An Update on Monitoring Moisture Ingression with Fiber Optic Sensors

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ABSTRACT

Newly developed advanced aircraft structures are utilizing composite technology for improving stiffness, strength and weight properties. Such structures are commonly found in inaccessible regions where current NDE techniques are limited. The development of low profile, distributed, embeddable, real-time, optical fiber sensors capable of detecting the onset of composite failure in aircraft structures would eliminate a significant portion of related maintenance costs. Notable composite failures that are difficult to assess include delaminations and moisture ingression issues. Optical fiber-based sensors add the inherent advantages of being lightweight, low profile, immune to EMI, resistant to harsh environments, and highly sensitive to a variety of physical and chemical measurements. Optical fiber-based sensors can also be embedded directly into the composite part during manufacturing and co-cured. This creates a monitoring system that has little impact on the properties of the final part while providing significant benefits.

Fiber optics embedded in composite honeycomb panels were fabricated and tested using ground – air – ground thermal cycles to determine moisture ingression monitoring capabilities of the sensors. Two different types of moisture sensing fiber optics were measured. One type of installed moisture sensor is based off of a Bragg grating system, while the other moisture sensor is based off of a long period grating system. Presented herein is a comparison of the two different types of fiber optic sensors that monitored the moisture ingression in honeycomb panels.

INTRODUCTION

Large areas of secondary structures such as fairings, high lift devices and control surfaces are constructed using thin composite face skin honeycomb panels. If surface finish systems degrade or damage occurs, moisture can accumulate in the honeycomb core. It is known that water ingression occurs in-service and that affected components could remain in operation for extended periods with substantial areas saturated prior to being repaired. Assessments for the continued airworthiness of these components relies on the ability to determine locations where damage is likely to initiate, accurately predicting the damage behavior, finding damage before it becomes critical and also requires knowing the material mechanical properties of saturated structures. Many of these issues have not been thoroughly validated to date, resulting in costly component replacements or extensive repairs. This paper studies the use of fiber optics to locate and determine the extent of moisture ingression.

BACKGROUND

Inherent advantages that optical fiber LPG's and Bragg grating strain sensors have over other commercially available sensors include size and flexible geometry, resistance to EMI, spark resistance, resistant to attack by most chemicals, immunity to electromagnetic interference, and configurations that allow for inexpensive distributed sensing capabilities. Both the optical fiber LPG and the Bragg grating sensors are fabricated by exposing UV light through a mask onto the optical fiber. This fabrication process offers the capability of maintaining the ultimate strength of the optical fiber. Foe example the Bragg gratings typically demonstrate tensile strengths on the order of 200 kpsi, with strain capabilities from 1% to 2%, and Young's modulus on the order of 10 Mpsi [1].

The following sections briefly discuss the sensing methodology behind the long period grating chemical sensors and the Bragg grating strain sensors. The LPG sensors were provided by Luna Innovations, while the Bragg grated sensors were provided by Blue Road Research.

Long Period Grating-Based Chemical Sensors

Long period grating chemical sensors can be fabricated to monitor environmental changes within the honeycomb panel. The principle behind the LPG sensor is that germania doped fused-silica glass is photosensitive such that optical fiber exposure to certain wavelengths of light, particularly 244 nm, will cause the refractive index of the doped glass to increase slightly [2]. If the fiber is exposed to a periodic index variation, the refractive index of the optical fiber is modulated forming a grating structure. Scientists at Bell Laboratories demonstrated a new type of photo-induced grating in which the grating spacing is on the order of hundreds of microns [3]. Based on the grating periodicity, the phase matching condition is satisfied such that the forward propagating fundamental mode is coupled into propagating cladding modes and the electric field extends out of the optical fiber. Figure 1a provides a schematic of an optical fiber long period grating and shows how it interacts with light propagating in the fiber. Figure 1b illustrates a typical spectral response showing the discrete, spiky, loss bands. These loss bands correspond to coupling of the fundamental guided modes into the discrete cladding modes. This light travels mostly in the cladding and partly within the evanescent field just outside the cladding and is the mechanism in which the LPG can be used in sensing applications.

