MONITORING HYGROTHERMAL DAMAGE IN GRAPHITE-EPOXY LAMINATE USING FIBER BRAGG GRATING

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Abstract

Composite structures used in humid and high temperature environment may face hygrothermal damage which causes a swelling and weakening of the matrix. In this work, simulated hygrothermal damage on a carbon fiber reinforced epoxy composite laminates with 60°C under a relative humidity of 95% for 72 hours decreased the tensile strength by about 7%. Non-destructively it is difficult to detect such damage. Embedded fiber Bragg gratings (FBGs) was shown to be able to detect the internal swelling. When the laminates subsequently suffered a low-energy impact followed by cyclic loading, the easier spread of the damage in the weakened matrix was revealed by a pre-matured disappearance of the FBG reflection peak in 10000 cycles versus that beyond 130,000 cylces for specimens without the hygrothermal treatment.

1. Introduction

Composite structures are used in various fields such as automotive, aircrafts, and wind turbines applications because of their high specific strength and stiffness. In some of these applications, composite structures may suffer high temperature and humidity that may lead to degradation in mechanical properties [1-3]. In the meantime, these structures are also prone to internal damage caused by bird strike, foreign object impact, tool drop, hail storm and cyclic loading. Impact and cyclic loading damages will normally induce insidious defects such as delamination, debonding and matrix cracking [4]. Structural reliability will be seriously compromised if the property degradation remains undetected. Hygrothermal degradation may be readily revealed by destructive testing but is difficult to detect using conventional non-destructive evaluation techniques. The current work proposes to use embedded fiber Bragg grating (FBG) sensors to monitor the occurrence of hygrothermal degradation and give an early warning if the structural health is compromised. Fiber Bragg grating (FBG) has recently been extensively investigated not only because their small size, high sensitivity, lightweight, but also their EMI immunity, and resistance to corrosive. Due to their small size and compatibility with composite materials, such sensors can be easily embedded into composite patch without affecting the material properties. FBG sensors embedded in composite materials have been used in structural health monitoring applications [5-7]. The FBG sensors have been shown to be able to monitor impact event occurrence [8, 9] and also detect impact locations and monitor the spread of damages during subsequent fatigue loading in composites [10, 11, 12].

2 Experimental procedures

2.1. Specimens preparation

Composite laminates were made from T300/3501 Graphite/Epoxy prepreg stacked in the quasi-isotropic sequence $[0/45/90/-45]_s$. The stacks were cured at 150°C under a pressure of 10kg/cm^2 for 30 minutes in a diaphragm type forming mold. After the curing process, the formed laminate (200mm×200mm×1mm) was cut into specimen coupons (200mm×25.4mm×1mm) using abrasive diamond-coated wheel cutting machine. The Schematic of embedded FBGs and lay out of the Graphite/Epoxy prepreg is shown in Figure1. FBG sensors were embedded in the two outer 0^o laminates and were parallel to the carbon fibers there. This was also the loading direction. The FBG on the side that faces the impact is designated as L1 and the one on the back surface L4. Each of the FBG sensors was offset by 3mm from the center-line of the specimen. The schematic of the geometry and dimensions of specimen is shown in Figure2.

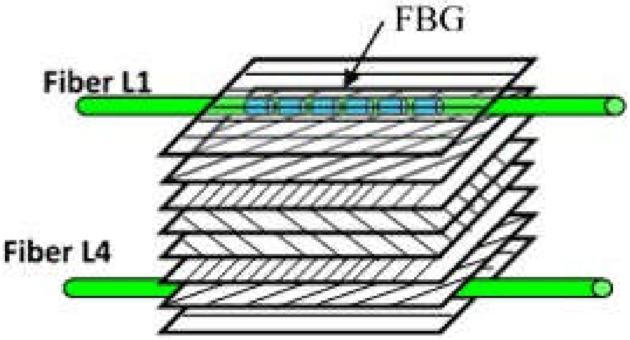

Figure1. Lay out of the prepreg stacking and the embedded optical fiber sensors in the composite specimen.

