detection of events such as fiber breaks and bend loss within the smart composite. OTDR was used to test the quality of the POF after weaving and after resin treatment. During impact testing, one protruded end of POF embedded in the composite was connected to the OTDR to measure the signal loss after each impact event.

2.3.2 Repeated Impact

In the proposed SHM system, the effectiveness of the composite sensor system is evaluated by exposing samples to multiple low energy impacts in a localized site. Such testing aims to mimic the accidental impacts a structure may receive during its manufacturing process and service life, which have been shown to result in decreased compressive strength. Low energy impact is considered the most dangerous because the damage may escape detection during a visual inspection of the impacted surface of the component [20]. When low energy impact events are being considered, rupture does not occur on a single hit [21]. Single hit testing may not generate significant damage in a composite. This is especially true for 3D woven composites which have higher impact damage tolerance than 2D woven composites [20, 22]. It is thus more important to determine the evolution of the damage than, solely the absorbed energy. To observe this evolution, the composite must not be completely penetrated. According to an early paper written by Jang et. al. exploring the benefits of repeated impact testing, these events promote a clear damaged region even when impact energy is very low and represent a convenient method for assessing the damage tolerance of fiber composites [23].

A high energy falling weight impact tester, CEAST 9350, was used to evaluate the response of the POF embedded sensors to impact forces. A testing fixture with diameter 76.2 mm and a tup with diameter 12.7 mm was used for the test. Impact energy of 9 J and18 J were chosen to create slow damage accumulation in the composite. Multiple impact events were conducted in the same location, with the observation of POF signal loss, by OTDR after each event.

The ASTM D7136 [24] standard for measuring damage resistance of a fiber reinforced polymer matrix composite to a drop weight impact event was used with modification to the width of the sample. The standard recommends a flat rectangular composite plate of dimensions 15 cm x 10 cm be subjected to an out-of-plane, concentrated impact [24]. Specimens with dimension 15 cm x 42 cm were used to accommodate the critical bending radius of the POF and the use of the 3D weaving machine.

2.3.3 Compression

High strength reduction occurs under compression loading and thus it is an important problem to be considered in the design of composite structures [25]. Compression after impact (CAI) testing is an experimental method to obtain the degradation of the compressive strength of composite plates due to impact loading. ASTM D7137 [26] the standard test method for measuring residual strength properties of damaged polymer matrix composite plates was followed to characterize the damage. ASTM D7137 required a 150 mm by 100 mm flat rectangular composite sample that had been subjected to impact testing. After impact, the specimens were cut according to these dimensions (with the impact location in the center) using a computerized waterjet cutting technology available at ADR Hydro-Cut, Inc., Morrisville, NC. The waterjet cutting was very precise in terms of dimensions, with very low coefficient of variation (less than 0.1%). To gather a baseline compressive strength for the data a combined loading compression test was performed following ASTM D6641 [27]. The specimen size was 140 mm x 13 mm and was also cut using the computerized water-jet for improved accuracy. Both tests were performed on the MTS model 370 servo hydraulic load frame using the compression fixture associated with the appropriate ASTM standard and a compressive speed of 1 mm/min.

3. RESULTS AND DISCUSSION

The composite sensor system was evaluated by establishing a relationship between the sensor's location, composite damage, and the resulting POF signal. This was used to determine the best location for optic fiber sensors to be placed within the composite, so that they can accurately predict structural damage. Due to the destructive nature of the testing and the fragility of the POF all tests were conducted on individual specimens, which have variation from one sample to another. Ideally, repetition of these samples would produce more conclusive results. Regardless, there are clear trends apparent in the data.