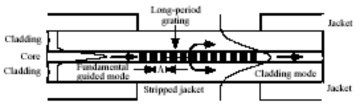

Figure 1a. Schematic of long-period grating coupling element.

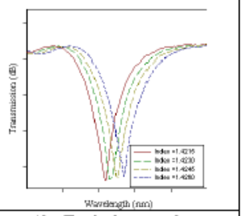

Figure 1b. Typical spectral response of LPG coupling element.

Thus, the LPG is a spectral loss element that scatters out light at a particular wavelength based on the grating period, fiber refractive index, and the refractive index of the surrounding environment [3]. This coupled wavelength can be designed for an isolated response to the refractive index of the surrounding environment. Figure 1a shows a representative spectrum shift of the fundamental mode with refractive index change for a LPG sensing element operating at the 1500 nm wavelength. The magnitude of this spectral shift can be tailored by adjusting LPG fabrication parameters. By tracking the location of this spectral loss dip, real-time refractive index measurements can be accomplished.

The LPG-based chemical sensors operate based on specially designed coatings that cause a measurable change in the refractive index 'seen' by the LPG in the presence of target molecules. For each LPG chemical sensor, a target specific coating is applied to the surface of an LPG and optimized for specificity, responsivity, and reliability. The coating absorbs target molecules, resulting in refractive index changes, causing a shift in the wavelength of the scattered light. This sensing platform has been used to detect moisture, metal-ions, pH changes, biological targets, and pesticides [4, 5, 6, 7]. Presented are preliminary results that demonstrate this sensing platform for moisture detection within a cured honeycomb composite sandwich panel. Luna Innovations provided all LPG fiber optic sensors.

Bragg Grating Strain Sensors

Complementary to the long period grating, Bragg grating strain sensors can also be fabricated to measure moisture content due to strain changes in the sensor housing.

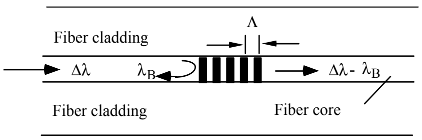

Figure 2a. Schematic of the Bragg grating sensor illustrating refractive index variation within the core.

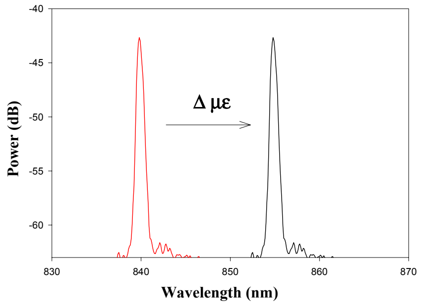

Figure 2b. Spectrum of Bragg grating sensor, showing spectral shift with induced strain.

Bragg gratings are formed in the core of Ge-doped optical fiber when exposed to the interference pattern of two, crossed UV laser beams. The resulting sensor element is illustrated below, in Figure 2a, along with the optical spectrum shift with strain shown in Figure 2b.

Here, the photo-induced planes of constant index of refraction will be oriented perpendicular to the axis of the fiber as shown in a schematic of the Bragg grating in Figure 1a. In this configuration, part of the light incident on the grating gets back reflected while most of the light will be transmitted. The reflected wavelength, λ_B, will interfere constructively after reflecting off each of the layers, satisfying the Bragg equation relationship

$$\lambda_B = 2n\Lambda, \qquad \text{(I)}$$

where n is the index of refraction, and $\Lambda$is the grating spacing. If strain is applied to the Bragg grating, the resonant reflected wavelength λ_B will shift by an amount given by $\Delta\lambda_B$, where

$$\Delta\lambda_B/\lambda_B = (1 - P_\varepsilon)\,\varepsilon, \qquad \text{(II)}$$

where P_ε is the photo elastic constant for the silica fiber core. Hence by tracking $\Delta\lambda_B$, residual strain can be accurately monitored. Figure 1b illustrates strain measurements using the spectral shift from a Bragg grating.