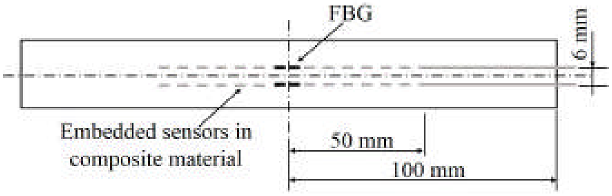

Figure 2. Geometry and dimensions of specimen.

2.2. Fabrication of fiber Bragg grating sensors

FBGs were fabricated in Ge-B co-doped single mode photosensitive fibers by side-writing using KrF Excimer laser and the phase mask technique. The sensing length of the FBG is about 10 mm and the period of the grating is 1.05 μm. The reflectivity of the resulting FBG was about 99%. The peak wavelengths and the FWHM (full width half maximum) of the FBGs were ~1550 nm and ~ 0.175 nm respectively.

The schematic of FBG interrogation setup is shown in Figure 3. Broadband light was introduced into the FBGs through a circulator. An optical switch was used to choose between L1 and L4. The reflected spectra from the FBGs were interrogated periodically using an Anritsu optical spectrum analyzer (MS9710C OSA) and recorded to the computer by data acquisition software t o a resolution of 0.05 nm.

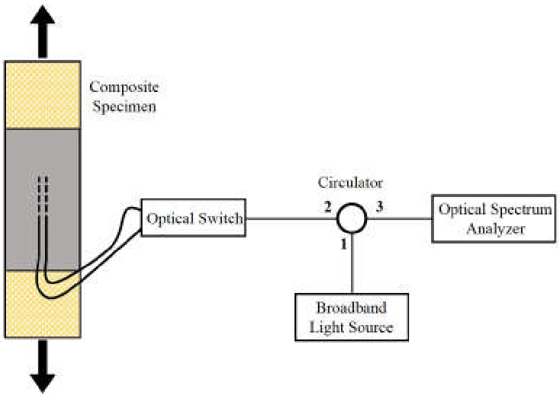

Figure 3. The schematic of experimental setup.

2.3. Hygrothermal treatment

For hygrothermal treatment, the specimen coupons were put in an environmental chamber and kept at 60°C under a relative humidity of 95% for 72 hours. Temperature and humidity were controlled to within ±0.5°C and ±1% respectively. The reflected spectra of the embedded FBG sensors were recorded periodically during the hygrothermal treatment.

2.4. Impact and fatigue testing

Impact damages were made at the center of the specimens using a 90g aluminum falling weight from a height of 140cm with an apparatus that conforms to ASTM D5628. After impact the coupons were subjected to cyclic loading from 1.4kN-14kN at a frequency of 4.5Hz using an MTS servo-hydraulic test machine.

3. Basic properties of fiber Bragg grating sensors

When broadband light is coupled into an optical fiber with a uniform Bragg grating, a single peak with a characteristic wavelength satisfying the Bragg diffraction criterion will be reflected while the other wavelengths will be transmitted through. The reflected wavelength which is called the Bragg wavelength (λ_B) can be defined as follow:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the grating and Λ is the periodicity of the grating. If the uniformity of the grating period is perturbed, the single peak reflected spectrum will become broadened or chirped. When either or both of the n_{eff} and Λ are changed by physical quantities such as strain, temperature and pressure, the center wavelength of the reflected spectrum shifts. In general, the reflected wavelength will shift by ~1pm under a strain of 1 $\mu\varepsilon$. It has been shown that when the damage in a composite laminate caused by post-impact fatigue reaches the vicinity of an FBG sensor, the characteristic peak will chirp and its intensity gradually submerged into the background intensity [12]. The lost of the reflection peak may be used as an indication of the extensive development of post-impact fatigue damages.

