Abstract

Chirped fibre Bragg grating (CFBG) sensors have been embedded within the adhesive bondline of single-lap bonded composite joints, fabricated using a transparent glass fibre reinforced plastic (GFRP) adherend bonded to a carbon fibre reinforced plastic (CFRP) adherend. During fatigue cycling, disbonds initiated adjacent to the cut ends of one, or both, of the adherends and the disbonds propagated with continued fatigue cycling. The results show that the CFBG sensor within the bondline can detect the initiation of the disbond and can also monitor the position of the disbond front as it propagates during fatigue cycling. As the disbond front propagated, there was reasonable agreement between the measurements of the position of the disbond front using the CFBG sensor spectra and photographic measurements of the location of the disbond front taken through the transparent GFRP adherend. This method of monitoring disbonding (with the sensor embedded in the adhesive bondline) could be used to monitor bonded composite structures when it is difficult to embed the sensors within the adherends themselves.

1. Introduction

Chirped fibre Bragg grating (CFBG) sensors are being used in an increasing variety of applications, from the measurement of physical parameters such as temperature and strain [e.g. 1-5] to damage monitoring in composite materials and adhesively bonded composite joints [6-12]. Adhesive bonding of composite structures is an attractive alternative to mechanical fasteners because the stresses are distributed over the entire bond area and bonded structures generally provide a weight-saving compared to bolted structures. However, the detection of defects in a bonded joint, both after fabrication and during service, remains a major concern, particularly for joints which are in inaccessible parts of the structure. Among various non-destructive evaluation methods suggested for monitoring bonded joints [e.g. 13-19], CFBG sensors have been shown to be able to detect the initiation of disbonding in bonded composite joints and to monitor the propagation of the disbond due, for example, to cyclic loading [20-22]. In previous work, the sensor was embedded within one of the two adherends of the joint. However, in some circumstances, it may not be easy to embed the sensor within one of the adherends (for example, when adding a plate-bonded composite reinforcement to a concrete or metallic beam) in which case it would be necessary to locate the sensor within the adhesive bondline itself. In this paper, the possibility of monitoring disbonding when the CFBG sensor is embedded within the adhesive bondline is examined.
2. Experiment

2.1. Materials

The single lap joints studied in this paper are shown schematically in Figure 1. Two types of cross-ply composite laminates have been used as the adherends of the joint: glass-fibre reinforced plastic (GFRP) and carbon-fibre reinforced plastic (CFRP).

The epoxy-based GFRP laminate was fabricated using a frame-winding/resin impregnation process which has been described in detail elsewhere [e.g. 21, 22]. The ply lay-up of the transparent cross-ply GFRP coupons used as one of the adherends of the joint was [0/90/90], with a nominal ply thickness of 0.25 mm and coupon thickness of 3 mm. The CFRP laminate was made from pre-preg supplied by the Advanced Composites Group. The pre-preg consisted of high-strength 12K carbon fibre and epoxy resin MTM44-1. The nominal thickness of the pre-preg was 0.25 mm and the stacking sequence of the laminate was [0/90/0/90], with a nominal laminate thickness 2.5 mm. The CFRP laminate was manufactured using the out-of-autoclave route which has been described in detail elsewhere [23].

After fabrication, the adherends were cut from the laminates using a wet diamond saw. The approximate dimensions of the coupons were 20 mm x t x 120 mm (i.e. width x thickness x length), where the values of t, the thickness of coupon, were 3 mm and 2.5 mm for the GFRP and CFRP adherends, respectively (Figure 1). The overlap length of the joints is 60 mm and the joints were bonded with a single part, heat-curing epoxy adhesive, AV119. CFBG sensors with sensor lengths of 60 mm were embedded into the bondline during fabrication of the joints. Before embedding, the protective outer coating was removed from the optical fibre so that the thickness of the adhesive bondline in these experiments was the same as the outer diameter of the optical fibre cladding i.e. 125 μm. The high wavelength end of the sensor was positioned at the cut end of the CFRP adherend as shown in Figure 1. To prevent unnecessary bending of the joint under load, aluminium end tabs and spacers were bonded to the adherends. A schematic of the optical system, incorporating a broadband laser source and optical spectrum analyser is shown in Figure 2.

