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Multiplexed FBG and etched fiber sensors for process and health monitoring of 2-&3-D RTM components

Casey J. Keulen[1], Mehmet Yildiz[1,2] and Afzal Suleman[1]

Abstract

This paper presents research being conducted on the use of a combination of fiber optic sensors for process and health monitoring of resin transfer molded (RTM) composite structures. A laboratory scale RTM apparatus has been designed and built with the capability of visually monitoring the resin filling process and embedding fiber optic sensors into the composite. Fiber Bragg gratings (FBG) and etched fiber sensors (EFS) have been multiplexed and embedded in quasi-2-D panels and 3-D hollow semicircular structures using a novel ingress/egress technique for the purpose of both process and structural health monitoring. The objective of this work is to demonstrate the simultaneous usage of FBGs and etched fiber sensors on a single optical fiber for resin flow monitoring and strain monitoring throughout the life of the composite. Three specimens are presented: one quasi-2D panel with two FBGs and three etched fiber sensors, one semicircular tube with two etched fiber sensors and one semicircular tube with two FBGs. Etched fiber sensors have been correlated with visual inspection to detect the presence of resin. Specimens with embedded FBG sensors have been tested in a tensile test machine to characterize the FBGs for strain monitoring.

Keywords

process monitoring, structural health monitoring, FBG, RTM, fiber optic sensors, smart materials, mechanical testing

Introduction

Composite materials are becoming increasingly more valuable in the transportation industry as they offer lighter weight options to traditional metallic structures. More than 20% of the Airbus A380 is made of composite[1] and over 50% of the Boeing 787 is made of composites.[2] Two major drawbacks of composites compared to metallic materials are the relatively difficult processing characteristics and damage assessment.

A number of processing methods exist for composite materials. One method that is particularly suitable to produce primary composite parts satisfying stringent specifications of the aircraft industry is the Resin Transfer Molding (RTM) technique. RTM will enhance the cost effectiveness of composites leading to affordable composites for primary structural components.[3] RTM can produce high quality near net-shape parts with high fiber volume fractions, two high quality surfaces and little post processing in a fully contained system that eliminates human operator exposure to chemicals and reduces the chance of human error.

A major drawback of RTM occurs during the resin injection stage. Due to a high resistance to resin (a relatively viscous material) flow through the preform (a material with low permeability) and geometry changes throughout the mold, it is not always possible to achieve a uniform flow pattern through the mold.[4] This can lead to areas of the mold that do not become fully saturated with resin known as 'dry

[1]University of Victoria, Department of Mechanical Engineering Victoria, Canada.
[2]Sabanci University, Faculty of Engineering and Natural Sciences, Advanced Composites and Polymer Processing Laboratory, Turkey.

Corresponding author:
Afzal Suleman, University of Victoria, Department of Mechanical Engineering, Victoria, B.C. V8W 3P6, Canada
Email: suleman@uvic.ca

spots'. These regions have a profound effect on the performance of the composite part since they are essentially a defect in the material.

Another drawback to composites is the difficulty in assessing damage. For example internal flaws in a composite component such as a dry spot, crack or delamination may be present that are not visible. This defect may subsequently grow leading to catastrophic failure with little warning. With traditional inspection methods it is difficult, time consuming and expensive to detect and assess damage in composites. Fiber optic sensors that are embedded in critical regions of composite components can be used to monitor the condition or health of the material in real time and accurately characterize stress and strain and detect damage in a component.[5] This is known as Structural Health Monitoring (SHM).[6] Fiber optic sensors also have the ability of detecting the presence of resin and can be used during the injection process to ensure that the mold is fully saturated. The small diameter and flexibility of optical fiber allows it to be embedded into composite materials with negligible impact to the structural integrity of the host material.[5]

Fiber Bragg Gratings (FBGs) are becoming increasingly more popular for such applications due to their advantages such as their size, immunity to electro magnetic interference, multiplexing potential and absolute reading. FBGs can be used to measure strain and temperature among other properties. Another useful sensor is an etched fiber sensor (EFS). This type of sensor is quite simple; a small section of optical fiber is etched to expose the core. When this etched region is surrounded by resin (fluid) flowing through the mold, the light power that is transmitted through the optical fiber changes hence enabling the sensor to detect fluid.[7] Since both EFS and FBG sensors allow light to pass there is potential for them to be multiplexed on one single fiber.

Many researchers have studied the use of a single type of embedded fiber optic sensor, however, there is less exploration into the use of a combination of sensor types on a single optical fiber. Most of the work that has been done involves the combination of FBG and extrinsic Fabry–Perot interferometer (EFPI) sensors.[8] EFPI sensors cannot be multiplexed on a single fiber; this severely limits their use when multiple sensors are required. Since ingress/egress issues of fiber optics are not trivial it is highly desirable to minimize the number of instances by placing the largest practical number of sensors on one single fiber. If optical fiber is embedded for the use of sensors in one particular stage of a composite material's life (such as in service) then it is only logical to optimize the use of the fiber and combine sensors that could be used during other stages such as manufacturing.

