DAMAGE DETECTION IN COMPOSITE PLATES USING FIBER BRAGG GRATINGS

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Abstract
A composite plate was manufactured using an in-house resin transfer molding with an FBG sensor embedded into the composite at the manufacturing step. To be able to convert the measured shift in the Bragg wavelength to strain, a strain gage was bonded onto the surface of the composite plate in such a way that both FBG and strain gage are vertically aligned. The embedded FBG sensor was characterized by applying different loads on the composite plate using a cantilever beam set up. To be able to show that the FBG sensor is capable of detecting damage formation in composites, the composite plate was drilled to create artificial defects of different size. The wavelength shift of the FBG was monitored as a function of the size of the hole and wavelength measurements are compared with those of sound structure to conclude on the health of the structure.

1 Introduction
Composite materials have been utilized in load bearing structures such as airplanes, wind turbines, pressure vessels as an alternative to metallic materials due to their high strength-to-weight ratios, stiffness, corrosion resistance, and fatigue performance [1-3]. Structural health monitoring (SHM) of these composite materials used in these structures is crucial to prolong the longevity of its usage and prevent any possible accidents due to the failure of the material caused by the development of cracks or defects. In this regard, detecting the existence and size of the defects becomes important. The presence of the damage or defect in a composite structure alters the local strain distribution under structural load. Hence, damage can be detected when the measured strain deviates appreciably from that of a healthy structure. This allows one to be able to monitor the structural health of composite components under service conditions.

Due to their high sensitivity, immunity to electro-magnetic waves and multiplexing ability, fiber Bragg grating (FBG) sensors have been widely used for process and SHM of composites. Its wide applicability has been demonstrated in monitoring airplane wings, buildings, bridges and dams [4-6]. An FBG sensor is a segment of a single mode optical fiber core with a periodically modulated refractive index in the direction of fiber length. The grating segment acts as an optical filter by reflecting a specific wavelength back known as the Bragg wavelength while transmitting others. The Bragg wavelength satisfies the Bragg condition as [7,8]

$$\lambda_b = 2n\Lambda \tag{1}$$

where λ_b is the Bragg wavelength, n is the effective refractive index of the fiber and Λ is the pitch of the gratings. If an FBG sensor is under a mechanical or thermal load (temperature variation), the spacing between gratings and effective refractive index of the fiber will change due to the strain, and thermal expansion. Since the Bragg wavelength is a function of the effective refractive index and grating pitch, any change in these variables will cause the Bragg wavelength to shift, meaning that the center wavelength of the reflected spectrum changes. Expanding Eq. (1) into a Taylor series yields the differential change in the Bragg wavelength resulting from applied strain and temperature variations as

$$\frac{\Delta\lambda_b}{\lambda_b} = \left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial l} + \frac{1}{n}\frac{\partial n}{\partial l}\right)\Delta l + \left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{n}\frac{\partial n}{\partial T}\right)\Delta T \tag{2}$$

where Δl is the change in the length of the grating section. Here, the terms $(\partial\Lambda/\partial l)$ and $(\partial n/\partial l)$ correspond to a change in the grating spacing due to strain, and the strain-optic induced change in the refractive index, respectively. The terms $(\partial\Lambda/\partial T)$ and $(\partial n/\partial T)$ represent the change in the grating spacing due to the thermal expansion and the thermo-optic induced change in the refractive index, in the given order. Defining thermal expansion and thermo-optic coefficients for an optical fiber as $\alpha_\Lambda = (1/\Lambda)(\partial\Lambda/\partial T)$ and $\alpha_n = (1/n)(\partial n/\partial T)$, respectively, one may write the shift in Bragg wavelength due to temperature and strain changes respectively as

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T\,,\ \Delta\lambda_B = \lambda_B(1 - p_e)\varepsilon_x \tag{3}$$

where p_e is the so-called effective photoelastic coefficient and defined as $p_e = (n^2/2)\left[p_{12} - \nu(p_{11} + p_{12})\right]$ and ε_x is the axial strain. Here, p_{11} and p_{12} are the components of strain-optic tensor, and ν is the Poison's ratio. In this work, all the experiments are conducted at constant ambient temperature.