For axial strain measurements, the Bragg grating can be interrogated by tracking the shift in the reflected wavelength from the grating. As the period of the grating changes due to photo elastic effects, the wavelength shift can be correlated to strain using Equation 2. Several Bragg gratings can be multiplexed on a single optical fiber by writing them to operate at different wavelengths and interrogating the response through Wave Division Multiplexing (WDM). In this manner the Bragg grating can be used for quasi-distributed and quasi-point sensing [8]. All supplied Bragg grating fiber optic sensors were provided by Blue Road Research.

TEST SETUP

Two 12” x 12” honeycomb cured composite panels were fabricated. Different fibers were placed into each panel. Panel 16-1 contained Bragg grating fiber optic sensors while panel 18-1 contained LPG sensors. The lay up used the following materials:

1. Kevlar Phenolic 1/8-3 PCF honeycomb core 1 inch thick.
2. Epoxy Prepreg graphite fabric per AS4C/8552S Style 3K-70-PW,
3. Epoxy Prepreg graphite tape per AS4/8552-1, Grade 190
4. Film Adhesive per BMS 5-154, Type II, Class I, Grade 05

The sequence used in the lay-up was (using the above numeric designations):

2	0/90
3	90
2	+/-45
3	0
2	+/-45
3	90
2	0/90
4	
1	
4	
2	0/90
3	90
2	+/-45
3	0
2	+/-45
3	90
2	0/90

After the panels were completely laid up and assembled small holes were drilled in the face sheets to place the fiber optic sensors into the panel. The fiber optic sensors were then inserted into the sandwich panel and adhesive was placed around the sensor to not only seal the hole completely, but to also provide strain relief to the sensors.

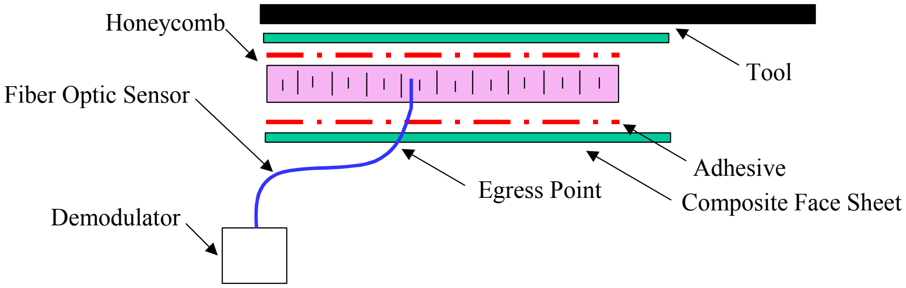

Figure 3. Schematic of Fiber Optic Sensor Placement – Side View.

After curing, it was found that all of the LPG fiber optic sensors did not survive the curing process while the Bragg grating fiber optics had a 50 % survival rate. A third panel, identical to 18-1 was created but this time, the sensors were not inserted into the panel until after curing had occurred. An additional Bragg fiber optic sensor was also inserted into panel 16-1 panel. A 0.1" open hole to allow moisture to be introduced into the sandwich panel was also drilled. Potting was placed around the edges of the panels to prevent moisture from seeping in through the edges of the panels. Therefore, only moisture introduced through the face sheets and the open hole was measured.

The final sensor placement for each of the panels is shown in figure 4. The blue dots are locations of Bragg sensors while the pink dots are locations of LPG sensors. The actual panels appear as in figure 5 below.

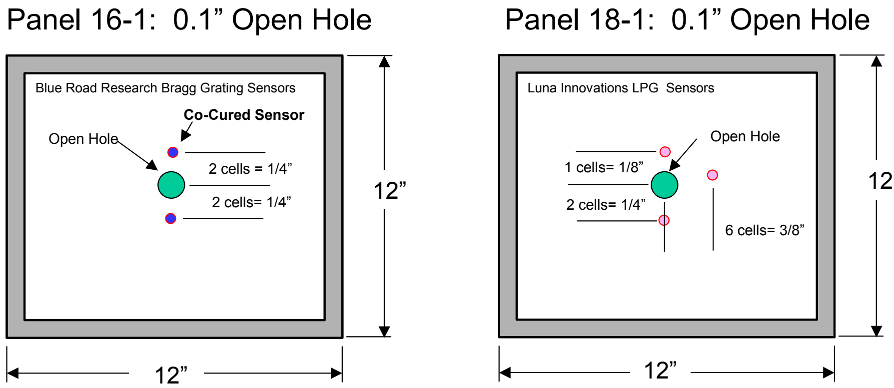

Figure 4. Schematic of Fiber Optic Sensor Placement – Top View.

