RESPONSE OF A FBG SENSOR TO MATRIX CRACK DEVELOPMENT

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ABSTRACT

The response of an optical fibre Bragg grating sensor to the development of a single transverse matrix crack in a simple GFRP cross-ply laminate has been studied. The sensors were embedded in one longitudinal ply of a simple cross-ply laminate, close to the interface between the longitudinal ply and the middle transverse ply. The light spectra reflected by the Bragg gratings were recorded and observed in quasi-static tensile tests carried out on the composite coupons before and after the development of the crack. The results show that there is no change in the position of the peak in the reflected spectrum, but that side bands develop on the long wavelength side of the spectrum. This is in agreement, qualitatively, with the strain distribution developed in the longitudinal ply in the vicinity of a transverse ply crack.

Keywords: Bragg grating, optical fibre sensor, cross-ply laminate, matrix crack

1. INTRODUCTION

Multidirectional laminates of polymer composite materials are often characterised by a first ply failure consisting of matrix cracks developing parallel to reinforcing fibres in off-axis plies. This damage is typically very difficult to detect, since it generally occurs at internal locations of laminates. However, off-axis matrix cracks induce a degradation in the mechanical properties of the material, which may prove unacceptable in many applications. The use of fibre optical sensors (FOS) for monitoring the health of composite material structures has gained increasing attention from researchers in recent years [1]. Besides strain detection and temperature measurement, the use of FOS has recently extended to other functions, such as damage detection [2]. One of the most widely studied types of FOS at present is based on the optical fibre Bragg grating (FBG), which allows sensors of high sensitivity to be manufactured [3] and the use of FBG sensors in several different applications has been demonstrated. For instance, the description of vibration modes in structures has been achieved [4], as well as monitoring of polymer curing process advancement [5]. With regard to the detection of damage occurring in composites, studies have been carried out to demonstrate the capabilities of these sensors to detect different types of damage [6-9]. In particular, it has been shown [6] that the onset and development of matrix cracks at a location next to the FBG sensor in cross-ply laminates affects the characteristics of the sensor optical output and that the use of a chirped FBG can identify the location of matrix cracking [10].

In this work, the response of an optical fibre Bragg grating (FBG) sensor to the development of a single transverse matrix crack in a GFRP cross-ply laminate has been investigated. Quasi-static tensile tests were carried out using transparent cross-ply composite specimens Comparison of the FBG reflected spectra before and after the development of a crack enabled the response of the sensor output to the development of a single crack to be determined.

2. EXPERIMENTAL

The composite material used in the present study was a continuous E-glass fibre-reinforced epoxy resin cross-ply laminate, whose lay-up was ($0/90_5/0$). The thickness of a single ply was 0.5mm, with a total laminate thickness of 3.5mm. A single 10mm long Bragg grating was written in the core of separate lengths of a commercial single mode optical fibre typically used for communication applications. Optical fibres were acrylate-coated over the whole length, except for a short length of approximately 40mm within which the Bragg grating was written. GFRP cross-ply tensile specimens have been manufactured, each containing a single optical FBG sensor embedded within one 0° ply as close as possible to one 0/90 interface. In Figure 1 a schematic diagram is shown of the composite laminate with the embedded FBG sensor. Before embedment, the optical fibres were given an additional silicone rubber coating layer over the length near the composite specimen ends. This helps to prevent the optical fibre from breaking at these locations during laminate fabrication and handling of the specimens. Details of laminate fabrication can be found elsewhere [11].

