Response Fibre Bragg Grating (FBG) strain sensors embedded at different locations through the thickness around a delamination in a composite laminate

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ABSTRACT

A few FBG strain sensors were embedded at a vicinity of delamination of a laminated composite plate. Reflected spectra of FBG sensors which located in the same layer as the delamination and one layer above the delamination were investigated in order to understand the change of the reflected spectra due to stress concentrations at the delamination. The reflected waveforms of sensors were broadened with the increase of loading, as expected. A considerable difference in the response of two sensors was observed during both uniaxial and flexural loading. These differences show that the FBG sensors are capable of capturing the precise nature of the delamination under various loading conditions. Further, these observations provide evidence of the feasibility of using FBG sensor responses obtained from various locations allows the location of the delamination to be determined. This paper details some new and interesting findings of the use of spectral shapes and strain measurements from embedded FBG sensors in damage detection.

KEYWORDS

composite structures, structural health monitoring, FBG sensors, delamination

1. INTRODUCTION

Over the past few decades, advanced fibre composite materials have revolutionized the fields of aerospace, marine, energy and civil infrastructure industries. The expansion of composites in the industry is facing new challenges due to imposed standards in the field. Advanced fibre composites structures which are being used in defense, aerospace and civil infrastructures, suffer harsh static and dynamic loading that will degrade material properties and cause disintegration of the structure and catastrophic failures over time. As such there exists a growing demand for reliable and an accurate structural health monitoring (SHM) systems to maintain the structural integrity and extended life-span of these expensive and critical advanced composite structures.

There are many non-destructive test procedures available for damage detection of composite structures which are, unfortunately, not possible to use as in situ monitoring of structural health and integrity. Recent advances in fibre optic sensor technologies, on the other hand, have provided great opportunities to develop more sophisticated in-situ SHM systems [1-3]. These structural health monitoring systems principally monitor static and dynamic responses of structures in order to detect damages and estimation of residual life. The embedded FBG sensors are therefore excellent candidates for measuring internal structural responses of composite structures. There has been a substantial amount of research work done on the use of FBG sensors in damage detection and structural health monitoring using FBG sensors and some of the selected important works are listed in the reference 4-15. The key objective of the majority of the work has been on the investigation of FBG response, including modification of the grating spectra observed with reflected or transmitted light. Many researchers have been attempting to establish relationships between modification of FBG spectra and the damage type. A noteworthy work on quantification of damage has been performed by Okabe et.al [4] Mizutani et.al [5] and Ussorio et al. [8].

Embedded FBG sensors are readily providing the information about the strain distribution around the embedded location such as strain variations along the grating. These FBG sensor spectra and the strain measurements can be translated to describe the damage condition at the location up to a reasonably reliable level. These predictions are only true if the damage is following a known path. As such, over the long-term, the proposed models may provide an approximate estimate of the damage at the embedded location. On the other hand, if the FBG sensor failed prematurely during the operational life of the structure, there is no guarantee that any FBG located in a different place of the structure could be used to provide, or extract, information on the damage at the failed FBG location. In order to overcome these problems, higher spatial resolution can be obtained using more FBG sensors at different locations of the structure and this should be investigated under various loading conditions. In addition a detailed knowledge on the change of FBG spectral shape due to the geometry of the damage is warranted for reliable SHM procedures which depend on embedded FBG sensors outputs.

At present the majority of research work on embedded FBG sensors is leaning towards the modeling of FBG spectrums using "coupled mode" and "inverse scattering" theories. Unfortunately, the use of re-constructed spectrums for structural integrity prediction has some limitations due to the wide range of parameters associated in the FBG spectra. In other words a FBG spectra is not unique to a particular damage situation. As such, further investigations in to the behaviour of FBG sensor spectrums at damage locations are critical in order to develop a significant global knowledge to predict the damage status inside a structure. However, re-constructed spectrums would be an important input for an accurate structural health/integrity prediction process. This paper provides new data and additional insight to further develop SHM systems for composite structures.

2. RELATIONSHIP BETWEEN STRAIN AND THE SPECTRAL WAVELENGTH

The grating is a region which has a periodically varying refractive index reflects only a narrow band of light wave corresponding to Bragg wavelength, λ_B, which corresponds to period of gratin Λ_0 as [3,4]:

$$\lambda_B = \frac{2n_0\Lambda_0}{k} \qquad (1)$$

Where k is the order of the grating and n_0 is the refractive index of the core material. Due to an axial strain, ε, there is a change in wavelength, grating pitch and the refractive index and therefore following relationship can be obtained [Ref. 3,4 for details]:

$$\frac{\Delta\lambda_B}{\lambda_B} = p_e\,\varepsilon \qquad (3)$$

where, p_e is the equivalent strain optic coefficient which is a function of refractive index strain optic coefficient in axial and transverse directions.

