Use of conventional and chirped optical fibre Bragg gratings to detect matrix cracking damage in composite materials

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Abstract. A comparison is made between conventional (i.e. uniform) and chirped optical fibre Bragg gratings (FBGs) for the detection of matrix cracking damage in composite materials. Matrix cracking damage is generally the first type of visible damage to develop under load in the off-axis plies of laminated composites and is generally the precursor of more serious damage mechanisms, particularly delamination. The detection of this type of damage is thus important, particularly in aerospace applications. Using a uniform FBG, characteristic changes develop in the reflected spectrum which can be used to identify crack development in the composite. The additional advantage of using a chirped grating is that the crack position can also be located.

1. Introduction
Matrix cracking is a generic type of damage in composite materials which occurs in many fibre architectures, including laminated composites with off-axis plies fabricated from unidirectional pre-preg material and textile reinforced composites [1,2]. In many composite systems, matrix cracks running parallel to the fibre direction in the off-axis plies are the precursor to more serious types of damage, particularly delamination. Hence in some applications, and particularly in aerospace, a structural health monitoring system would be beneficial which not only monitors strain, but also detects and, if possible, locates damage.

There has recently been a general increase in interest in using optical sensors for monitoring the behaviour of composite structures [3,4,5]. Of the various optical fibre sensors which are available, the uniform FBG is now the most widely used, being employed for various functions including point strain measurements and damage detection [6,7,8,9,10]

In addition to uniform fibre Bragg gratings, chirped fibre Bragg gratings (CFBGs) are also now being considered for damage detection. The operation of a uniform FBG is well known [11]. A uniform spacing of the periodic variation of refractive index in the core of the fibre (the “grating”) reflects light so that the reflected light is centred on a particular wavelength related to that period (figure 1(a)). A change in the grating period due to a uniform strain produces a proportional shift in the peak wavelength of the reflected spectrum. By contrast, a chirped fibre Bragg grating has a variation of the grating period and reflects a range of wavelengths. For example, a chirped grating with a linear variation of the grating period reflects a spectral band of wavelengths related to the effective range of

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grating periods over the grating length (figure 1(b)). When unloaded, or when subjected to a uniform strain field, such a chirped grating reflects the spectral band with approximately uniform intensity. Such chirped gratings have potential uses in monitoring wear and damage in composite materials and structures [12,13].

In this paper, a direct comparison of the response of uniform and chirped FBG sensors to the development of transverse cracks in transparent cross-ply GFRP coupons is presented.

![Figure 1](image)

Figure 1. Schematic grating period and reflection spectra of (a) uniform FBG, and (b) CFBG.

2. Experiment

2.1 Materials

The composite material used in the present study was a continuous E-glass fibre-reinforced epoxy resin cross-ply laminate, with the lay-up (0/90/0/90). The thickness of a single ply was 0.5 mm, with a total laminate thickness of 3 mm. Uniform FBGs 10 mm in length and CFBGs 30 mm in length were 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 to be embedded in the composite laminate, except the small length within which the Bragg grating was contained. GFRP cross-ply tensile specimens were manufactured, each containing a single optical FBG sensor embedded within one 0° ply as close as possible to the 0/90 interface. In figure 2, a schematic diagram is shown of the composite laminate with the embedded FBG sensor at the 0/90 interface and crack development in the transverse (i.e. 90°) ply. The production of the laminate involves several steps. A dry preform was first produced by winding a 600 TEX glass fibre onto a square steel frame. The middle 90° ply fibers were wound twice to obtain the 90° layer whose thickness was 2 mm. The frame was then rotated through 90°, the sensors glued to two thin Perspex strips which were then bolted to the frame, and the 0° ply fibers were finally wound to form the two outer longitudinal plies. Before embedding the optical fibres in the composite, the fibres were given an additional silicone rubber coating over the length near the composite specimen ends. This prevented fibre breakage at these locations during fabrication and handling of the specimens. A liquid impregnation process was used to introduce the epoxy resin whose composition by weight was 100 parts of Bisplenol A Epichlorohydrin resin 300, 60 parts of MNA hardener and 4 parts of Ancamine K61B catalyst. The impregnation process consists of two stages: liquid resin is first introduced manually over the reinforcement stack and then followed by a vacuum stage, aimed at removing the air bubbles in the laminate. The laminate was cured for 3 hours at a temperature of 100°C and a pressure of 100 kPA. Coupon specimens with dimensions 220 mm x 20 mm containing the sensors
were cut from the laminates and aluminium end tabs, length 20 mm, were bonded to the specimens using 3M Scotch-Weld epoxy structural adhesive (Figure 3).

Figure 2. Location of FBG sensor in GFRP crossply laminate within 0-ply, at 0/90 interface.

Figure 3. Schematic of a specimen containing a sensor.

2. 2. Setup and Procedure
A schematic diagram of the optical arrangement is shown in figure 4. The FBG system consists of a broadband light source, coupler, optical spectrum analyzer (OSA) and refractive index matching liquid, which was used to eliminate the unwanted light reflections at the fibre ends.

Quasi-static tensile load was applied to the specimen by an Instron computer-controlled servo-hydraulic testing machine at room temperature in a temperature controlled laboratory. The tensile strain was measured with a 50 mm gauge length extensometer attached to the surface of the coupon. The tensile tests were carried out by loading and unloading the specimens to increasing values of applied strain, with reflection spectra obtained for coupons both unloaded and at various values of applied strain.