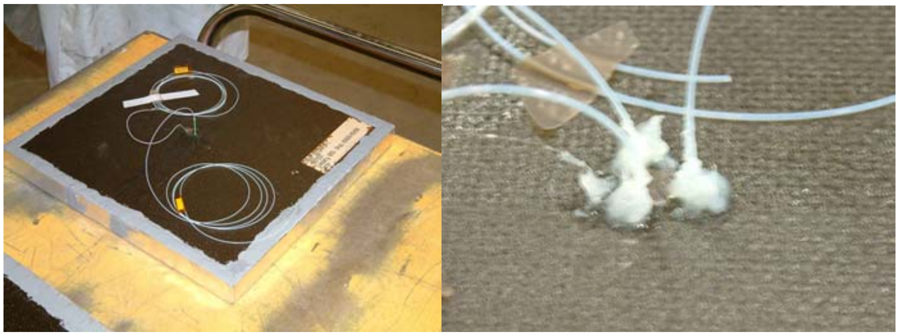

Figure 5. Panels with Sensors Installed (Left is Bragg sensors, Right is LPG sensors).

Note that none of the LPG sensors survived the co-curing process – only the Bragg grating sensors survived. As a result, an LPG temperature sensor was placed in the chamber for data collection purposes only. It was also apparent that this initial installation proved to be rather bulky and not conducive to mass installation or production even though the Bragg grating sensors survived.

Panels were then placed into a humidity/thermal chamber. Sensors were monitored via a remote Boeing proprietary data acquisition box and a spectrum analyzer. Interrogation of the sensors occurred every minute for the LPG temperature sensor and every hour for the Bragg sensors. The testing cycle is shown in table 1.

Precondition:

TEMP	RH	TIME
70F to 120F	50% to 95%	10 min
120F	95%	12 hr
120F to -65F	95% to 0%	15 min
-65F	0%	1 hr

Cycle (400 times):

TEMP	RH	TIME
-65F to 160F	0%	15 min
160F	0%	15 min
160F to -65F	0%	15 min
-65F	0%	15 min

RESULTS

During the first 30 minutes of pre-conditioning data was taken at a rate of once every minute. Figure 6 shows the response of the Fiber Bragg grating sensors. The relative humidity sensor wavelength corresponds well to the change in humidity in the chamber. The system ramps up in wavelength corresponding to the change in relative humidity in the chamber. The system held constant with little drift during the measured pre-conditioning time.

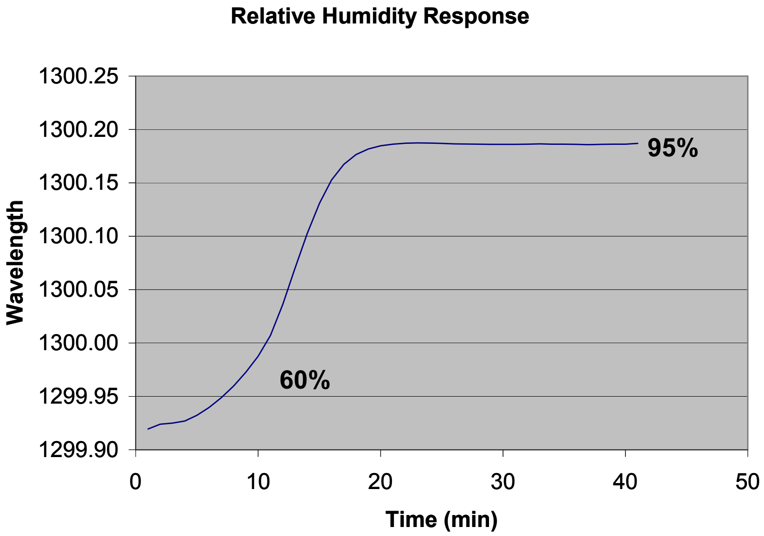

Figure 6. Fiber Bragg Grating Pre-Conditioning RH response.