![Figure 1. Schematic of the joint geometry, where LW and HW indicate the low- and high-wavelength ends of the CFBG, respectively. All dimensions shown are in mm.](image)

2.2 Testing procedure

The joint was subjected to fatigue loading using a computer-controlled servo-hydraulic test machine (Instron 1175) with a peak load of 8 kN (equivalent to a GFRP adherend tensile stress of 121 MPa), an R-value of 0.1, and a sinusoidal waveform with a frequency of 6 Hz. As a consequence of the fatigue loading, disbonds were initiated and propagated from the cut end of the adherends. The cyclic loading was interrupted at increasing numbers of cycles in
order (a) to record the position of the growing disbond front in the lap joint using an *in-situ* digital camera (as mentioned above, the GFRP adherend was transparent), and (b) to record the reflected spectra from the CFBG sensor for different disbond lengths. Spectra were recorded with the joints unloaded.

### 3. Results and discussion

#### 3.1. The reflected spectra from the CFBG sensor prior to, and after, embedding in the bondline

Figure 3 shows the reflected spectra from the CFBG sensor both before, and after, embedding the sensor within the joint. After embedding the sensor within the adhesive bondline, the spectrum from the sensor shifts to lower wavelength values by about 0.4 nm, which indicates that there is a compressive longitudinal strain acting on the sensor embedded within the bondline compared to the (unstrained) bare sensor. This shift can be explained by comparing the thermal contraction experienced by the lap-joint when cooled from the lock-on temperature of the adhesive (taken to be the glass transition temperature of the AV119 adhesive, which is 102°C [24]) to room temperature, with the thermal strain that would be experienced by a free CFBG sensor. For this comparison to be made, the coefficient of thermal expansion (CTE) of the lap joint parallel to its length needs to be estimated, which in turn requires a knowledge of the CTEs of the CFRP and GFRP adherends of the joint.

![Figure 3. Reflected spectra from the CFBG sensor prior to, and after, embedding within the adhesive bondline](image)
The CTE of both adherends can be estimated with reasonable accuracy using an approximate one-dimensional expression. The coefficient of thermal expansion, \( \alpha \), of each cross-ply composite adherend is given by [11]

\[
\alpha = \left( \frac{t_1 E_1 \alpha_1 + t_2 E_2 \alpha_2}{E_1 t_1 + E_2 t_2} \right)
\]

Eqtn (1)

In Equation (1), \( t_1 \) and \( t_2 \) are the total thicknesses of the \( 0^0 \) plies and \( 90^0 \) plies in the adherends, and \( \alpha_1, \alpha_2, E_1, E_2 \) are the coefficients of thermal expansion and the Young’s moduli for the \( 0^0 \) plies and \( 90^0 \) plies, respectively. Using the values in Table 1 (taken from [25] and [26]), the CTEs of the CFRP and GFRP adherends are estimated to be \( 0.26 \times 10^{-6} \) K\(^{-1}\) and \( 9.7 \times 10^{-6} \) K\(^{-1}\), respectively. In the same fashion, Equation (1) can also be used to estimate the CTE of the CFRP-GFRP lap joint, ignoring (i) any bending which occurs as a consequence of the asymmetry of the joint, and (ii) any thermomechanical contribution from the thin adhesive layer. The CTE of the overlap length of the lap-joint is then found to be about \( 2.9 \times 10^{-6} \) K\(^{-1}\).

<table>
<thead>
<tr>
<th></th>
<th>CFRP</th>
<th>GFRP</th>
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<tbody>
<tr>
<td>( \alpha_1 ) (x ( 10^{-6} ) K(^{-1}))</td>
<td>-0.2(^*)</td>
<td>6.7(^*)</td>
</tr>
<tr>
<td>( \alpha_2 ) (x ( 10^{-6} ) K(^{-1}))</td>
<td>27(^*)</td>
<td>29.3(^*)</td>
</tr>
<tr>
<td>( E_1 ) (GPa)</td>
<td>124(^*)</td>
<td>42(^*)</td>
</tr>
<tr>
<td>( E_2 ) (GPa)</td>
<td>8.5(^*)</td>
<td>13(^*)</td>
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\(^*\) From reference [25]; \(^*\) From reference [26]