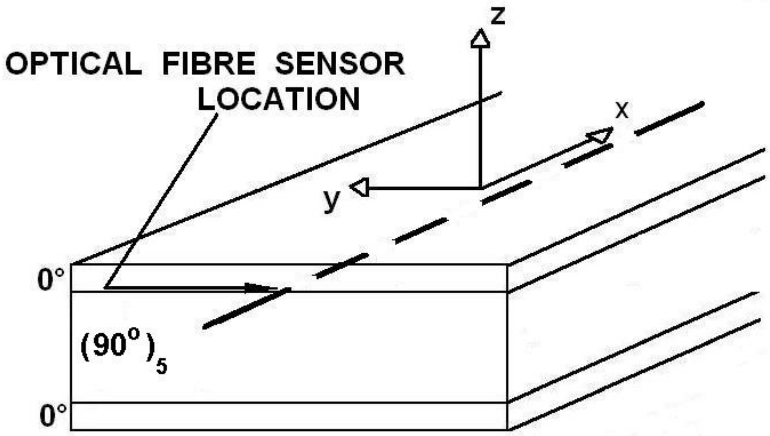

Figure 1. Diagram showing the FBG sensor location in the GFRP cross-ply laminate.

FBG sensors were operated by connecting the input end of the optical fibres to an Amplified Spontaneous Emission (ASE) broadband light source, while the other fibre end was contained in a refractive index-matching liquid (commercial paraffin); the latter operation eliminates unwanted light reflections at the fibre end. A schematic of the arrangement is shown in Figure 2.

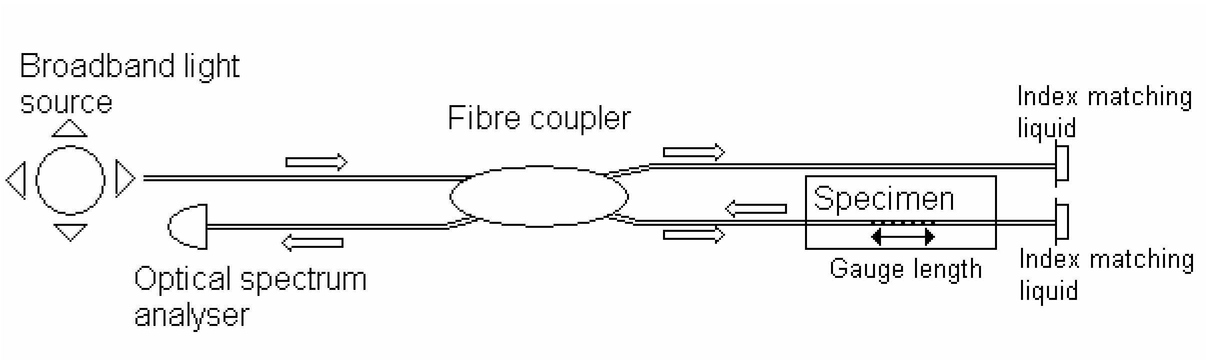

Figure 2. Schematic of the FBG sensor arrangement

Analysis of the optical response of the FBG sensor was carried out by observation of the spectrum of the light back-reflected by the grating using a computer-controlled Optical Spectrum Analyser (OSA).

Quasi-static tensile tests before cracking were carried out by applying unidirectional tensile strain to the undamaged specimens in discrete, increasing steps. Records of the FBG reflected spectra were taken under the different load levels. This allowed the evaluation of the sensor response to increasing values of the applied strain in terms of its peak wavelength shift and reflected spectrum shape for undamaged material. In order to characterise the sensor output with a matrix crack, a single crack was grown slowly in the transverse ply of the coupons by manually initiating the damage with a scalpel blade and subjecting the specimens to fatigue cycles with a peak strain of 0.15% and an R-value of 0.1 at a frequency of 5Hz. The transverse crack was initiated at a position along the specimen length within the length of the Bragg grating, so that crack growth took place in a transverse plane adjacent to the sensor location. Crack growth was interrupted at an intermediate stage when the crack tip had not yet reached the sensor position, as shown in the diagram in Figure 3, and the FBG reflected spectra was again recorded at several values of increasing strain.