4. Results and discussion

4.1. Tensile strength of hygrothermally treated specimens

The average tensile strength of specimens after the impact without undergoing any hygrothermal treatment is 27.5MPa while that with a T60H95 treatment preceding impact is 25.4MPa. Thus the strength of the composite coupons has been clearly degraded by about 7% by the T60H95 treatment.

4.2. Effect of Impact and post-impact fatigue on specimens without hygrothermal treatment

Figure 4 shows the reflected spectra of FBG after embedded into composite, before and after impact for the fibers L1 and L4. Originally each of the FBG spectra has a single sharp reflected peak. On embedding, curing and cutting into testing coupons, a shift in peak wavelength together with slight widening and splitting of the peak occurred as is evident in Figure 4. When the FBG is under a uniform strain distribution, the characteristic wavelength will shift but the reflected spectrum will keep its original shape with a single sharp peak. However, under a non-uniform strain distribution, the period Λ along the grating will be different and this changes the shape of the reflected spectrum. Spectrum shape changes after curing may be attributed to residual stresses that arose during the composite fabrication process. Impact damages probably induced highly non-uniform strains by perturbing and concentrating the residual stress field, causing and the original peaks to widen even more and split heavily into a number of distinct peaks.

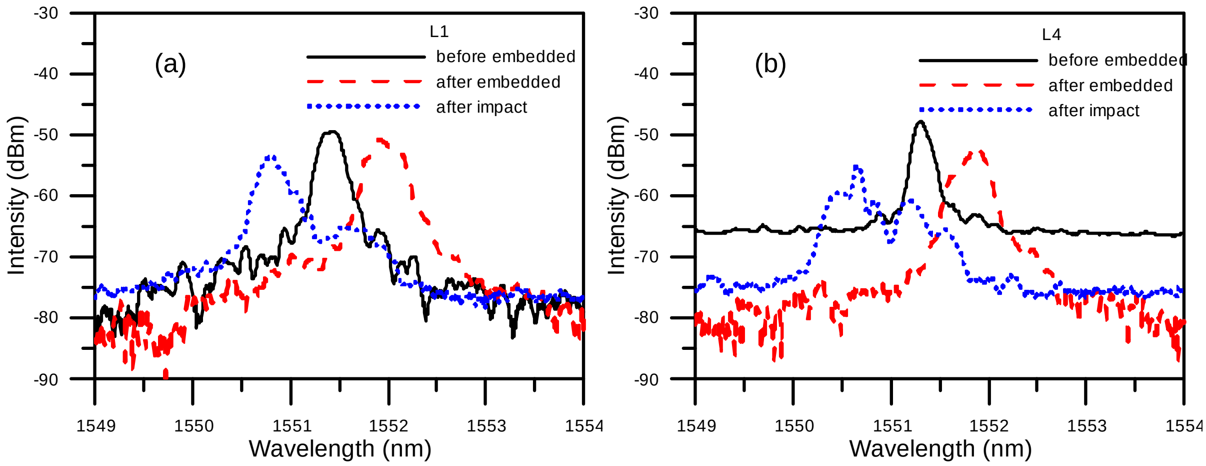

Figure 4. Comparison of FBG spectra before and after embedded in CFRP as well as after an impact from fiber sensor (a) L1; (b) L4.

Figure 5 shows the change in reflected spectra with fatigue cycle after impact for 130000 cycles. Development of the internal defects by fatigue loading, caused the peak intensity to drop slightly when the fatigue loading just began. By 20000 cycles, the drop in peak intensity slowed down and the peak remained well defined, suggesting that with the current impact and fatigue loading, the degree of internal damage has not yet spread to seriously affect the strain field surrounding the FBGs.