3.1 OTDR

The signal obtained from OTDR is unique to the environment in which the POF is tested. Slight changes in the connection of optic fiber to the OTDR can produce shifts in the signal obtained. Therefore each signal tested must be considered on an individual basis. For the following data, the signal produced at impact 0, before the impact test was started, was considered the baseline. Figure 5 shows the signal of a POF embedded in the top layer of a composite after being impacted 10 times and 20 times at an impact energy of 9 J. In this optic fiber, there was a loss of about 4 dB after 10 impacts and a loss of 8 dB after 20 impacts compared to the baseline. This shows that the optic fiber was sensitive to the impact event, but it was not completely damaged. Complete damage to the optic fiber would result in a spike in the signal at the impact location, like the reflection observed at the ends of the optic fiber. At the 9 J impact energy level POF located in the middle and bottom layers were also tested. The signal for these POF did not change as drastically as the POF located in the top layer. At 9 J impact the POF located in the middle layer only showed a reduction of 2.4 dB after 30 impacts. The POF located in the bottom layer showed hardly any loss with a reduction of only 0.2 dB after 30 impacts.

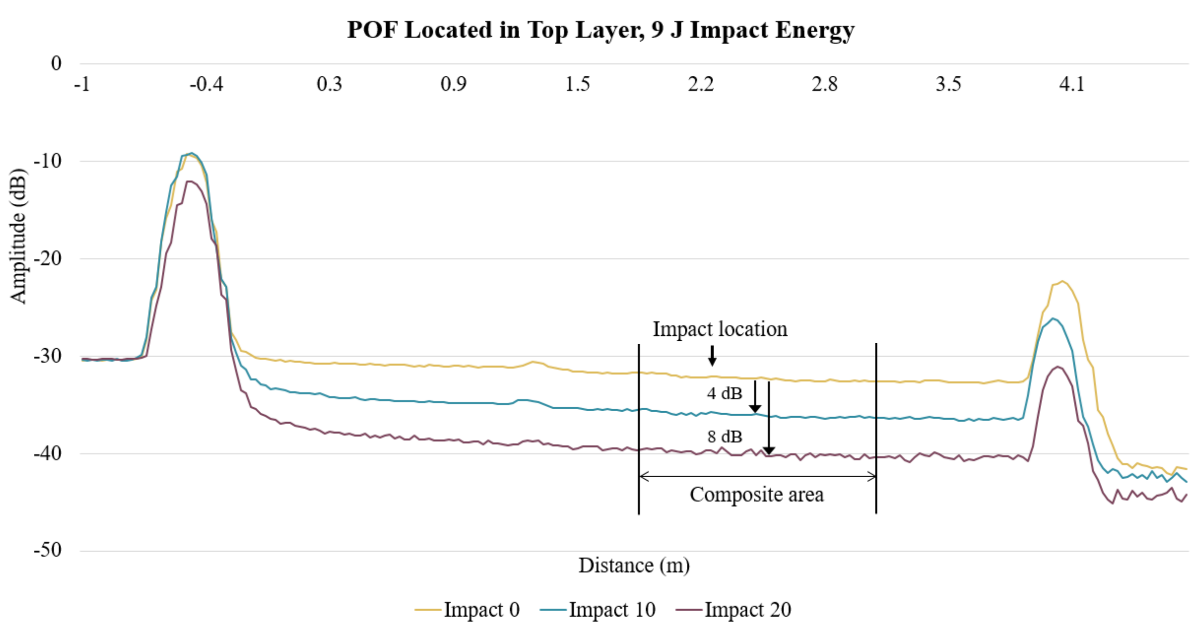

Figure 5. OTDR signal for a composite impacted at 9 J, directly on the POF embedded in the top layer

A POF embedded in the top layer of the composite impacted at 18 J, figure 6, shows a similar reduction in signal to the POF shown in figure 5. During this impact event there was a loss of 3.5 dB after 10 impacts and 5.5 dB after 20 impacts. This optic fiber shows a decrease in signal beginning at impact location, indicating that the fiber was working normally to this point and then was directly affected by the impact event. At 18 J impact energy a POF in the bottom layer was also tested. The POF was not sensitive to the impact events and the signal was only reduced by 0.2 dB after being impacted 30 times.

