Embedded fiber optic sensors for monitoring processing, quality and structural health of resin transfer molded components

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Abstract. Due to their small size and flexibility fiber optics can be embedded into composite materials with little negative effect on strength and reliability of the host material. Fiber optic sensors such as Fiber Bragg Gratings (FBG) or Etched Fiber Sensors (EFS) can be used to detect a number of relevant parameters such as flow, degree of cure, quality and structural health throughout the life of a composite component. With a detection algorithm these embedded sensors can be used to detect damage in real time while the component remains in service. This paper presents the research being conducted on the use of fiber optic sensors for process and Structural Health Monitoring (SHM) of Resin Transfer Molded (RTM) composite structures. Fiber optic sensors are used at all life stages of an RTM composite panel. A laboratory scale RTM apparatus was developed with the capability of visually monitoring the resin filling process. A technique for embedding fiber optic sensors with this apparatus has also been developed. Both FBGs and EFSs have been embedded in composite panels using the apparatus. EFSs to monitor the fabrication process, specifically resin flow have been embedded and shown to be capable of detecting the presence of resin at various locations as it is injected into the mold. Simultaneously these sensors were multiplexed on the same fiber with FBGs, which have the ability to measure strain. Since multiple sensors can be multiplexed on a single fiber the number of ingress/egress locations required per sensor can be significantly reduced. To characterize the FBGs for strain detection tensile test specimens with embedded FBG sensors have been produced. These specimens have been instrumented with a resistive strain gauge for benchmarking. Both specimens and embedded sensors were characterized through tensile testing. Furthermore FBGs have been embedded into composite panels in a manner that is conducive to detection of Lamb waves generated with a centrally located PZT. To sense Lamb waves a high speed, high precision sensing technique is required to acquire data from embedded FBGs due to the high velocities and small strain amplitudes of these guided waves. A technique based on a filter consisting of a tunable FBG was developed. Since this filter is not dependant on moving parts, tests executed with this filter concluded with the detection of Lamb waves, removing the influence of temperature and operational strains. A damage detection algorithm was developed to detect and localize cracks and delaminations.
1. Introduction

Much research has been directed towards improving the energy efficiency of transportation vehicles. Reducing their weight is one way of increasing their efficiency. Composite materials show a lot of potential in this application due to their high specific strength and stiffness as well as good fatigue endurance, excellent corrosion resistance and the ability to produce complex shapes. Presently, more and more critical load bearing structures are being built from composites. More than 20% of the Airbus A380 [1] and over 50% of the Boeing 787 is made of composites [2]. Despite the numerous benefits of composite materials there are still two major drawbacks compared to metallic materials: the relatively difficult processing characteristics and damage assessment.

One processing 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 can produce high quality parts with high fiber volume fractions, two high quality surfaces with little post processing in a fully contained system that eliminates human operator exposure to chemicals and reduces the chance of human error. The quality of a composite can be determined by its fiber volume fraction, its uniformity throughout the laminate and void content [3]. Regions with no resin are referred to as “dry spots” or resin voids and are a result of poor processing techniques/parameters. Due to a high resistance to resin (a relatively viscous material) flow through the preform (a fairly low permeability material) 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 (called “dry spots”), these are essentially defects in the material. By visualizing the fluid flow, for example through a glass panel, resin can be injected into the mold until all of these dry spots have been saturated. In industry, however, molds are almost always made of non-translucent materials such as composites or metals and it is not possible to visually monitor the resin flow [5]. Fortunately various other techniques have been employed to monitor this process.

Another drawback to the application of composites in load bearing structures is the difficulty in assessing damage. Internal flaws in a composite component such as a dry spot or a delamination may exist without being visible. In composite materials damage growth can occur with little warning leading to catastrophic failure due to the poor response of composites to stress concentrations. Current methods of inspection are time consuming and often require highly skilled operators and the component to be taken out of service resulting in high costs.

Fiber optic sensors that are embedded in critical regions of composite components can be used to monitor their health in real time during their service life and accurately characterize stress and strain and detect damage globally in a component [6]. This is known as Structural Health Monitoring [7] (SHM). Fiber optic sensors also have the ability of detecting the presence of resin and can be used during the injection process (manufacturing). The small diameter and flexibility of optical fiber allows it to be embedded into composite materials with negligible impact to the structural integrity of host material [6].