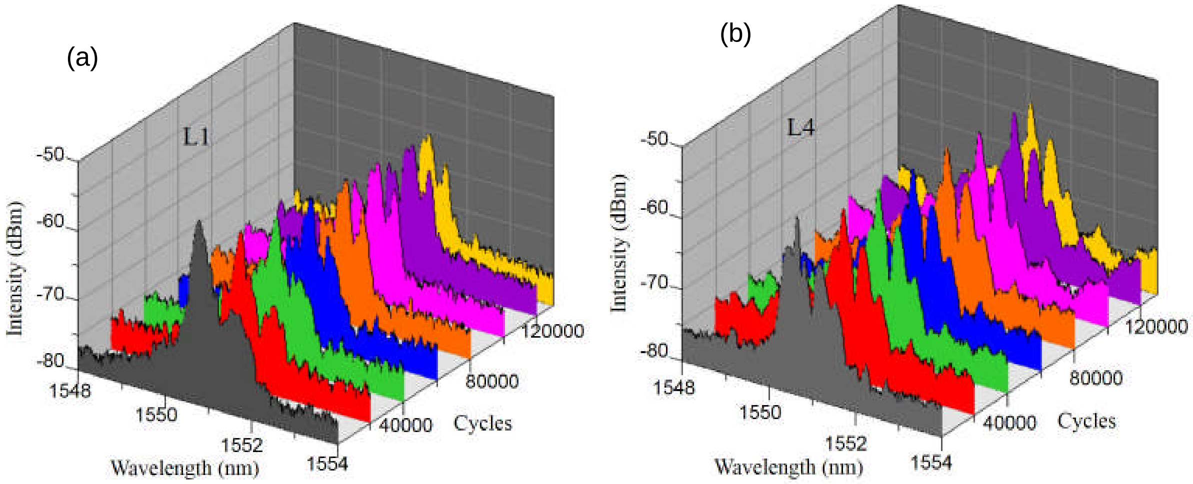

Figure 5. Development of spectrum with fatigue cycling after an initial impact. (a) L1; (b) L4.

4.3. *Effect of Pre-impact hygrothermal treatment on Post-impact fatigue behavior*

Figure 6 shows the evolution of the reflected spectra when the virgin specimen was subjected to 60°C under 95% relative humidity for 72 hours before suffering the impact. The hygrothermal treatment shifted the reflected spectra to the longer wavelength direction without changing the shape of the waveform. On cooling down to room temperature, the reflected spectra shifted back towards shorter wavelength but it did not regain the original position, indicating that the specimen was under a tensile strain presumably caused by swelling due to the absorbed moisture. When the specimen was then subjected to impact

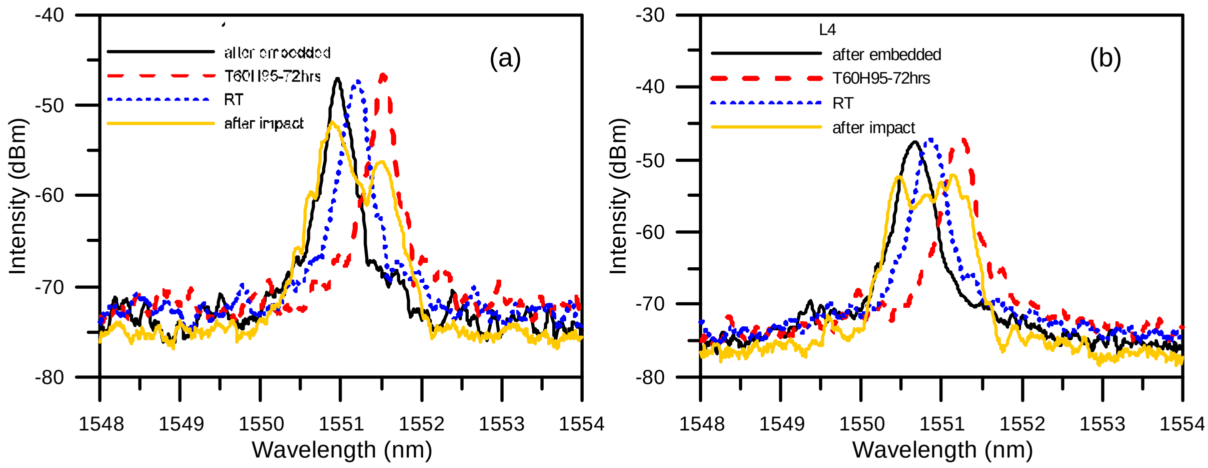

Figure 6. Development of the spectra with an initial 60°C 95% humidity treatment for 72hrs followed by impact. (a) L1; (b) L4.

damage, the reflected peaks split heavily into a number of distinct peaks. The above evolution of spectra applies to FBG spectra from both the L1 and L4 fibers.