In the first part of this study, two FBG sensors and three EFS sensors multiplexed on a single fiber are embedded in a fiberglass panel with a purpose built RTM mold that has a glass viewing window that allows for visual monitoring of the resin injection process. The sensors are monitored during injection to detect the presence of resin and indicate possible dry spots. The viewing window in the mold is used to confirm the sensor readings. Two EFS sensors are also embedded in a semicircular tube to demonstrate their applicability to 3D surfaces such as those found in aerospace applications.

The second part of this study involves the use of embedded FBG sensors to detect strain in the composite. Specimens are prepared and tested in a material test machine to determine the strain sensitivity of the FBGs.

Resin transfer molding

The RTM process involves loading a two sided, fully enclosed mold with a fiber perform, closing the mold, injecting resin into the mold until fully saturated, allowing the resin to cure and removing the molded part.[4]

To produce RTM composite components with embedded fiber optics a sophisticated laboratory-scale apparatus has been designed and built. The apparatus has the flexibility of accommodating different mold designs and thicknesses, with the feature of a glass viewport to allow for visual monitoring of resin flow during the injection process. It has been tested by producing composite parts with different geometries such as flat panels, hollow and foam cored square, and semicircular tubes made from various types of reinforcements.

Experimental apparatus

The general layout of the experimental apparatus is shown in Figure 1. The apparatus can be separated into seven separate components: the injection system, injection valve, mold, manipulating/clamping fixture, catchpot, vacuum pump, and temperature controller. It can be described as a clamshell system with the mold mounted on it. For a mold to be used with this apparatus it must be 533 mm $\times$ 850 mm. Any thickness is possible with minor modifications to the clamping system.

Embedded optical fiber

Fiber optic ingress/egress is one of the most important issues for the application of embedded fiber optic sensors in real composite components[9] and has been addressed by various researchers,[5,8,9] however, little information on ingress/egress with RTM is available

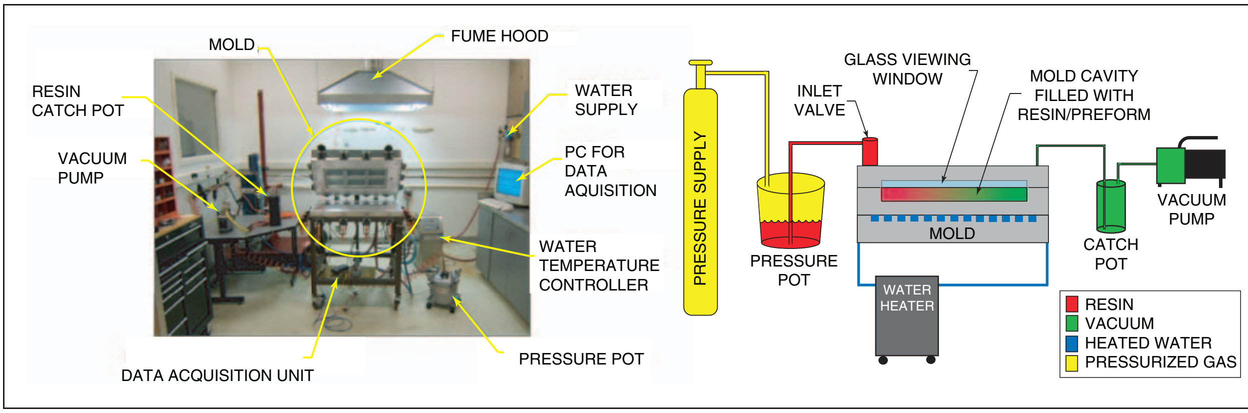

Figure 1. Layout (left) and schematic of RTM apparatus (right).

in the literature. The closed nature of the RTM process as well as the extremely fragile nature of optical fiber makes the ingress/egress of FBG sensors into the mold challenging. Sealing issues also arise due to the extremely small diameter of the optical fiber.

When optical fiber is embedded with the in-plane method, the ingress/egress point of the optical fiber is located at the edge of the composite. This eliminates the possibility of trimming the outer edges of the composite to size, a very common practice in the industry. To remove a composite part from a mold it must be removed normal to the mold, therefore, the embedded fibers must enter and exit through the mold so that upon removal, the fibers are not severed. A novel through thickness ingress/egress method has been developed, which can overcome the limitations of the in-plane method and be applicable to closed mold processes such as RTM.

Ingress/egress technique

A novel method to achieve a through thickness ingress/egress that is applicable to pressurized injection molding such as RTM has been developed. Two major obstacles were overcome when developing this technique, sealing the optical fiber and protecting the fiber as it entered the mold.

Optical fiber is quite delicate and must maintain a minimum bend radius before it fractures. When a through thickness fiber ingress technique is used the fiber sees an abrupt 90° bend as it travels through the mold and into the thin composite part as shown in Figure 2 (left). This is inherent to any through thickness ingress/egress technique.