**Table 1.** Required thermomechanical properties of the \( 0^0 \) and \( 90^0 \) plies of the CFRP and GFRP adherends for the one-dimensional analysis

Taking the CTE of the optical fibre to be \( 0.5 \times 10^{-6} \) K\(^{-1}\) [27], and the change in temperature from the lock-on temperature of the adhesive to room temperature to be 80 K, then the calculation suggests that on cooling the joint to room temperature, the CFBG sensor is subjected to a compressive strain of about 200 \( \mu \)e. Assuming the typical strain sensitivity for CFBG gratings of this type to be approximately \( 1 \times 10^3 \) nm/\( \mu \)e [11], then this compressive strain corresponds to a predicted shift of the CFBG reflected spectrum of about 0.2 nm towards lower wavelengths. This is in reasonable agreement with the shift to lower wavelengths of about 0.4 nm shown in Figure 3.

### 3.2. Monitoring of disbonds growth

The results in this section describe the monitoring of disbonds growth using the CFBG sensor. Figure 4(a) shows the overlap length of the lap joint after 100,000 cycles, by which point a disbonds has initiated adjacent to the high-wavelength end of the sensor (see Figure 1) and is growing towards the low wavelength end. The disbonds front at the position of the sensor is marked with an arrow at “A”, and the disbonds has a length of about 4 mm. Figure 4(b) shows a comparison of reflected spectra from the CFBG sensor embedded within the adhesive
bondline of the joint before testing (i.e. 0 cycles) and after 100,000 cycles, in both cases with the joint unloaded. A dip in the spectrum, marked with the letter “a”, and a shift of the high wavelength end of the spectrum to higher wavelength values, are indications that the disbonds has developed.

After failure of the joint (following 125,270 fatigue cycles), the fracture surface was examined and it was noted that the disbonds was located at the interface between the adhesive bondline and the GFRP adherend (shown by the zigzag line in Figure 5), so that the sensor remained bonded to the CFRP adherend. This observation helps to explain the changes observed in the spectrum. When the disbonds grows adjacent to the high-wavelength end of the sensor, the locked-in compressive thermal strain in the CFRP adherend is relaxed within the disbonds region and, consequently, the grating spacings of the sensor at the high-wavelength end increase, with the result that the spectrum shifts to higher wavelengths. The dip in the spectrum at “a” is also related to the release of thermal strain. In the disbonds

![Figure 4.](image)

(a) CFRP-GFRP composite joint where the disbonds has propagated to point A; (b) comparison of reflected spectra from the CFBG sensor after 0 cycles and 100,000 cycles

region just behind the disbonds front, the grating spacings have increased in size due to the release of the thermal strain. The reflected intensity at any wavelength for the CFBG sensor is related to the number of gratings with the corresponding grating spacing. Consequently, since all the grating spacings have increased behind the disbonds front, there is a loss in intensity for those wavelengths that correspond to positions just behind the disbonds front, and a dip appears in the spectrum (a similar result has been analysed elsewhere for a GFRP/aluminium bonded joint with a sensor embedded within the GFRP adherend [11]). Ahead of the disbonds front, where the adherends are still bonded, the strain field in the bondline is not disturbed and the reflected spectrum retains its undisturbed shape.
Figures 6 and 7 show the growth of the disbond with increasing numbers of cycles. In figure 6(a), the disbond has grown to a length of about 18 mm (after 116,000 cycles), and the disbond front is now located at “B”. Matrix cracks can be seen in the transverse ply of the [0/90/90], GFRP adherend which is not surprising since the peak load in the fatigue cycle corresponds to a strain of around 0.4%, which is above the strain at which matrix crack development would be expected in these cross-ply laminates under fatigue loading [28]. Figure 6(b) shows the reflected spectrum from the sensor and it is clear that the peak in the spectrum has shifted to lower wavelength values and is now located at “b”. Similarly, after 124,000 cycles, the disbond has grown to a length of about 27 mm (“C” in Figure 7(a)) and the dip in the spectrum has shifted further towards the low-wavelength end of the spectrum (to “c” in Figure 7(b)).