Figure 7 shows the response of the LPG temperature sensor to change in temperature. Notice that while the temperature sensor responds to the change in temperature in the chamber as it is ramping up from 70F to 120F it appears that the calibration of the sensor is not accurate. This issue could be resolved by properly calibrating the fiber optic sensor.

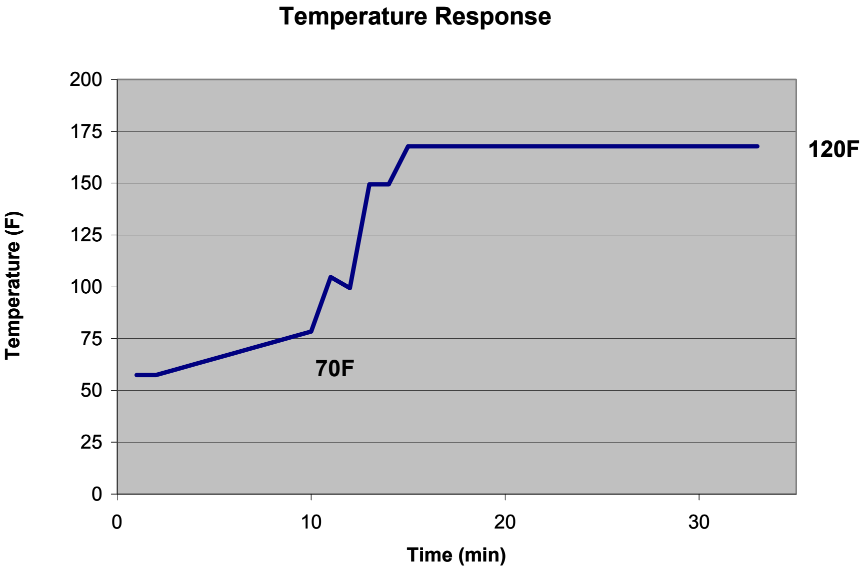

Figure 7. LPG Pre-Conditioning temperature response.

Figure 8 shows the response of the Bragg relative humidity sensor to the temperature cycling of the composite part. Data points were taken every 30 minutes – at the extreme ends of the temperature cycling. There appears to be a small amount of drift in the results, however, that may have resulted from drift inside the actual chamber. It should also be noted that the drift was also less than 0.1nm. In general, however, the Bragg relative humidity sensor varied with temperature. Through calibration at the extreme temperatures the temperature effect is eliminated and a true relative humidity is measured. This was not currently performed due to timing limitations on the project.