To protect the fiber with minimal disturbance to the composite material a thin hypodermic tube is placed around the fiber. This protects the fiber through the radius of the bend as well as reinforces the fiber at the ingress/egress point once the part is removed from the mold. As one would imagine it is difficult to seal around something as small as an optical fiber that has an outer diameter of 250 μm without permanently caulking or bonding the fiber into the mold. A tapered silicone stopper was used to seal around the hypodermic tube as shown in Figure 2 (right). A custom fitting is used to keep the stopper and fiber in place. Figure 3 shows the panel and semicircular tube with embedded optical fiber.

The novelty of this technique lies in the use of the tapered silicon stopper and custom fitting. One technique briefly reported by Kosaka T, et al.[10] involves the use of a plastic plug that seals the fiber into the mold and remains bonded to the surface of the composite once it is demolded. The detraction of this technique is that the plastic can become debonded from the composite while in service thereby severing the fiber and rendering the system useless. Also, the fiber must be sealed to the plastic, likely with a caulking that requires time to cure and cannot be removed or adjusted if required. The technique developed and described here overcomes these detractions by using a tapered silicon stopper that applies pressure to the hypodermic tube thereby sealing it instantly without any caulking. This allows the fiber to be adjusted at any point prior to injection. Since the stopper is silicon it is easily removed after molding. This technique can be applied to a mold of any thickness over 10 mm by simply adjusting the length of the fitting. This modularity comes in useful due to the wide variation of RTM molds. The fitting also allows the injection pressure to be quite high since it is threaded into the mold making this technique applicable to higher-pressure injection techniques such as SRIM and thermoplastic injections.

Fiber Bragg gratings

Fiber Bragg gratings (FBGs) are becoming increasingly more popular for many applications due to their

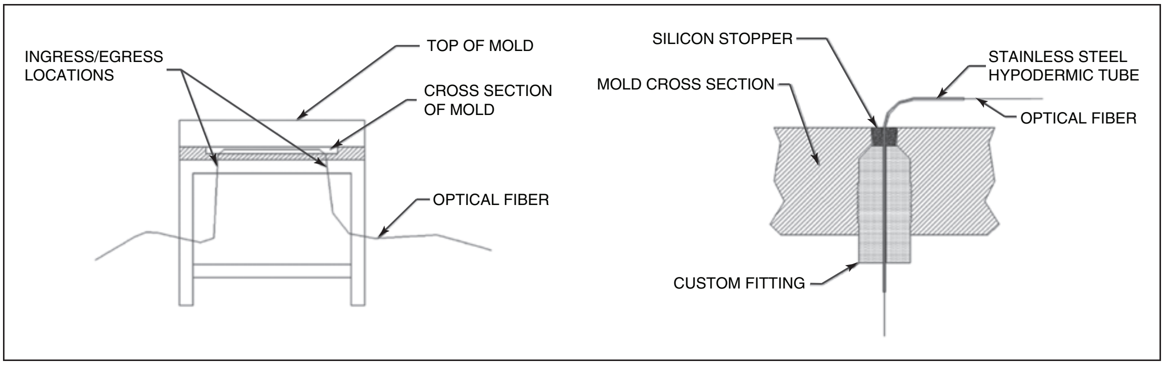

Figure 2. Path of fiber for through thickness ingress/egress (left), and the schematic of fiber sealing (right).

previously stated advantages. They have been used to measure properties such as displacement, strain, temperature, pressure, humidity, and radiation dose among others.[11] FBGs were first demonstrated by Hill in 1978.[12] Embedded FBGs can be used for three distinct purposes during the life of a resin transfer molded part. An array of FBGs in a mold can monitor the mold filling process and can ensure that the mold is completely filled with resin as demonstrated by Novo et al.[13] Once injected the resin must go through a specific time–temperature cure cycle. In complicated 3-D parts with varying thicknesses and surface areas, different regions of resin cure at different rates and to varying degrees across the part. FBGs have been used to monitor the cure throughout the part.[8,14–16]Once in service the embedded FBGs can be used in a variety of ways to monitor the health of the part thereby reducing maintenance cost and service time while increasing safety.[17–19]

A fiber Bragg grating is a segment of a single mode optical fiber core with a periodically varying refractive index in the axial (longitudinal) direction and commonly created using a high intensity UV laser.[20] It allows a broad band of light to pass through while reflecting back a narrow band based on a wavelength known as the Bragg wavelength. The reflected wavelength depends on the grating pitch (spacing between the refractive index variations) and the variation in refractive index. The periodic modulation of the refractive index at the grating location will scatter the light traveling inside the fiber core. Out of phase scattered waves will form destructive interference thereby canceling each other and in phase light waves will add up constructively forming a reflected spectrum with a center wavelength known as the Bragg wavelength. Figure 4 describes an FBG.

The Bragg wavelength satisfies the Bragg condition as Equation (1): [20]

$$\lambda_B = 2n\Lambda \qquad (1)$$

Figure 3. A panel and semicircular tube with embedded optical fiber.

where λ_B is the back-reflected Bragg wavelength, n is the average refractive index of the fiber core and Λ is the spacing between gratings. The change in spacing of the periodic refractive index modulation is a function of strain and temperature. If an FBG sensor is under a mechanical or thermal load (temperature variation), the spacing and average refractive index will change due to the strain, and thermal expansion, respectively. Since the Bragg wavelength, $\lambda_B(n,\Lambda)$ is a function of the average refractive index and grating pitch, any change in these variables will cause the Bragg wavelength to shift.