2 Experimental Procedure and Results

Fig.1 shows a lab scale in-house Resin Transfer Molding (RTM) system used to manufacture composite plates in this work. The RTM apparatus in fig.1 is a modular clamshell system with the flexibility of accommodating different mold designs and thicknesses. The composite plate manufactured is made of nine layers of biaxial glass fiber reinforcements (X 800 E05 800g/m^2, manufactured by METYX) and the epoxy resin system which is a mixture of ARALDITE LY 564 epoxy resin and XB 3403 hardener, mixed with the ratio of 100 and 36 parts by weight. The FBG sensor is located between the fourth and fifth layers of the composite. Due to the fragile nature of the optical sensor, ingress and egress of optic sensors into composite structures manufactured with close-mold process is rather challenging. To avoid any possible breakage of optic sensors, the fiber was introduced into the composite through a thin hypodermic tube which protects the fiber through the radius of the bend at the ingress/egress point. A custom fitting consisting of a silicone stopper is used to keep the fiber in place [9].

Figure 1. RTM apparatus together with optical equipments.

During the manufacturing of the composite plate, the curing process was monitored continuously using the embedded FBG sensor. Plot of the variation of the Bragg wavelength as a function of time is shown in fig.2. The first sudden drop in the Bragg wavelength in fig.2 is due to the contact of room temperature resin with the FBG in the preheated mold. Subsequently, the mold is heated to cure temperature of 50 °C resulting in a shift of the Bragg wavelength. The fluctuations in fig.2 correspond to a region where the temperature of the mold was set to the cure temperature. Since the cure process is exothermic, the released heat further shifts the Bragg wavelength. As the strength of the exothermic process diminishes, the water-cooling system in the RTM mold attempts to bring the temperature of the mold to the preset cure temperature. Given the presence of residual stress build up in the composite (due to various effects such as thermal gradients, shrinkage, and differentials in thermal expansion coefficients), the Bragg wavelength does not return to its original value. As the polymerization reaction nears completion, the shift in Bragg wavelength ceases. The region marked with two vertical lines corresponds to the curing of the epoxy system.

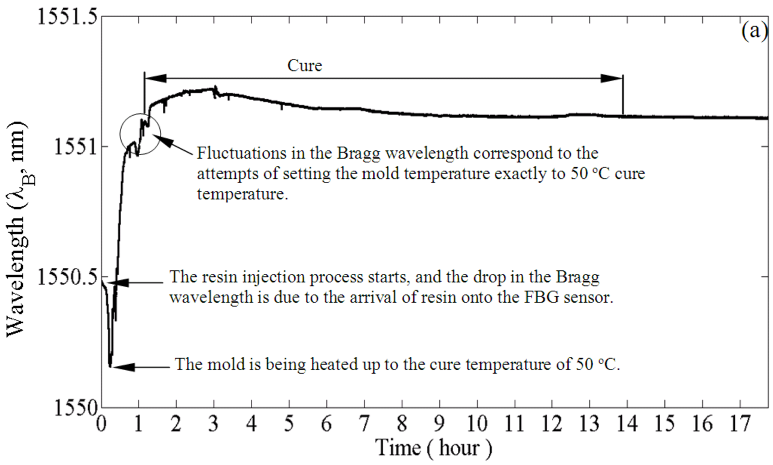

Figure 2. Bragg wavelength versus time for cure monitoring with the FBG sensor.

The composite plate manufactured with the dimensions of 305x610x3 mm using the RTM system with the embedded FBG sensor was set up in a cantilever beam configuration as illustrated in fig.3 with one end being fixed while the other end being free. To calibrate the FBG sensor, load was applied to the free end in steps of 0.5 kg up to 3.5 kg. At each load, the strain and the Bragg wavelength were recorded. The strain is measured using a quarter bridge 350Ω strain gage aligned vertically above the embedded FBG sensor and fixed on the surface of composite. The FBG sensor was interrogated using Micron Optic SM230 interrogator, and the strain gage was read using NI Signal Express. To be able to determine the strain sensitivity of the FBG sensor, the Bragg wavelength is plotted as a function of the measured strain, and the slope of this linear plot in fig.4 is determined to be 0.08 pm/με. This very low value is a result of embedding the FBG close to the neutral axis of the composite. The very high sensitivity of free and bare FBG enables measurements even close to neutral axis.