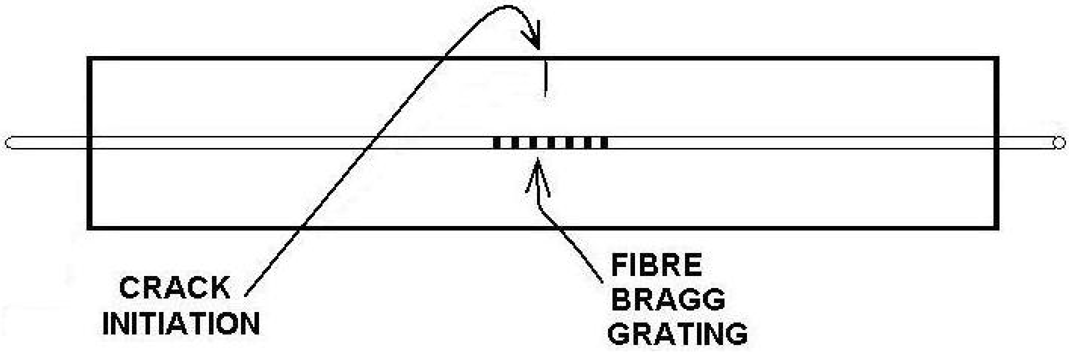

Figure 3. Schematic diagram showing the position of the part-grown matrix crack in relation to the location of the FBG sensor.

Fatigue cycling was then continued, allowing the crack to grow past the sensor location and to the other edge of the coupon, at which point further spectra were recorded.

3. RESULTS AND DISCUSSION

As described above, the spectra reflected by the FBG sensors were recorded for different discrete values of the longitudinal strain applied to the host material in quasi-static unidirectional tensile tests. The effect of increasing values of strain was to shift the peak wavelength along the wavelength axis, while keeping the symmetrical shape of the reflected spectrum unchanged. This is shown in Figure 3, which shows that the reflected spectrum is shifted to higher wavelengths with increasing strain, as expected.

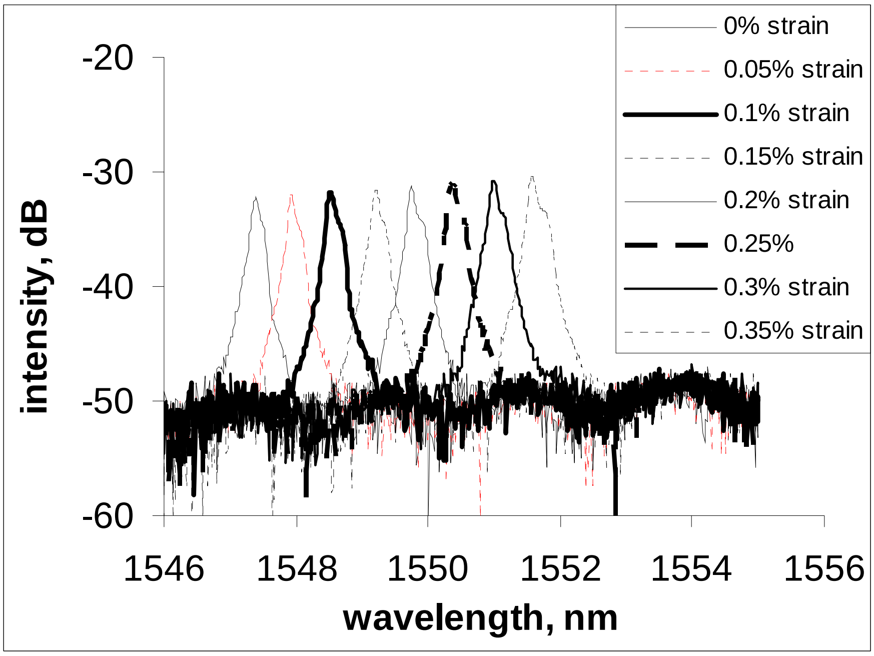

Figure 4. FBG reflected spectra are shifted to higher wavelengths at increasing strains for the undamaged GFRP material.

Subsequently, a transverse ply crack was grown from the left-hand edge of the coupon across about one quarter of the width of the coupon. The transparency of the glass/epoxy composites used in these experiments allowed the crack growth to be followed visually and digital pictures of the crack at subsequent stages to be taken. Figure 5 shows the cross-ply coupon together with the extensometer used for strain measurement.