Since the center wavelength of Bragg gratings are sensitive to both temperature and strain variations, in sensing applications where only temperature or strain measurement is of interest, the effect of temperature or strain on the grating must be compensated to measure only one of these effects. The literature reveals that Bragg gratings offer a very good linearity between the measured strain and applied stress. Multiple Fiber Bragg gratings sensors can be easily multiplexed onto a single strand of fiber, thereby forming an array of FBG sensors for distributed strain measurements over a large distance. An array of FBG sensors minimizes

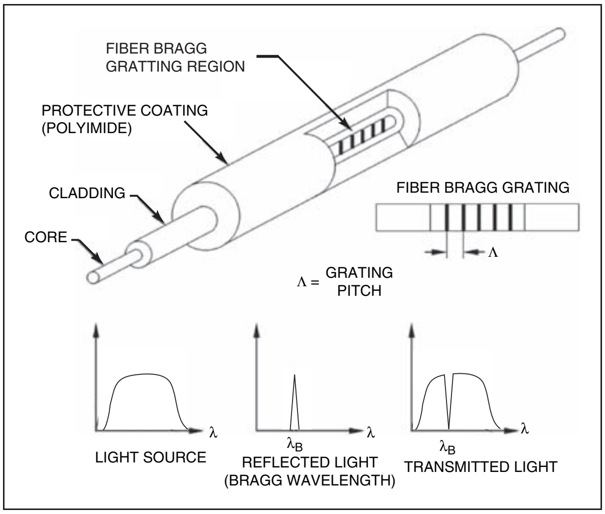

Figure 4. Schematic describing an FBG sensor.

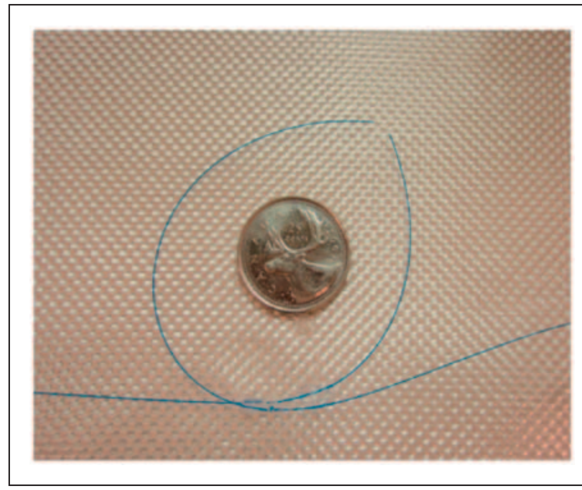

Figure 5. Looped etched fiber sensor.

the number of ingress/egress locations during the embedding process in the smart structure.

In the case of embedded FBGs, the load on the host is directly transferred onto the grating region through shear action, resulting in the change in the length of the grating region. As a result, the grating spacing and the refractive index of the grating change, allowing the determination of mechanical properties. The presence of the damage or defect formation in a composite structure alters the local strain distribution under a structural load. Damage can be detected when the measured strain deviates appreciably from the value expected of a healthy structure at the sensor location. This allows for monitoring the structural health of composite components under service conditions.

Etched fiber sensors

Etched fiber sensors are an excellent low cost method of detecting the presence of resin. Operation of etched fiber sensors is quite simple requiring only standard equipment found in most optics lab. Essentially, a light source launches light into one end of the fiber optic and an optical power meter measures the light intensity at the other end. When resin makes contact with the sensor there is a sudden, sustained drop in the transmitted light intensity.[21] The amount of light lost through the etching is a function of the refractive index of the medium it is in.[22] This type of sensor has been used to measure the permeability of fiber perform materials by Ahn et al.[9] and Lim et al.[23] among others.

The theory behind the etched fiber sensor is very basic; it pertains to the fundamental principles of light transmission through optical fiber. The sensor consists of a small section of optical fiber roughly 3–5 mm long with the cladding removed leaving the fiber core exposed. Light is contained in the core of an optical fiber by the cladding. As light travels through the core of a fiber it is continuously bouncing off the cladding. When the light reaches the section of fiber where the cladding is removed a small portion of it escapes while most is transmitted.[24] When resin contacts the core its refractive index being higher than that of the glass causes more light to escape. Therefore, the amount of light transmitted through the fiber is less.

A novel variation of the basic sensor is used in this study. This variation involves looping the etched sensor to create a bend in the etched portion of the fiber. This is done to allow more light to escape from the sensor while leaving some of the cladding on the core to physically protect it. The looped variation is a more robust version of the sensor that is easier to handle and implement. Another benefit of looping the fiber is that the sensitivity can be tuned by adjusting the radius of the loop. As the radius of the loop increases the amount of transmitted light increases. This option is desirable when multiple sensors are used on a single strand of fiber and minimum light loss is desired so that all sensors can make readings. Figure 5 shows the sensor with a Canadian quarter for reference (23.81 mm diameter); note the etched section in the upper right portion of the loop.