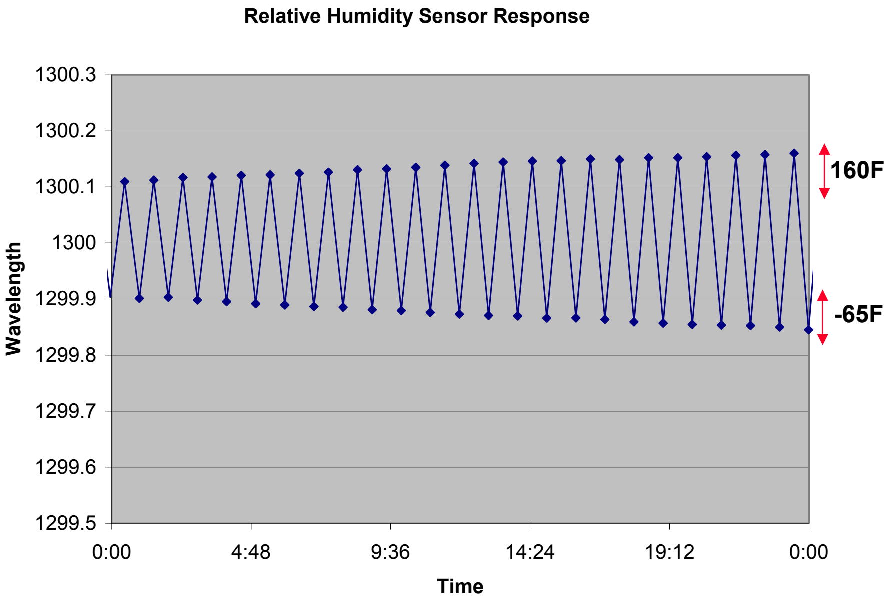

Figure 8. Bragg Cycling Response

Figure 9 shows the response of the LPG temperature sensor to cycling in the chamber. Once again, the sensor responds to the temperature change in the chamber but appears to have a calibration error. This sensor also tended to stop functioning at the lower temperatures for short periods of time. Upon warming, however, the sensors functioned properly.

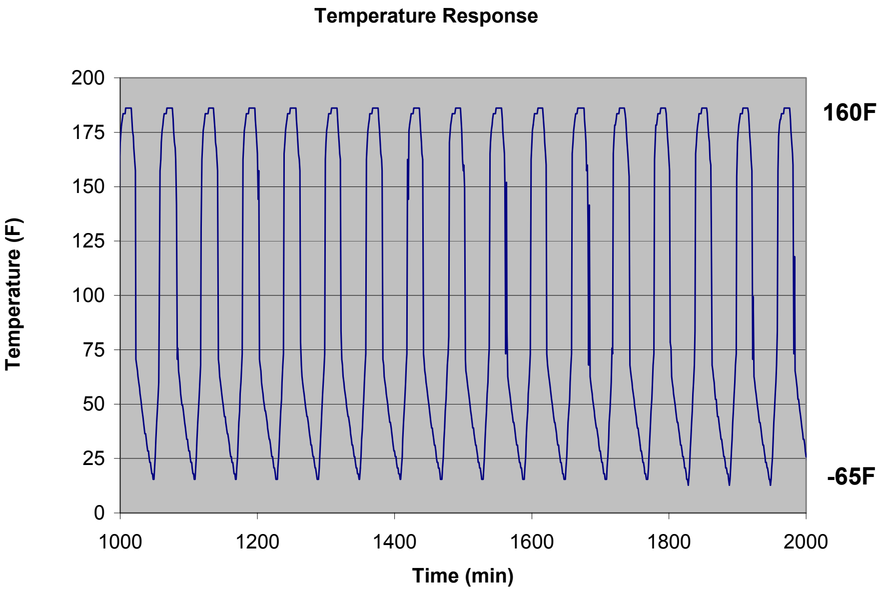

Figure 9. LPG Cycling Response

CONCLUSIONS

While the installation of the sensors into the uncured part was easy, bagging the part and having the sensors survive the rough handling of trimming and edge sealing proved difficult. This could be circumvented however by creating robust housing around the sensor. This is the main reason the Blue Road Research Bragg grating sensors survived - they had a housing around the sensors. Luna's LPG sensors required a Teflon tubing to be slide over the entire fiber optic to provide handling protection. Even with precautions taken, none of the LPG sensors survived the curing process. It is recommended that significant work be placed into developing more rugged housings and in particular, ingress and egressing of fiber optics between trimmed parts.

The Blue Road Research Bragg grating sensor performed well, behaving in direct relation to the chamber. The Luna LPG temperature sensor also had a direct relationship with the chamber, but calibration was in error.
It is recommended that additional testing take place which tests longer duration of humidity cycling both with and without open holes. Sensors also need to be tested more thoroughly at the extreme ends of the temperature scale. Depending on placement of the sensors in the actual structure this could become a significant issue. The issue of false positives and reliability of data also comes into question at the extreme temperature ends.

Other testing which should be performed includes actual wetness rather than relative humidity measurements.

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