At the stage shown in Figure 5, when the crack had not reached the sensor location, the strain experienced by the optical fibre was not influenced by the presence of the crack. This is shown in Figure 6, which shows the FBG reflected spectra at increasing values of applied strain.

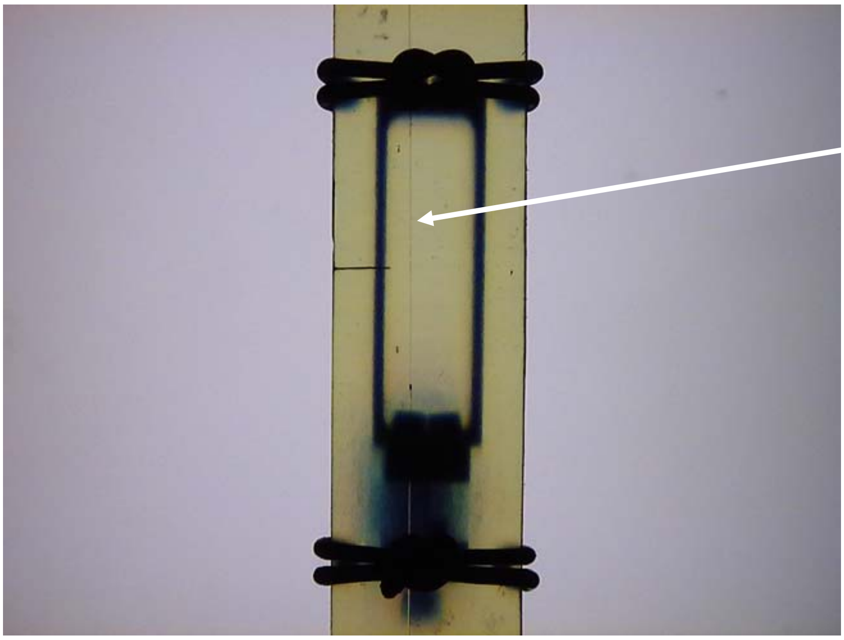

Figure 5. Specimen with a matrix crack which has grown has grown partly across the coupon, but has not yet passed the FBG sensor (the position of the sensor is indicated by the arrow).

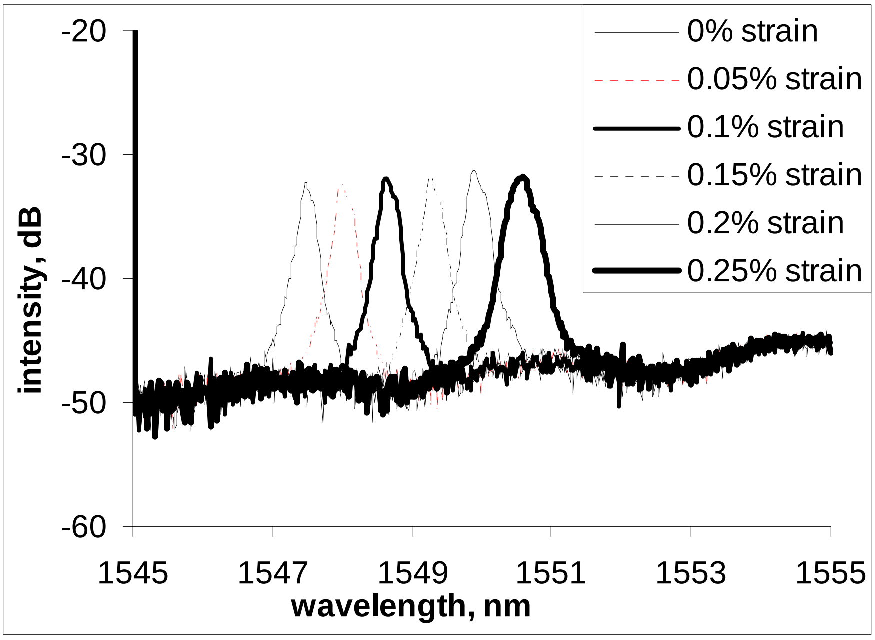

Figure 6. Plot of FBG reflected spectra at increasing strains for the part-grown crack of Figure 5.