Sensor characterization

To demonstrate the capabilities and multiplexing potential of FBGs and etched fiber sensors, experiments were performed in the aforementioned RTM apparatus using the described ingress/egress technique. The experiments validated the ability of the EFS sensors to detect the presence of resin during the RTM process and the FBG sensors to be used to detect strain all while multiplexed on a single fiber. To explore the versatility and potential for different applications of these sensors three different specimens were produced; a quasi 2-D flat panel and two 3-D hollow tubes with a semicircular cross-section.

The flat panel was composed of 18 plies of 200 gsm plain weave glass fiber cloth and Huntsman Renfusion 8601 epoxy resin, with dimensions of 610 mm × 305 mm × 3 mm. An optical fiber containing three EFS sensors and two FBG sensors was embedded on the upper ply of the panel.

Two semicircular tube specimens were produced; one composed of five layers and the other composed of six layers of 200 gsm plain weave glass fiber cloth and Huntsman Renfusion 8601 epoxy resin fully enclosing a steel mandrel that is removed after molding. The tube has an outer radius of 38 mm, length of 500 mm, and wall thickness of 1.5 mm. In the specimen composed of five layers, an optical fiber containing two EFS sensors is embedded between the fourth and fifth ply on the curved surface of the specimen. The specimen composed of six layers contains two FBGs embedded between the fourth and fifth ply on the curved surface of the specimen. The inner layer is considered the first layer in these specimens increasing towards the outside of the tube.

Flow monitoring

Flow monitoring experiments were performed during the resin transfer molding process. The general procedure was similar for both specimens and involved embedding the optical fiber in the mold, closing it, and injecting the resin. The optical fiber was connected to a photodetector and measurements were logged throughout the injection process.

Flow monitoring of panel specimen An optical fiber containing three EFS sensors (EFS#1,2,3) and two FBG sensors (FBG#1,2,3) was embedded into the mold on the upper ply of the laminate, the mold was closed and the resin was injected. Etched fiber sensor readings were recorded with a photodetector and data logger while the FBGs were manually observed with an OSA. A simple circuit was used to interrogate the sensors as shown in Figure 6. A BBS light source is connected to one end of the optical fiber, the fiber runs through the mold, a 50/50 coupler is connected to the other end of the fiber with one branch of the coupler going to the photodiode and the other to an OSA.

Figure 7 shows the sensors through the glass viewing window prior to injection. Figure 8(a) shows the resin approaching EFS #1 while Figure 8(b) shows the resin just after the sensor is saturated and the transmitted light intensity is reduced. This occurs roughly 2.4 min

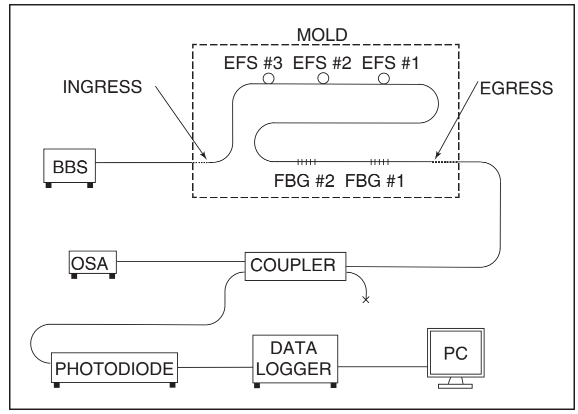

Figure 6. Interrogation system.

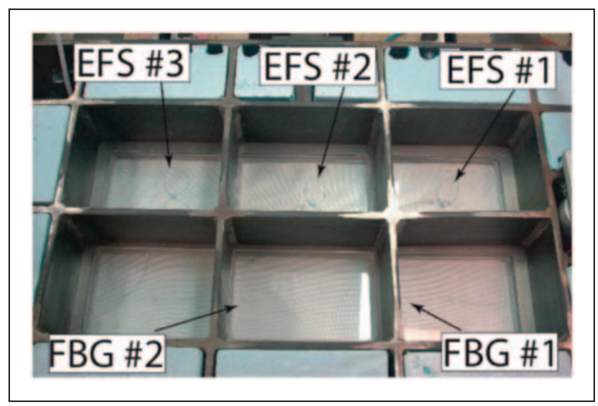

Figure 7. Sensors positioned in RTM prior to injection (mold closed).