Optical fiber based sensors present advantages in terms of their size, immunity to electro-magnetic interference, multiplexing potential and absolute reading. From the different fiber optics sensors, Fiber Bragg Gratings (FBGs) can be used to measure strain and temperature among other properties. Another useful optical fiber sensor is an Etched Fiber Sensor (EFS). This type of sensor is quite simple, consisting of removing the cladding from a small length of the optical fiber to expose its core. When this etched region is surrounded by resin (fluid), flowing through the mold, the light power transmitted through the optical fiber changes, hence enabling the detection of fluid flow [8]. Both EFS and FBG sensors can be multiplexed on one single fiber and used simultaneously.

Multiple sensors of the same type in a single optical fiber have been extensively used in different research efforts, however the use of various types of sensors on a single fiber has been less common [9]. Since ingress/egress issues of fiber optics are not trivial, it is highly desirable to minimize their number by placing the highest quantity possible of sensors on one single fiber to monitor both manufacturing and service of the component.
In the first part of this study, three EFS and two FBG sensors were multiplexed on a single fiber which was embedded in a composite panel manufactured in a purpose built RTM apparatus. The light power transmitted through the fiber was monitored during the resin injection process in order to detect the presence of resin and possible dry spots. Furthermore, this mold has a glass viewing window to enable visual monitoring of the resin flow through the mold and confirm sensor readings.

The second part of this study involved the use of the embedded FBG sensors to measure strain and detect Lamb waves propagating in the composite panels. First these panels were tested in a tensile test machine to determine the sensitivity of the FBGs. Afterwards, an FBG interrogation technique was implemented to enable them to detect propagating Lamb waves generated by a PZT bonded to the surface of the panel. Initial tests have been performed. This work consists of the initial steps towards the future development and implementation of an FBG Lamb wave based SHM system to be applied to the in service condition inspection of the RTM manufactured composite panels.

2. Background
To proceed with this research, a sophisticated laboratory-scale RTM apparatus was designed and built to manufacture the composite panels with embedded optical fiber.

The apparatus has the flexibility of accommodating different mold designs and mold thicknesses, with the feature of a glass top to allow for visual monitoring of resin flow during the injection process. Furthermore, the apparatus has integrated automatic control of both resin injection process and cure temperature. Mold and part temperature are monitored with thermocouple sensors and the temperature is controlled with an automated water temperature controller that pumps water through channels in the mold. This mold produces panels with dimensions up to 305mm x 610mm x 3mm. The general layout is shown in Figure 1.

The fiber optic ingress/egress is one of the most challenging aspects for the application of embedded fiber optic sensors in composite components [10]. This difficulty has been addressed by various researchers [6],[9],[10]. The closed RTM mold, injection pressure and the extremely fragile nature of optical fibers makes their ingress/egress a complicated task.

It is impossible to finish trim the outer edges of a composite panel (as is common practice in industry), after its manufacture in the RTM mold, if optical fibers ingress/egress the component through its edges, known as the in-plane method. To solve this problem, a novel surface ingress/egress method has been developed. This technique assures also the sealing of the optical fiber, during resin injection and its protection, while it is introduced in the mold, embedded into the preform. In the developed ingress/egress method the fiber enters the component close to a 90º angle with relation to the component’s surface. A minimum bend radius must be insured to avoid fiber fracture.

![Figure 1. Experimental RTM apparatus](image)
To protect the fiber with minimal disturbance from the fiber reinforcement preform (introducing a fragile area around that point), a thin hypodermic tube with a certain minimum radius (such that fiber fracture is avoided) is placed around the fiber. This protects the fiber from breaking, as well as reinforces the fiber at the ingress/egress point in service after the part is removed from the mold. Most RTM systems operate under an injection pressure in the range of 35-450 kPa. This requires the ingress/egress to be sealed and able to withstand this pressure range. It is also desirable to be able to use the sealed system instantly without waiting for a sealant to cure. It is also beneficial to have the option to remove it if there is a problem. To achieve these criteria a tapered silicon stopper is fitted in a hole in the mold and held in place by a custom fitting. The hypodermic tube passes through the stopper and is sealed as the stopper is compressed into the hole. Figure 2 shows a schematic of this technique.

![Schematic of fiber sealing technique](image)

**Figure 2. Schematic of fiber sealing technique**

### 3. Process monitoring

As mentioned above it is very desirable to monitor the resin injection during the RTM process. This information can be used to both optimize the injection process by ensuring the mold is fully saturated and does not require more resin to be injected and ensure that the parts produced are free of voids or process related defects.