3. EXPERIMENTAL PROCEDURE

A [0/(0/90)/(90/0)/0] glass/epoxy laminated plate was prepared. Nuplex 460g uniaxial and 450g 0/90 biaxials and Kinetix Thixotropic Epoxy resin were used for laminate construction. During the fabrication of the laminated plate, two pieces of baking paper were placed between a uni axial layer and a biaxial layer as shown in the Figure 1 in order to create the areas of delamination. A FBG sensor grating at centre wavelength 1538 nm was embedded closer to the delamination on the middle biaxial layer and another FBG was embedded on the top side of adjoining uniaxial layer (00) layer as shown in the Figure 1. Two sensors were aligned with 0 uniaxial layers. The plate was cured at controlled room temperature before being cut into the final shape using a water cooled diamond saw.

Figure 1

The plate was then loaded on a four point flexural test rig up to 2.5 kN in steps of 0.5kN. The FBG sensor readings and the reflected wave spectrum were then recorded using MICRON OPTICS fm 125 Optical Spectrum Analyser (OSA). In rder to locate FBG2 sensor in the compression side the loading side of the sample was changed after completing one loading regime with FBG2 on the tension side. Subsequently, the sample plate was loaded uni-axially up to 10kN in steps of 1 kN. The reflected FBG spectra and the strain readings were recorded. The samples cut from the test laminate were evaluated to establish the mechanical properties of the laminate. These tests were performed on an MTS 100kN servo-hydraulic universal testing machine.

4. RESULTS AND DISCUSSION

Figure 2 shows the spectrums of FBG1 under uni-axial loading. In the case of uni-axial loading, the sensor FBG1 which was embedded in the middle layer, shows widening of the spectra and multiple peaks as anticipated.

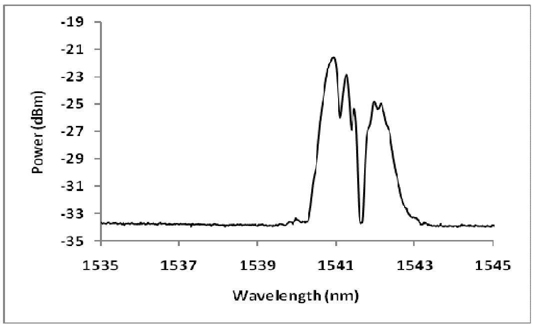

Figure 2 FBG 1 @ 8 kN Uni-axial load

However, FBG1 spectra did not exhibit significant scattered peaks that usually expected from FBGs located in cross ply layers. This disparity may be an indication of comparatively low transverse crack density around the delamination at the low load levels. The broadening of the spectra is accompanied by a drop in intensity is anticipated as the increased load levels are chirping the grating. However, FBG2 which was located on the topside of the uni-axial layer exhibited packed scattered peaks with the increased load levels as shown in Figure 3.

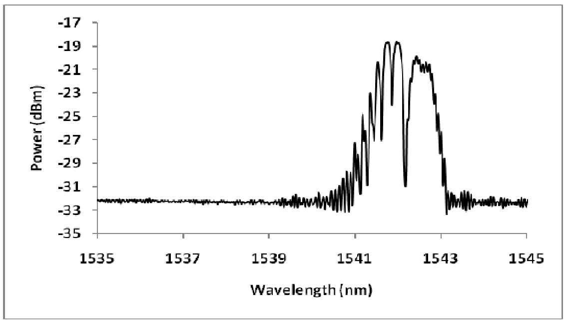

Figure 3 FBG 2 @ 8 kN Uni-axial load

This observation shows a non uniform strain distribution on the area above the delamination. As shown its clear one half of the grating is experiencing more strain than the other so half is stretch in period enough to create two reflections next to each other (dip in the middle). The linear variation of strain along the grating will increase the grating bandwidth and therefore will decrease the strength of the signal.