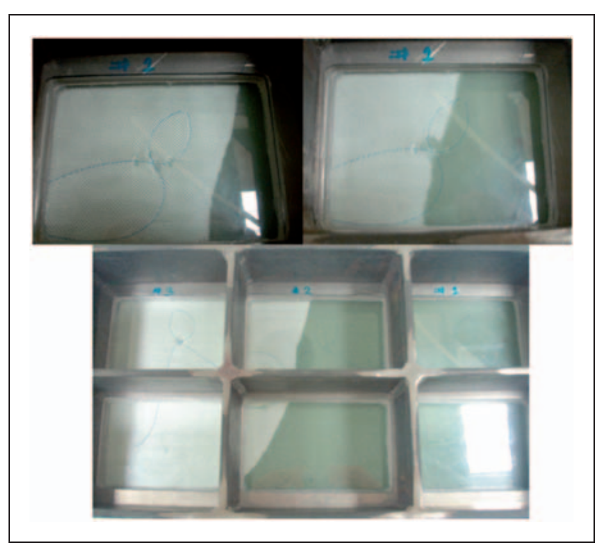

Figure 8. CW from top left: (a) resin approaching sensor, (b) resin just after contacting sensor, and (c) mold midway through injection.

into the injection. Figure 8(c) shows the mold midway through the injection.

Figure 9 shows a plot of the photodiode voltage output vs. injection time. It can clearly be seen that as the resin reaches the first sensor at roughly 2.4 min there is a sharp and sustained drop in the transmitted light. Another drop occurs at roughly 7.7 min when the resin reaches the second sensor and again at 12.2 min when the resin reaches the third sensor. Once the mold was saturated and the injection was complete, the light source was turned off to ensure that the readings could be differentiated from a change in minimal transmitted light and no transmitted light. When the light source was off the photodiode output was zero. The light source was turned back on and the transmitted light intensity was the same as before it was turned off, therefore, indicating that light was indeed being transmitted. During this time the FBG sensors were manually observed with the OSA to ensure that they were still functional. Due to the arrangement of the sensors on the fiber (FBG before EFS) no change in power was noticed when resin contacted the EFS sensors, therefore, demonstrating that the EFS do not effect the FBG sensors as long as they are situated after the FBGs on the fiber. The FBG output is not included here, however this technique has been thoroughly researched by others such as Novo et al.[23] and Eum et al.[24,25]

Flow monitoring of 3-D semicircle specimen To demonstrate the versatility and applicability of these sensors to more realistic structures, an optical fiber containing two EFS sensors was embedded in a hollow tube with a 3-D semicircle cross-section using the aforementioned RTM apparatus. The sensors were embedded between the fourth and fifth layers on the curved surface of the semicircle. The flat side of the semicircle is visible through the viewing window, however the curved surface is not. Due to the relatively small radius of the tube and uniform resin flow it can be estimated with a high level of confidence that the resin is in contact with the sensors and their output can be verified. This is a more realistic experiment for these sensors since the majority of industrial molds are not translucent.

The sensors were interrogated in a manner similar to that shown in Figure 6. Figure 10 shows the specimen with the sensors visible. Data was recorded during the injection and is shown in Figure 11 showing resin arrival at the first and second EFS at roughly 2.9 and 4.0 min, respectively.

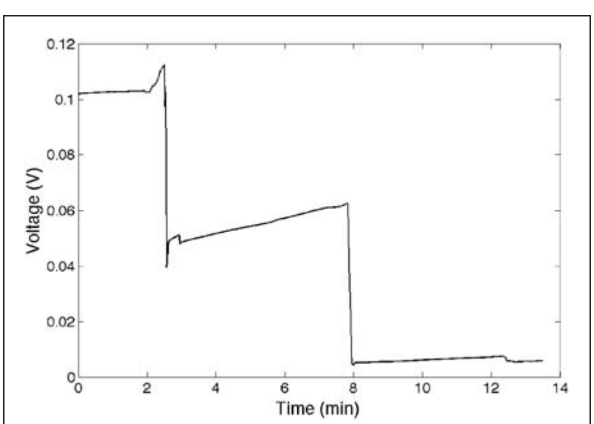

Figure 9. Plot of photodiode output vs. injection time for panel.

Strain sensitivity characterization

For FBGs to be used as strain sensors after they are embedded in a composite material the relationship between the shift in the Bragg wavelength and the axial strain in the sensor must be known. This relationship is known as the sensitivity or the strain gage factor, *S*. Embedded FBG strain gages experience additional radial strain field in application, therefore once integrated into a structure, every gage must be recalibrated.[26]

The strain gage factor for an electrical foil strain gage can be described as the relationship between the resistance of the wire, *R,* axial strain ε_a and the change in resistivity of the wire.[27] The expression for the strain gage factor is given in Equation (2):

$$S = \frac{dR/R}{\varepsilon_a} \qquad (2)$$

For an FBG, the gage factor would be the relationship between the change in the Bragg wavelength and axial strain. The expression for this is shown in Equation (3):

$$S = \frac{\delta\lambda_B}{\varepsilon_a} \qquad (3)$$

To determine the gage factor for both 2- and 3-D specimens they were tested in an MTS 810 material test machine. A 6 mm grid, 120 ohm strain gage from Omega Engineering Inc. was bonded to the surface directly beside the FBG. The strain gage was connected to a Measurements Group Instrument Division P-3500 strain indicator and the FBG was hooked up to an Ando AQ6331 OSA, JDS Uniphase broadband light source and a 50:50 optical coupler. Figure 12 shows the 2-D specimen in the MTS machine with the instrumentation equipment (left) and a close up of the 3-D specimen (right).