Standard equipment found in any optics lab can be used to interrogate EFSs and detect resin presence during the mold filling process. In practice, a light source is connected to one end of the optical fiber and an optical power meter measures the light intensity at the other end. When resin makes contact with each EFS there is a sudden, sustained drop in the transmitted light intensity [11]. Light is contained in the core of an optical fiber by the cladding. When the light reaches the section of fiber where the cladding is removed a small portion of it escapes. When resin contacts the core, with its refractive index being lower than that of the glass, causes more light to escape. Therefore the amount of light transmitted through the fiber is decreased.

To demonstrate the capabilities and multiplexing potential of these sensors to monitor the manufacturing process, i.e., the resin filling of the RTM mold, a Broad Band Source (BBS) light was connected to one end of an optical fiber (with 3 EFS and 2 FBGs), and a 50/50 coupler was connected to the other end of the fiber, with one branch of the coupler going to a photodiode and the other to an Optical Spectrum Analyzer (OSA). The voltage signal from the photodiode was recorded by a data logger and the FBGs reflected light spectrum was monitored with the OSA.

Figure 3a) shows the resin approaching EFS #1 while Figure 3b) shows the resin just after the sensor is saturated and the transmitted light intensity is reduced. This occurred at roughly 145 seconds into the injection, as can be observed in Figure 4, a plot of the photodiode voltage output vs. injection time. It can clearly be seen the different sudden drops in the transmitted light, when resin reaches the different EFS.
4. Structural health monitoring

Structural health monitoring can offer many benefits. If for example the structural integrity of an aircraft component is monitored in real time then the safety of this component is increased considerably. If any damage occurs then it is known instantly and it can be decided when to take the component out of service i.e. an immediate landing or a number of future flights before it is replaced. SHM can also reduce the down time required for traditional inspection methods resulting in more time in operation and less time on the ground ultimately resulting in lower operating costs.

To begin the development of an SHM system for composite materials FBG sensors were embedded in a panel using the aforementioned RTM apparatus. Tensile test specimens were prepared from this panel and characterized with a strain gage in a material testing machine. Once characterized another panel was produced in order to detect Lamb waves generated by a piezoelectric (PZT) actuator that was bonded to the surface.

4.1. Fiber Bragg grating strain characterization

Fiber Bragg Gratings (FBGs) have been used to measure properties such as displacement, strain, temperature, pressure, humidity and radiation among others [12]. They were first demonstrated by Hill in 1978 [13]. FBGs can be used for three distinct purposes during the life of a RTM part. Being sensitive to temperature variations, an array of FBGs in a mold can monitor the mold filling process and can ensure that it is completely filled with resin [14]. Once injected, the resin must go through a specific time-temperature cure cycle. In complicated 3-D parts with varying thicknesses and surface areas, resin cures at different rates in different regions. FBGs have been used to monitor the cure throughout the part [8],[15]-[17]. Once in service the embedded FBGs can be used to measure strain and then in a variety of ways to monitor the health of the part [18]-[20].

As referred previously, the sensitivity of embedded FBGs has been determined through the execution of tensile tests - the relation between the change in the reflected wavelength and the axial strain sensed by the sensor. To determine this, a tensile specimen was prepared from the previously manufactured panel with embedded optical fiber and mounted in an MTS tensile test machine. The same light source, interrogation scheme and OSA were used. The Bragg wavelength of the FBGs was observed during the tests on the OSA screen and recorded for different test phases. To measure strains, a foil strain gauge was mounted on the surface of the specimen directly adjacent to the central FBG. A strain gauge reader with the application of a full bridge was used. To note that assuming a perfect
tensile test, strains measured by the strain gauge in the panel’s surface will be equal to the ones sensed by the FBG in the middle of the panel cross section, just below the referred strain gauge.

The RTM manufactured quasi-isotropic panel was composed of 18 layers of 6oz./yard2 plain weave glass fiber and Huntsman Renfusion 8601 epoxy resin. A 6mm grid, 120 ohm strain gage from Omega Eng. Inc. was used.

The shift in Bragg wavelength was plotted versus the strain measured by the strain gauge and a line was fit to the data as shown in Figure 5. This was repeated with good agreement for the data obtained from several tests. The linear relation obtained is summarized by the equation: Bragg wavelength = 0.001(strain) + 1541, with an R^2 value of 0.999. From this equation we can ascertain that every 0.001nm shift in the Bragg wavelength is equal to one micro strain.