Further fatigue growth of the crack growth of the damage led the crack to extend over the whole width of the coupon, as shown in Figure 7. In this condition, the crack passed the location of the sensor and hence altered the reflected spectra, which are shown in Figure 8.

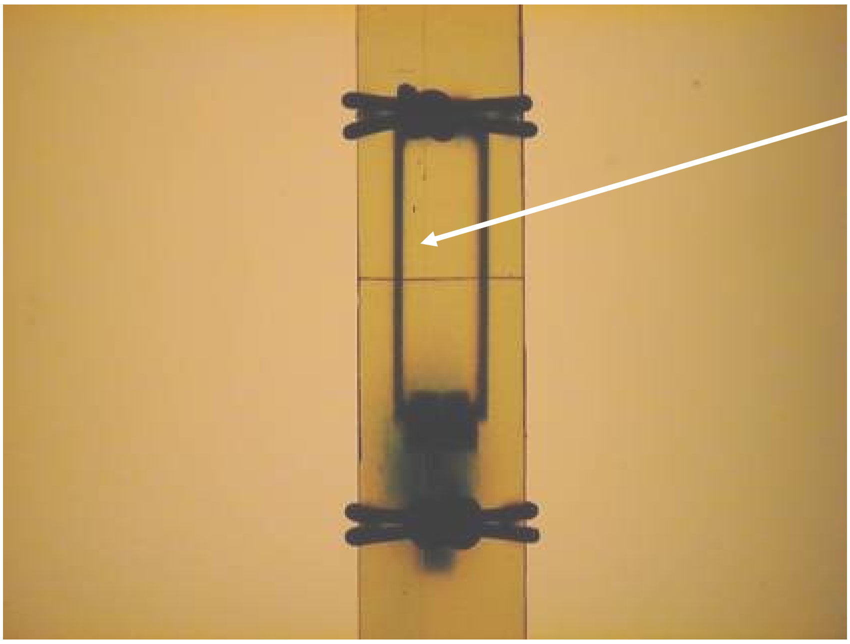

Figure 7. Image showing a GFRP cross-ply specimen during a tensile test. A matrix crack has grown fully across the coupon and has passed the FBG sensor (the position of the sensor is indicated by the arrow).

When the crack extends across the transverse ply, and hence passes the FBG sensor which is located in the adjacent 0° ply, the reflected spectrum becomes an asymmetrical bell-shape, skewed toward the long wavelength side of the main peak, as shown in Figure 8. Side peaks of weaker intensity with respect to the main peak of the spectrum are also present on the longer wavelength side of the spectrum. The skewed shape of the reflected spectrum, on the longer wavelength side, is related to the higher strains in the 0° ply due to the presence of the transverse ply crack. The position of the main peak of the spectrum, however, which is generated by the regions of the FBG sensor at some distance from the crack plane, is unchanged by the crack development. Figure 9 shows the shift undergone by the main peak for increasing tensile strains for the different situations of (i) undamaged material, (ii) part-grown transverse ply crack and (iii) fully grown crack. There is no significant difference in the shift of the main peak, in agreement with the suggestion that the main peak represents reflections from parts of the FBG at a sufficient distance from the crack plane that the longitudinal strain in these portions of the grating is the same as the strain seen in the uncracked parts of the coupon. The reflected spectra for the single cracks look quite similar to the spectra obtained by Okabe and colleagues [6] in work on $[0_2/90_4/0_2]$ cross-ply CFRP laminates. The spectra shown in reference [6] at low transverse ply crack densities (up to $6cm^{-1}$) also appear to be skewed to the long wavelength side, with additional peaks on that side of the spectrum.