Strain sensitivity of panel specimen To determine the gage factor for the panel a tensile specimen was cut out

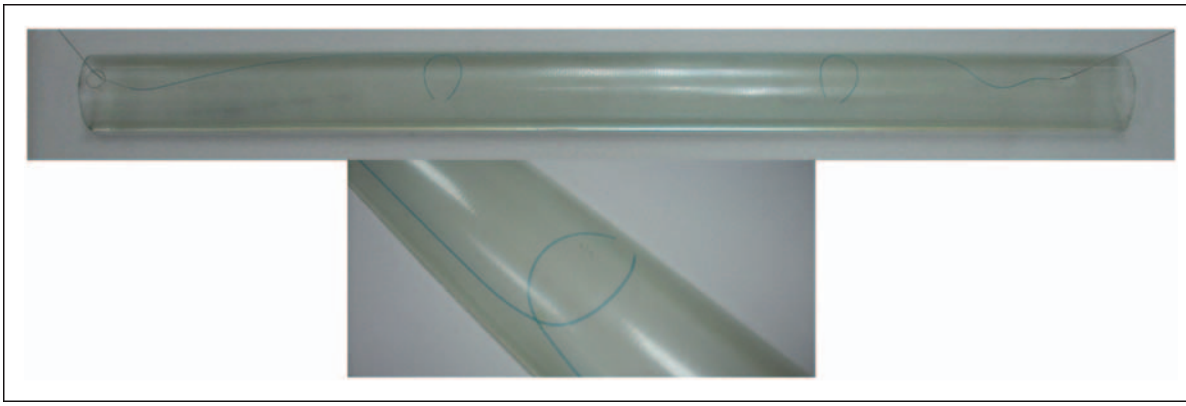

Figure 10. Semicircular tube with embedded fiber optic sensors.

of the RTM'd panel. The specimen has dimensions of 38.1 mm × 300 mm × 3 mm. The embedded FBG is located directly in the middle of the specimen along the length and width. Small pieces of sand paper were bonded to the ends of the specimen to help the test machine grip without slipping.

The specimen was loaded into the test machine and a tensile load was applied at a rate of 0.051 mm/min up to a maximum of roughly 2.88 mm. Readings were taken at roughly 0.254 mm intervals starting at zero strain. The test was repeated four times to ensure the repeatability of the results. Figure 13 shows a plot of the collected data, namely, Bragg wavelength vs. measured strain.

A linear line was fit to the data with an equation of $y = 0.001141x + 1541.04$ with an R^2 value of 0.999 obtained from four test runs. From this equation we can ascertain that $S = 1.141e\text{-}3$ or every $1.141 pm$ shift in the Bragg wavelength is equal to one micro strain.

Strain sensitivity of semicircular specimen To determine the gage factor for the semicircular tube a special fixture was designed to restrain the specimen in the aforementioned MTS machine for compression testing. Semicircular blocks, 38 mm long with the same cross-sectional dimensions as the mandrel were fastened to adapter plates that interface with the test machine. The tube was cut at it's mid-length to produce two specimens and simplify the testing process. Each specimen has one FBG at the midspan.

The specimen was slid onto the fixture and a compression load was applied then released. This was repeated twice to ensure repeatability. The strain gage output (in microstrain) and Bragg wavelength (in nm) was recorded as the load was applied and released. The recorded data is plotted and shown in Figure 14.

A linear line was fit to the data and an equation of $y = 0.001288x + 1541.28$ with an R^2 value of 0.999 was obtained from four test runs (two loading, two unloading). From this equation we can ascertain that

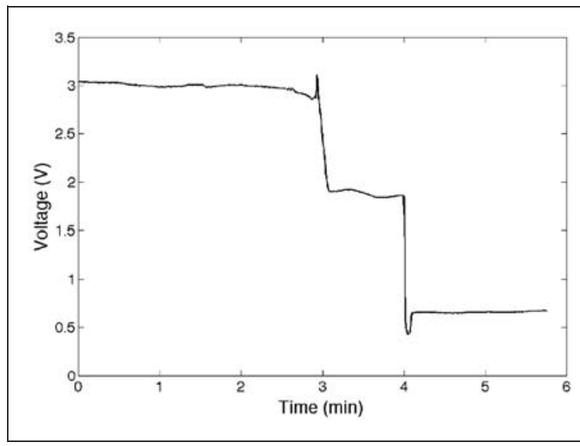

Figure 11. Plot of photodiode output vs. injection time for tube.