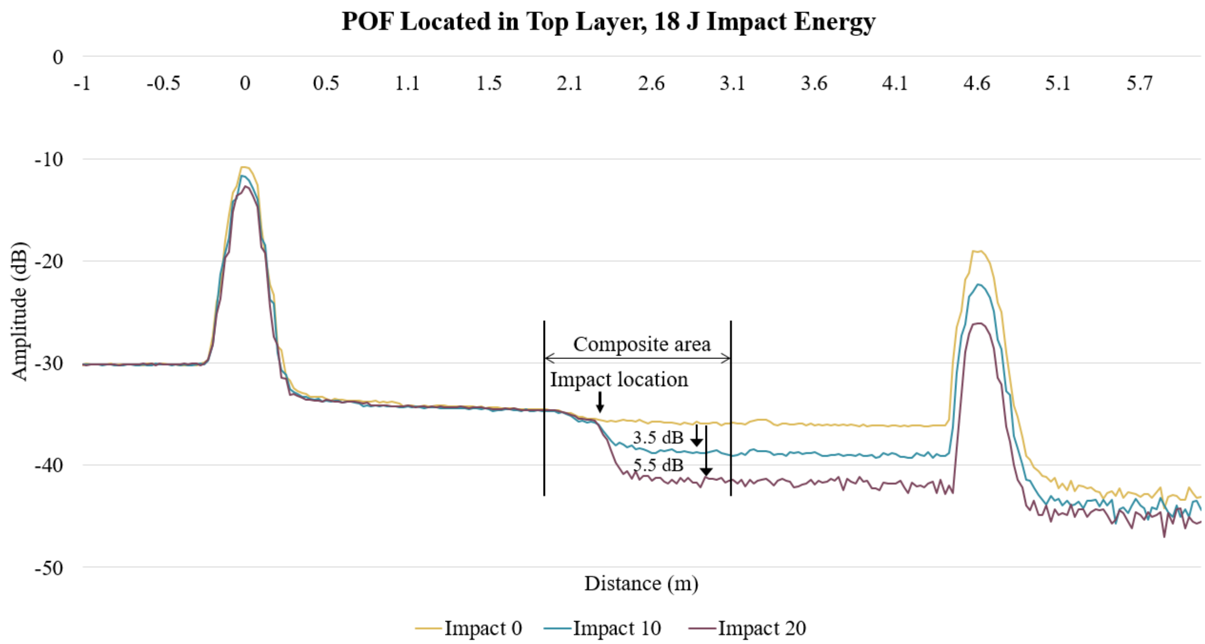

Figure 6. OTDR signal for a composite impacted at 18 J, directly on the POF embedded in the top layer

In theory, the loss that occurs at 18 J should be higher than that at 9 J, but each fiber must be treated individually due to the conditional nature of the test. The differences between the optic fiber signals obtained may have occurred because impact was at a slightly different position in relation to the POF. During testing, the impact position was determined by eyeballing the location the optic fiber in the composite and then centering it under the tup. A more accurate placement of the impact location and testing of multiple optic fibers under the same conditions would produce more consistent results.

3.2 Residual Compressive Strength

Residual compressive strength was measured for the composites, figure 7. The composites were fabricated with the same parameters as the composite used for the OTDR test, but they still may have slight variations due to the composite formation process. The composites exhibit a loss of about 45% in strength after being impacted 10 times at 9 J and almost 50% in strength after being impacted 10 times at 18 J. There is a clear downward trend in strength as the impact number increases from 0 to 30. The earliest impact events appear to have the most influence on the structural integrity of the composite structure, as the decrease in strength becomes less severe with an increase in the number of impacts.