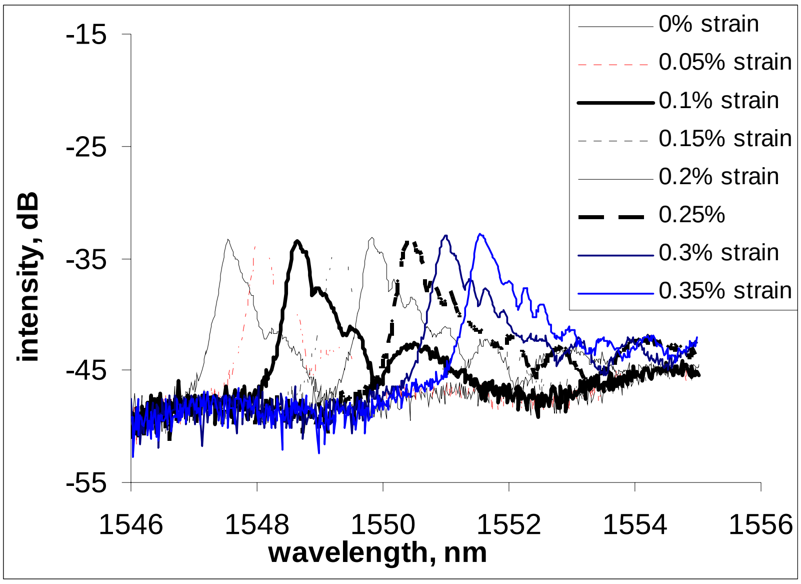

Figure 8. Plot of FBG reflected spectra at increasing strains for fully grown crack.

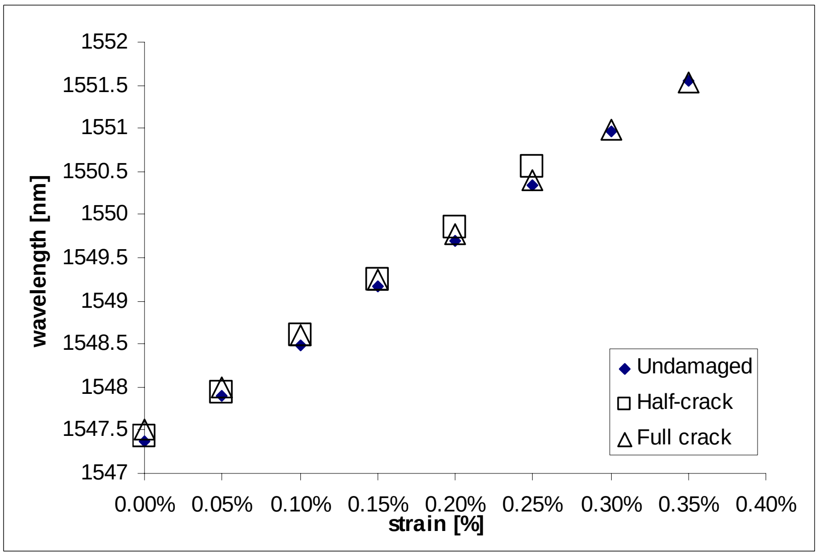

Figure 9. Plot of the strain-optic response of an FBG sensor in the three experimental conditions examined.

4. CONCLUSIONS

The reflected spectrum from a fibre Bragg grating sensor embedded in the 0^0 ply of a cross-ply GFRP laminate has been investigated in quasi-static tensile tests on undamaged coupons and on coupons containing a single transverse matrix crack. The spectrum shape in undamaged coupons, and in coupons where the crack had grown across the width of the specimen but had not yet passed the sensor, possessed a single peak and a symmetrical shape. However, when the crack grew past the sensor location, the reflected spectra were characterised by a main peak, unchanged in position compared to the undamaged material, with an asymmetrical bell-shape spectrum, skewed toward the longer wavelength side of the main peak of the reflected spectrum, with secondary peaks on the longer wavelength side of the main peak. This is consistent with a qualitative explanation of the form of the reflected spectrum which interprets the additional features on the longer wavelength side as due to the enhanced strain in the 0° ply due to the transverse ply crack.

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