The specimen was then subjected cyclic loading. Figure 7 shows the development of the spectra with the loading cycles. During the initial 10000 cycles, the reflected peaks intensity dropped substantially and the background intensity rose in both L1 and L4 spectra. After 10000 cycles, the peaks intensity practically disappeared in the L1 spectra. In the L4 spectra, the drop in the major peak was accompanied by a rise in the background peaks and the spectrum became heavily split after about 40000 cycles.

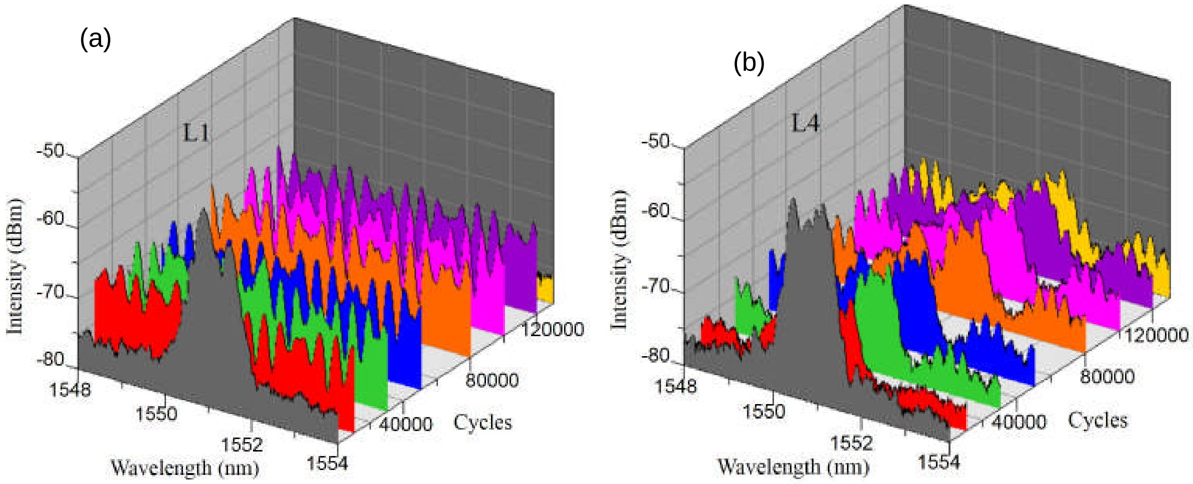

Figure 7. Spectrum evolution with cycle for specimen. (a) L1; (b) L4.

In Reference 12, it has been shown that the rise in background intensity and submersion of reflection peak signifies the spread of impact damages to the vicinity of the FBG. The occurrence of the above phenomena in the first 10,000 cycles of the fatigue loading in contrast to the absence of such phenomena beyond 130,000 cycles in the impact-fatigue of as fabricated specimens suggests that the hygrothermal exposure before impact has significantly weakened the material. This weakening is not strongly reflected in the lost in tensile strength, but is very prominently reflected in the development in the FBG spectra. As a result, embedded FBG sensors provide a powerful tool for monitoring whether a composite material has been affected by hygrothermal damage.

5. Conclusions

Hygrothermal treatment at 60°C and 95% relative humidity for 72 hours decreased the tensile strength of a quasi-isotropic carbon fiber epoxy laminate by about 7%. By monitoring the disappearance of FBG reflected peak which indicates spread of impact damage, the hydrothermally treated specimen showed peak disappearance within about 10,000cycles. This is in contrast to the maintenance of well defined peaks beyond 130,000cycles in the untreated specimen.

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