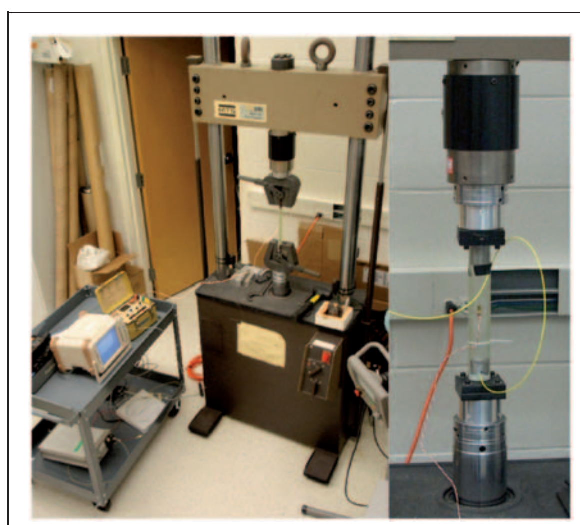

Figure 12. 2-D specimen in MTS machine with instrumentation equipment (left) and 3-D specimen loaded in MTS machine (right).

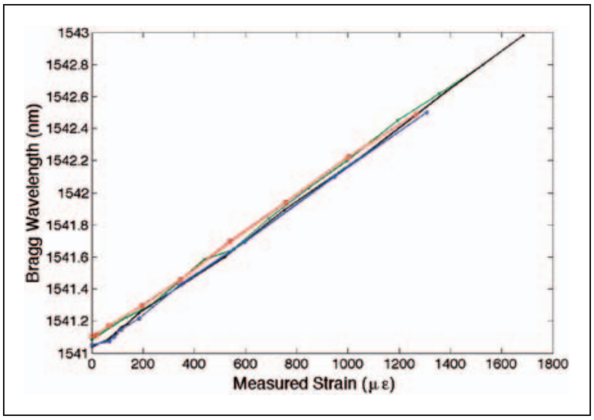

Figure 13. Bragg wavelength vs. strain gage measured strain for 2-D panel.

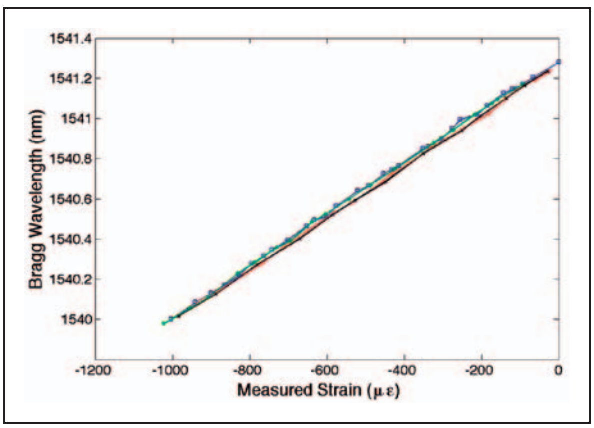

Figure 14. Bragg wavelength vs. strain gage measured strain for 3-D structure.

$S = 1.288e\text{-}3$ or every $1.288pm$ shift in the Bragg wavelength is equal to one micro strain.

Strain sensitivity discussion As mentioned earlier the strain sensitivity of the embedded FBG is 1.141 pm/με for the flat panel specimen and 1.288 pm/με for the semicircular specimen. These sensitivities deviate from the commonly referenced value of 1.2 pm/με for a bare FBG with typical material properties[20] by −4.9% and 7.3% for flat panel and semicircular specimens, respectively. These values fall within the range of deviation reported by Fan et al.[26] Factors such as variations in the material and manufacture of each individual FBG and experimental error in the processing and testing phase such as misalignment of FBG or strain gage with the axis of the specimen may contribute to this deviation. Another factor which may contribute to the variation in sensitivity between the two geometries is the mismatch of mechanical properties between the FBG fiber and host structure, particularly their Poisson ratio in the lateral direction as embedded sensors experience an additional radial strain field when load is applied along the sensor direction.[26]

Conclusion

The motivation behind this study is to advance the knowledge base of embedded optical fiber sensors by: **(i)** designing and fabricating an RTM apparatus capable of embedding optical fibers that allows visual monitoring of the injection process, **(ii)** embed EFS and FBG sensors on a single optical fiber into a composite panel with this apparatus, **(iii)** detect the presence of resin during the injection with the EFSs, and **(iv)** measure the strain in test specimens with the FBGs. The RTM apparatus has been manufactured and successfully tested. A method of embedding fiber optics has also been devised and tested. The apparatus was used to embed an optical fiber with three EFSs and two FBGs into a quasi-2-D panel, two EFSs in one semicircular tube and two FBGs in a second. The glass window in the mold was used to visually monitor the resin flow while a photodiode and data logger was used to take readings from the etched sensors. Both panel and tube specimens with a foil strain gage bonded to the surface were tested in a material test machine to determine the strain gage factor of the FBG.

This study successfully demonstrates the ability of multiplexing a number of optical sensors onto a single fiber and embedding them into resin transfer molded composite parts of various shapes and complexities. The FBGs were not used during the manufacturing process, however in the future they could be used to monitor the degree of cure of the resin as has been researched by.[14–16] The EFSs showed a high degree of accuracy at detecting the presence of resin however the readings of various EFSs could not be differentiated without a priori knowledge of the resin flow. Implementing OTDR would potentially allow the sensors to be differentiated.

With the implementations of the demonstrated techniques RTM parts could be manufactured more efficiently with a higher degree of quality at a lower cost.

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