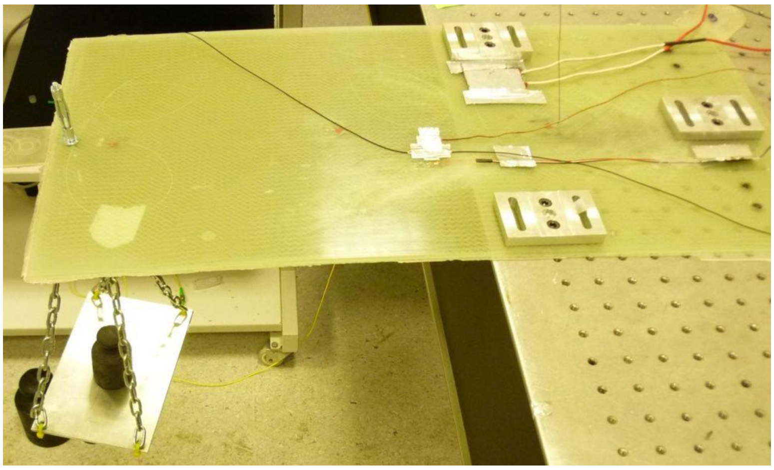

Figure 3. The picture of cantilever beam test setup.

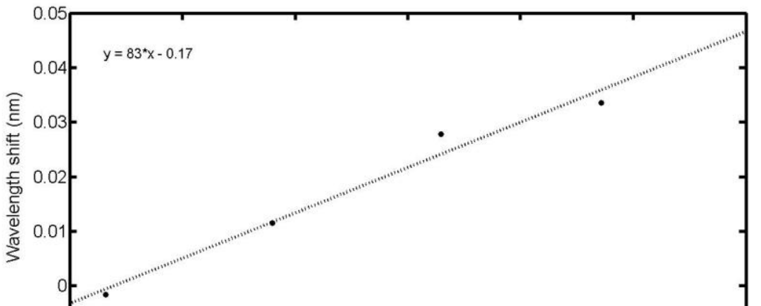

Figure 4. Calibration of the FBG with the surface mounted strain gage.

For structural health monitoring of composite under controlled environment, artificial defects were created in the composite panel manufactured. The composite plate was drilled at 7 cm away from the FBG sensor location as illustrated in fig.5. The diameter of the hole is 3 mm and then the hole size was subsequently enlarged to 6 mm. The Bragg wavelength of the embedded FBG sensor was monitored for healthy and damaged plates, as given in fig.6.

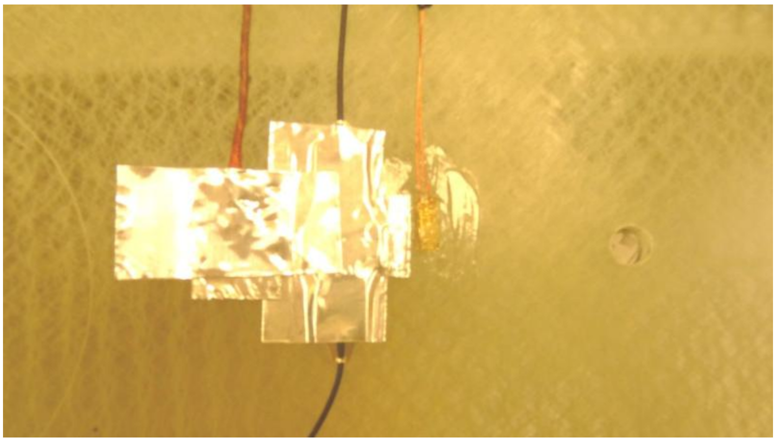

Figure 5. The picture of damaged composite panel with a hole diameter of 6 mm.