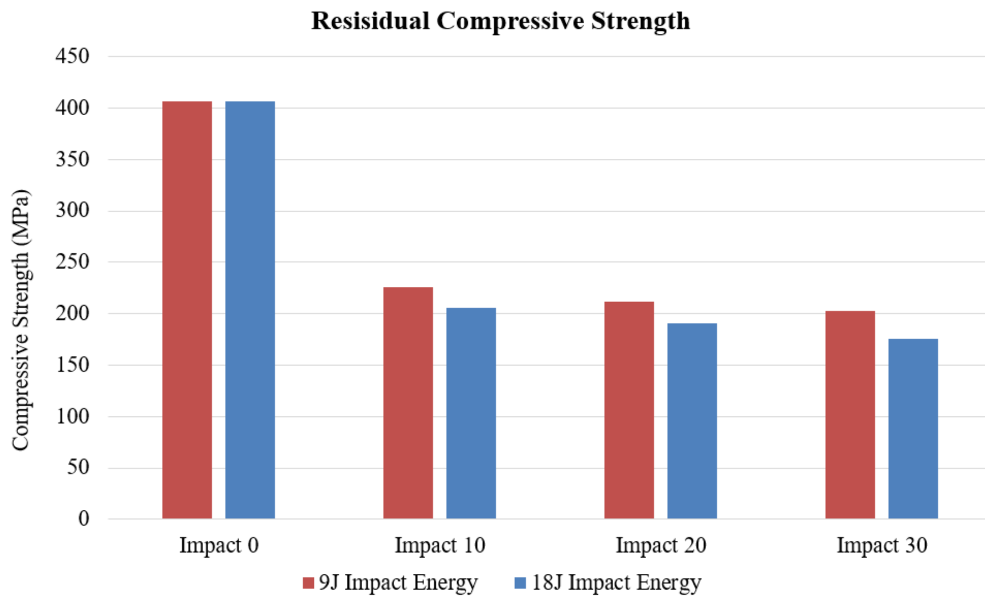

Figure 7. Residual compressive strength of the composite after repeated impact at 9 J and 18 J

To understand how well the sensor relates to the severity of the damage, the percent loss of compressive strength in the composite was correlated with the percent loss observed in the POF signal, figures 8 and 9. There is not a point for 30 impacts on the graph for the POF embedded in the top layer, because the dynamic range in the POF signal reaches zero before 30 impacts is complete. The optic fibers in the top layer of the composite appear to be more sensitive to the small changes in compressive strength associated with a higher number of impacts. Given that there is such a large reduction in strength, almost 50% after the initial impacts at each energy level, a system that is more sensitive to damage may be more advantageous. The POF located in the top layer, approximately 2 mm from the surface, is the most sensitive to the damage event and correlates best with the strength loss observed. Further testing, however, is needed to draw strong conclusions about the accuracy of the POF at predicting damage.