With the increased load levels more distortion in the FBG1 spectra was expected. However it has been observed that the reflected spectra of FBG2 being distorted rapidly by the increasing load levels. This tendency indicates an increase in matrix crack density on the uni-axial layer where FBG2 was located. In contrast Fig. 4 depicts the widening of the spectra and the change of intensity of the FBG2 with the increase of load levels, indicating the uneven strain distribution at the two ends of the grating which may have caused by the delamination itself.

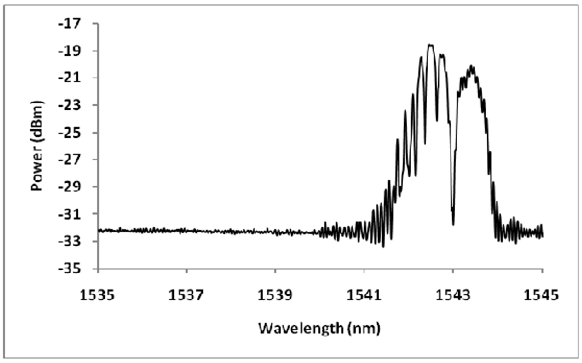

Figure 4 FBG 2 @ 10 kN Uni-axial load

It was noticed that the strains at FBG1 were considerably greater than the strains at FBG2 sensor for each loading step. This may have caused by the presence of significant strain concentrations at the vicinity of the delamination. On the other hand, it shows that more load is being carried by the uniaxial layer. Figures 5 and 6 are showing the recorded spectra of FBG2 sensor during the flexural loading of the sample. The spectra of FBG1 have not shown considerable change in its centre wavelength with the increase of load levels, as it was located in the middle layer of the plate.

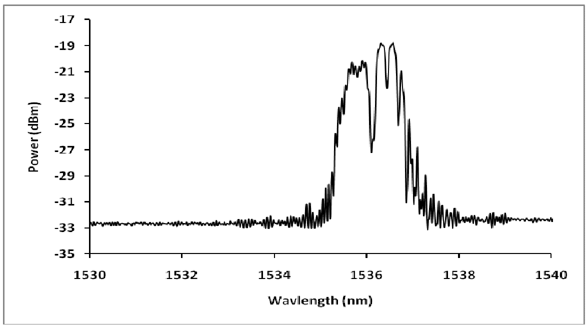

Figure 5 FBG 2 @ 300 N Flexural load in Compression

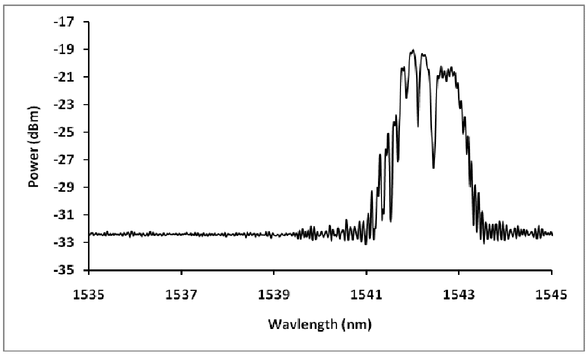

Figure 6 FBG 2 @ 300 N Flexural load in Tension

The sensor FBG2 has shown significant changes in its spectra with the increase of applied flexural loads, as anticipated. In the case of compression, the sensor FBG2 has shown some scatter in lower end of its wavelength showing some uneven strain distributions at the FBG2 grating. Interestingly, the intensity of the spectra has not shown considerable decrease of its power due to compression loading. This observation suggests that the compression loads are not broadening the grating bandwidth significantly.

5. CONCLUSION

Spectral response of the embedded FBG sensors at the vicinity of a delamination was investigated. The reflected spectra were showing stress concentrations at the FBG locations due to delamination. The FBG sensors have accurately grasped the local strain distribution at the particular layer of the composite. The spectra of FBG2 sensor which is located on the undamaged layer above the delamination displays the stress/strain concentration due to the damage below it. Similarly, if placed a FBG sensor one layer above the FBG2, there may be a strong possibility of capturing the effects of the damage two layers below it. Likewise a accurately planned and embedded FBG network on a critical section of a component will provide advanced warnings about the damage condition at the particular location. The other interesting observation made in this study is the similarities of spectral shape and the significant differences in the spectral power shown in uniaxial and flexural loading situation which was not reported in any of the previous studies.

It can be conclude that having multiple embedded FBG sensors will provide a tool to overcome the problems caused by premature failures of sensors in a SHM system, only if the sensor network is well planned and the network is trained for possible failure modes and mechanisms. As such, more detailed studies are warranted in order to quantify the damage intensity and the nature of the damage.

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