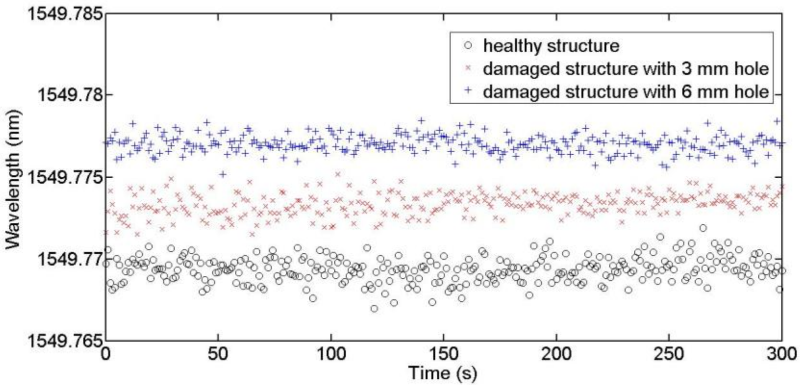

Figure 6. The Bragg wavelength of the embedded FBG sensor of sound structure and damaged structure.

As can be seen from fig.6, the wavelength shift of the embedded FBG sensor has increased after drilling a hole through the composite structure, and it increases more for a larger hole. This change in the Bragg wavelength is due to the release of the compressive residual stress accumulated within the composite structure due to the curing process. The damaged composite plate with the hole size of 6 mm was also employed as a cantilever beam, and the loading experiments were repeated and compared with the sound structure. The results of the wavelength shift of the embedded FBG sensor in fig.7 showed that damage near FBG sensor causes the wavelength shift to decrease for the given load. This is due to the fact that the presence of damage alters the strain distribution in the structure. Thus, the damage can be detected when the measured strain differs significantly from that of a healthy structure, thereby allowing one to be able to monitor the structural health of composite components under service conditions. This can be more readily seen in fig.8 where the wavelength shift of the embedded FBG sensor is plotted as a function of the applied load.

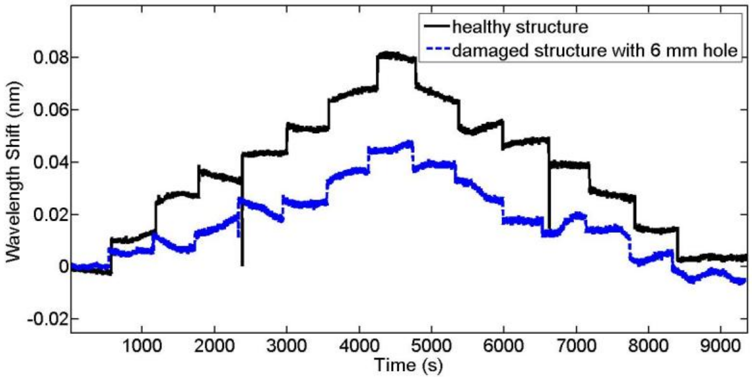

Figure 7. The wavelength shift over time in cantilever beam experiments with and without damage. The step-wise increments in the wavelength correspond to increase in the applied load to the cantilever beam in the steps of 0.5 kg.

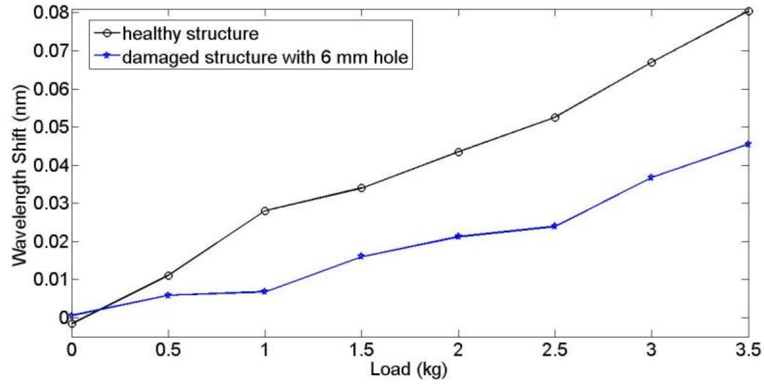

Figure 8. The wavelength shift versus the applied load in cantilever beam experiments with and without damage.

3 Conclusions

In this work, it is shown that FBG sensors can be used for both cure and health monitoring of composite structures. A composite panel manufactured by the RTM method with an embedded FBG sensor is artificially damaged for the purpose of measuring the curing induced residual stress built-up as well as revealing that the FBG sensor can detect the presence of damage formation in the structure. Given that the presence of damage alters the strain distribution in the structure, the difference in the wavelength shifts in the sound and the damaged structure for the same loading conditions could be attributed to the change in the strain field due to drilling.

Acknowledgements

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