As in previous work using sensors embedded within composite adherends (e.g. [22]), the reflected spectra enable the position of the disbond front to be measured using the CFBG sensor. For a CFBG sensor with a length of 60 mm, the spectral bandwidth of the reflected spectra (in this case about 19 nm) corresponds to the physical length of the sensor. As shown in previous work [21-23], the position of the perturbation in the spectrum is at approximately the same position as the position of the disbond front. For example, in Figure 7(b), where the
Previous modelling of disbonds in similar joints (e.g. [21-23]) suggest that the minimum of a dip in the spectrum has shifted to a position approximately ½ along the spectrum, this corresponds to a disbond front which has propagated about 20 mm (i.e. ½ x 60 mm) along the length of the sensor. The position of the disbond front can also be measured directly from in-situ photographs such as Figure 7(a). A comparison of the measurements of the disbond length obtained from the reflected spectra with the disbond length measured directly from photographs is shown in Figure 8 and there is reasonably good agreement between these two sets of measurements. The uncertainties shown in Figure 8 reflect the difficulty of identifying the precise position of the disbond front from the photographs and the uncertainty in defining precisely the physical position of the disbond front in relation to the dip in the spectrum. Previous modelling of disbonds in similar joints (e.g. [21-23]) suggest that the minimum of the dip in the spectrum will correspond to a physical position which is within a few millimetres of the actual position of the disbond front. For the sensor embedded within the adhesive bondline, a finite-element analysis to determine the strain at the position of the sensor is required to predict the reflected spectra, which will be a topic of future work.

Figure 7. (a) CFRP-GFRP composites joint where the disbond has extended to point C; (b) comparison of the reflected spectra from the CFBG sensor after 0 cycles and 124,000 cycles.

Figure 8. Comparison of the disbond front position from the CFBG reflected spectra and photographs.
Figure 9(a) shows a photograph of a GFRP/CFRP bonded joint after the joint had been subjected to 32,600 fatigue cycles and disbonds had initiated and propagated from both ends of the joint overlap length. Figure 9(b) shows the reflected spectra for this sensor initially, and after 32,600 fatigue cycles. Again, the dips (or perturbations) in the spectra, and shifts of the spectra at the high- and low-wavelength ends, relate to the growth of the disbonds.

Considering first the disbond front labelled “D” in Figure 9(a), the corresponding dip in the CFBG spectrum is shown at “d” in Figure 9(b). The reason for this dip is exactly the same as discussed above. For the disbond which initiated adjacent to the cut end of the GFRP adherend, i.e. adjacent to the low-wavelength end of the sensor, the perturbation (i.e. dip) in the spectrum again indicates the growth of a disbond, which can be seen at “E” in Figure 9(a) and at “e” in the reflected spectrum in Figure 9(b). For this disbond, observation of the fracture surface showed that the sensor remained bonded to the GFRP adherend and that the disbond had propagated at the adhesive/CFRP interface. The origin of the shift of the spectrum to lower wavelength values, and the perturbation at “e” in the spectrum, relate to the release of the thermal strain in the GFRP adherend when the disbond initiates and propagates. When the disbond initiates, the tensile thermal strain in the disbonded portion of the GFRP adherend is relaxed. Consequently, the grating spacings of the CFBG sensor at the low-wavelength end also relax, and hence the spectrum shifts to lower wavelength values. The dip in the spectrum is again due to the loss of some grating spacings behind the disbond front, where relaxation and contraction of the adherend has occurred.

4. Conclusions

GFRP-CFRP single lap joints have been manufactured using an elevated temperature curing adhesive, with CFBG sensors embedded within the adhesive bondline. When the GFRP-
CFRP joint cooled to room temperature, locked in thermal strains due to the mismatch in the coefficient of expansion of the GFRP and CFRP adherends made it possible to monitor the initiation and growth of disbonds (developed as a consequence of fatigue loading) without loading the joint. Disbond initiation was indicated by a shift in either the high- or low-wavelength ends of the reflected spectra and disbond propagation could be monitored by the movement of a perturbation (a dip) in the reflected spectra.

There was reasonable agreement between the position of the disbond front as indicated by the changes in the reflected spectra of the CFBG sensors with the measurements made from in-situ photographs of the disbond front position. The results demonstrate that CFBG sensors embedded within the adhesive bondline can be used to monitor disbonding in bonded composite joints.

References

[26] Advanced Composites Group Data Sheet, ACG MTM®44 MATRIX RESIN