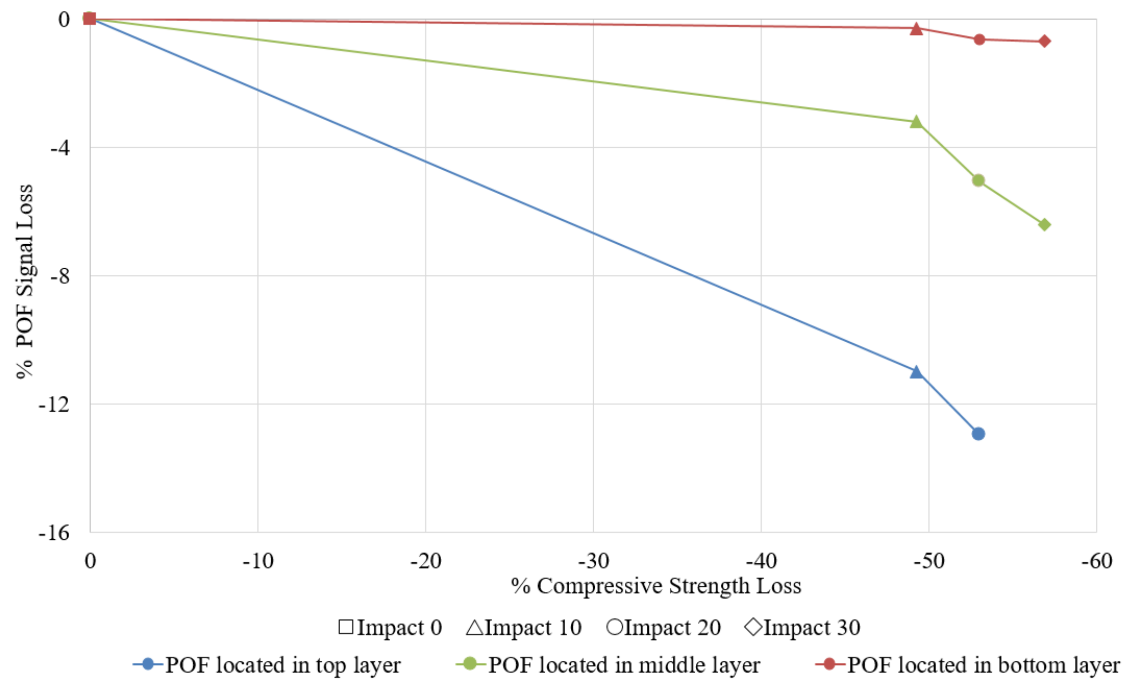

Figure 8. Graph of compressive strength loss vs. POF signal loss after repeated impact at 9 J energy

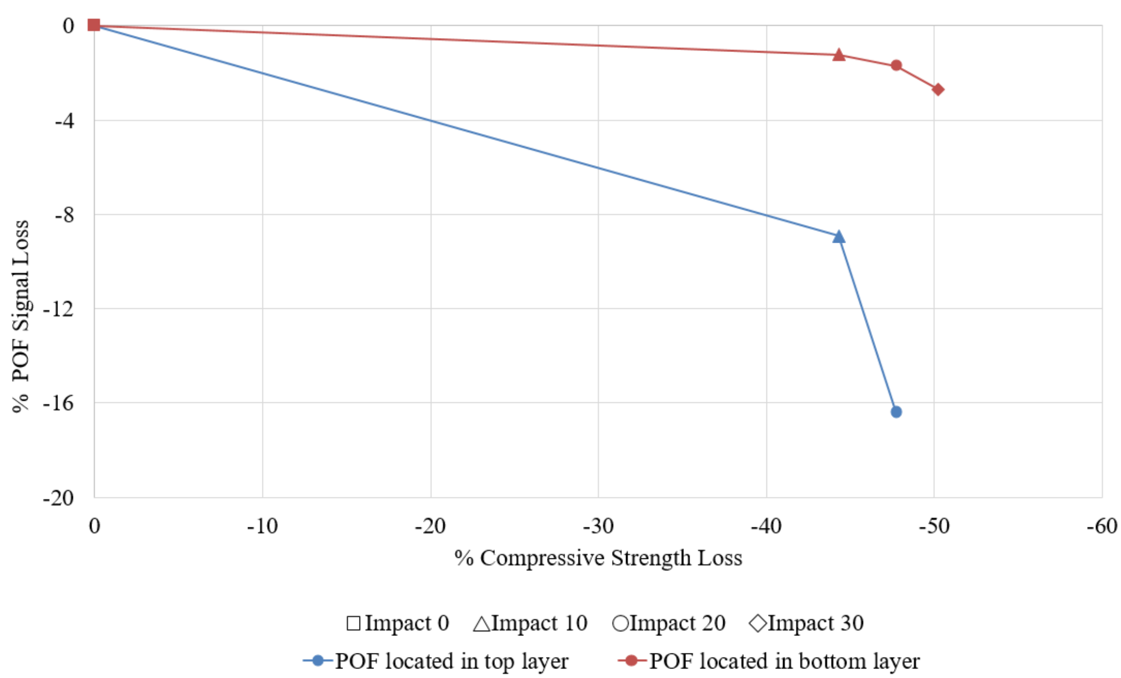

Figure 9. Graph of compressive strength loss vs. POF signal loss after repeated impact at 18 J energy

4. CONCLUSIONS

Combining a composite structure with optic fiber sensors results in a smart composite structure that offers advantages over traditional sensors. Advantages such as ability to tailor materials to specific uses, ability to embed the sensor in the material, and the ability of a structure to interact with its environment. Establishing relationships between signal loss and compressive strength loss enables better monitoring of the structural health. As with any technology, improvements in the optic fiber sensor, especially to the flexibility and attenuation will greatly improve the viability of the system. The proposed system smart composite system proves to be a viable SHM system and will continue to improve with further characterization and testing.

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