![Figure 5. FBG wavelength vs. measured strain](image)

4.2. Lamb wave based structural health monitoring

Previously, a Lamb wave based SHM system was developed and successfully tested with the detection of 1mm damages [21]. This system consists of a piezoelectric transducer network and/or phased arrays and was prepared for application to isotropic and orthotropic materials, subjected to different boundary conditions. In these initial experiments the same PZT actuation principles (actuation waveform, etc) and system, signal acquisition (now from the FBGs photodetectors) and data post processing systems were used. The objective of this part of the work is to implement an FBG interrogation technique and prove the ability of the embedded FBG sensors to detect the propagating Lamb waves (specifically the first symmetric mode). This will serve as the initial development and base knowledge to incorporate, in the future, FBGs and the developed interrogation technique into the previous SHM system, i.e., using the FBG readings instead of the PZTs to detect damages.

For application to the RTM composite panel, using the embedded (3mm long) FBGs, a PZT actuator (with the same dimensions as in [21]) was bonded to the composite panel, in its centre, to generate Lamb waves.

Initially, with the results from the previously performed tensile tests, the Young Modulus in the different planar directions of the panel were determined and the Lamb wave dispersion curves calculated, for this panel’s thickness. With the dispersion curves, excitation frequency was selected based on the applied PZT and FBG dimensions (according to optimum FBG dimension and wavelength to be sensed [22]).

A high precision tunable laser, with a well defined narrow peak wavelength is used to illuminate the optical fiber and embedded FBG sensor. The laser is tuned to a wavelength close to the Bragg wavelength of the FBG. The sensor through (transmitted) light intensity in the selected laser wavelength is then converted to a voltage by a photo-detector, connected to the optical fiber extremity opposed to the one connected to the tunable laser. The output of the photo-detector is connected to the signal acquisition of the SHM system.
Since the laser wavelength is tuned just before the scans, temperature influence and operational strain and vibration interference are removed. Furthermore, with no moving parts during the execution of the tests, the acquisition frequency is limited only by the signal acquisition system.

![Figure 6. Schematic of FBG Lamb wave acquisition system](image)

In Figure 6 a schematic of the interrogation technique is shown. Figure 7 shows the composite panel with embedded FBGs and bonded PZT with simply supported edges. In Figure 8 the experimental setup is presented.

![Figure 7. Composite panel with embedded FBG and bonded PZT for Lamb wave SHM](image)

![Figure 8. Experimental setup including composite panel and data acquisition system](image)

With this experimental setup the first symmetric Lamb wave mode ($S_0$) was detected by the system. In Figure 9 the FBG resultant sensor signal, obtained from these preliminary experiments is depicted. The propagating $S_0$ Lamb wave mode was clearly captured in the FBG sensor signal. To improve signal definition and remove off tone noise, a band pass filter is applied to the FBG signal.
5. Conclusions
In this study the capabilities of applying embedded optical fiber sensors into composite components were demonstrated. Specifically the ability of EFS and FBG sensors to monitor the manufacturing, the component quality and its health in operation, i.e., the component in its several life stages, was assessed and initially verified. This study shows the potentialities of such application in the future and serves as a basic knowledge for that objective. Panels with embedded sensors were manufactured in a developed RTM apparatus and an embedding technique was demonstrated. EFSs were applied and successfully detected the presence of resin during the filling of the mold, enabling the monitoring of resin flow. The resin injection monitoring was confirmed through a glass panel incorporated in the RTM, specifically for that objective. For this part of the work a BBS, a photo-detector and an OSA were used.

FBG sensors were used to monitor the component during the manufacturing process. These sensors were then used, after manufacturing, to assess the mechanical properties of the component, through the execution of tensile tests in a MTS machine and with the application of a strain gauge for benchmarking. The readings from the FBGs, in terms of their Bragg wavelength shifts, were compared to the strains measured by the strain gauge and FBG’s sensitivity was determined (relation in between the change in their Bragg wavelength and measured strain). The light spectrum was assessed though the OSA.

Afterwards an FBG interrogation technique, based in a tunable laser and photo-detector, was implemented to enable the use of these sensors to detect Lamb waves. With this technique temperature, operational strains and vibration effects are eliminated. The interrogation technique also does not limit by itself the acquisition/scanning frequency and speed – limitations are imposed instead by the frequency of the digitizer. This is important to enable the high speed acquisition required to assess the fast propagating Lamb waves.

The initial experiments proved the ability of the FBG sensor and interrogation technique in development to detect and assess the fast propagating Lamb waves.

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