Figure 4. Diagram of the optical arrangement

In order to characterise the sensor output when a transverse ply crack had developed in a coupon, a single crack was grown slowly in the transverse ply by manually initiating the crack at the coupon edge with a scalpel blade. The coupon was then subjected to fatigue cycles with a peak strain of 0.15%, an R-value of 0.1, and a frequency of 5Hz. Fatigue cycling was continued until the crack grew past the sensor location and across the full width of the coupon.

3. Results and Discussion

3. 1. Uniform FBG
The reflection spectra at various longitudinal strains were recorded in order to investigate the response of the uniform FBG sensors to strain for an undamaged coupon and for a coupon containing a
single crack in the 90-ply. Figure 5 shows an example of the reflected spectra for the undamaged coupon when unloaded and when subjected to 0.3% applied strain. As expected, the peak reflected wavelength is shifted to higher values in proportion to the applied strain. Figure 6 shows similar results for the coupon containing a single transverse ply crack. In this case, the peak in the spectrum behaves as before, but the reflected spectrum is asymmetrical at all strains and skewed towards the long wavelength side of the main peak. One or more distinct side peaks appear on the long wavelength side of the spectrum at higher strains.

![Figure 5. Reflected spectra of the undamaged specimen from uniform FBG at 0% and 0.30% strain, showing the shift in the peak wavelength.](image)

![Figure 6. Reflected spectra for a coupon containing a single crack adjacent to the uniform FBG at 0% and 0.30% applied strain.](image)

The reason for the skewing of the spectra and the development of side-band peaks is as follows. The presence of a transverse ply crack locally releases the residual thermal compressive stress in the 0º ply which was locked in during laminate fabrication. Consequently, there is an enhanced strain in the 0º ply close to plane of the crack, and reflections occur from here at higher wavelengths, producing a skewing of the spectrum. This effect is accentuated when a strain is applied to the composite, since the 0º plies see an enhanced local strain in the plane of the crack because the transverse ply crack has lost its ability to carry load across the crack plane. These strain changes due to cracking are localized and occur typically over lengths of about one transverse ply thickness on either side of the crack [14], in this case over a length of about 4 mm of the Bragg grating. For the remaining 6 mm of the Bragg grating, the grating period is undisturbed by the strain field surrounding the crack and hence the peak reflected wavelength from this length of the grating is shifted to a higher wavelength with increasing strain, as in the uncracked coupon.

3. 2.  Chirped FBG (CFBG)

The experimental procedures for testing the response of the CFBG to a transverse ply crack were the same as for the uniform FBG. Reflection spectra measured during loading at various increasing strains were recorded for the damaged and undamaged coupons. Figure 7 shows the reflected spectra of an undamaged specimen both unloaded and at 0.30% applied strain. The reflection spectra are shifted uniformly to higher wavelengths in proportion to the strain, as expected. A uniform strain increases the period of the chirped grating along the grating length, thereby shifting the reflected Bragg wavelength to higher values for all locations along the grating.

Changes occur in the reflection spectra when a transverse ply crack is present which are characteristic of the interaction between the strain field of the crack and the CFBG (figure 8), and these changes also correspond to the position of the crack. A reduction in the intensity of the reflected signal from the CFBG occurs as the crack is approached from the low wavelength end of the CFBG, followed by a rise and then a fall to the undisturbed value, with these changes corresponding to a length of about 4 mm overall. Away from the crack, the strain field in the composite is undisturbed, so that the reflected spectrum retains its undisturbed shape. As the crack position is approached,
additional strains in the 0° ply associated with the crack disrupt the linear increase of the pitch length of the chirped grating, causing the pitch length to change unevenly. The relationship between the strain field and the variation in intensity of the spectrum is complex, but essentially the loss of particular pitch lengths due to local strains gives causes a fall in intensity of the reflection spectrum at particular wavelengths and a corresponding increase in intensity at other wavelengths.

Figure 7. Reflected spectra of the undamaged specimen from a CFBG at 0 % and 0.30 % strain.

Figure 8. Reflected spectra of the undamaged specimen and the same specimen with a transverse ply crack. The coupon is unloaded.

Figure 9 shows the reflection spectrum of an unloaded coupon containing two transverse ply cracks located at 5 mm and 20 mm from the low wavelength end of a CFBG having a length of 30 mm. The positions of the changes in the reflection spectrum agree with the location of the cracks; the crack positions can be measured easily due the transparency of the GFRP laminate.

Figure 9. Reflected spectra from an unloaded coupon containing two cracks located at 5 mm and 20 mm from the low wavelength end of the CFBG.

4. Conclusions

Uniform and chirped FBG sensors have been embedded within the 0° ply of transparent cross-ply GFRP composite coupons and changes to the reflected spectra as a function of strain and crack development have been studied. In the case of a uniform FBG, the spectra of undamaged material have a single peak and a symmetrical shape. After the formation of a crack, the spectra become skewed in shape, with a broadening of the spectra on the higher wavelength side. Secondary peaks in the spectrum on the higher wavelength side become more prominent with increasing applied strain. For the chirped FBG, a spectral band of wavelengths is reflected which is shifted uniformly to higher wavelength values for undamaged composites. For coupons containing a crack, a CFBG shows a characteristic variation of the intensity of the reflected spectrum at the position of the crack, enabling both crack development and crack position to be identified. The changes in the spectra of both types of FBG are due to enhanced local strains in the 0° ply due to the development of a crack in the transverse ply.
5. References

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