The use of a CFBG fibre optical sensor to detect disbond development in composite/composite and metal/composite adhesively bonded joints

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Abstract

This paper describes a novel technique to monitor disbond initiation and propagation in both composite-composite and metal-composite adhesively bonded joints using chirped fibre Bragg grating (CFBG) sensors embedded within fibre-reinforced composite adherends. Characteristic changes in the reflected spectra from the sensors indicate both (a) disbond initiation (due, for example, to fatigue loading) and (b) the current position of the disbond front (to within about 2 mm). For composite-composite bonded joints, the reflected spectra are recorded with the joint under a small load (in practice, this could be the self-weight of the structure). In the case of a metal-composite joint, the difference in the coefficient of thermal expansion between the adherends is sufficient to enable disbond propagation to be monitored when the joint is unloaded. The experimental results have been modelled using a combination of finite-element analysis and commercial software for predicting FBG spectra, with very good agreement between the experimental observations of the reflected spectra and the predicted spectra, for disbonds of different lengths.

Summary

Joining of composites through adhesive bonding is an attractive alternative to mechanical fasteners because both similar and dissimilar materials can be joined with a uniform stress distribution over the bonded area. However, the difficulty with bonded constructions is, of course, that they cannot be disassembled easily and that structural health monitoring of joint integrity, both immediately after fabrication and during service, remains a major concern. Among optical techniques suggested for monitoring disbonding, the use of uniform fibre Bragg grating (FBG) sensors has been the most widely chosen method, with a number of such demonstrations available in the literature for monitoring bonded joints, repairs and structures [e.g. 1]. In addition to uniform fibre Bragg gratings, chirped fibre Bragg grating (CFBG) sensors have been investigated more recently for monitoring bonded joints (e.g. [2]), following demonstrations by Takeda, Okabe and colleagues [e.g. 3] that this type of sensor could be used for monitoring composite damage (such as matrix cracking, delamination etc). The chirped FBG sensors have a linear variation of the grating period and hence reflect a spectral band of wavelengths with roughly equal intensity. The spectral bandwidth of the reflected spectrum corresponds to the physical length of the sensor and this relationship can be used to monitor disbond progression.

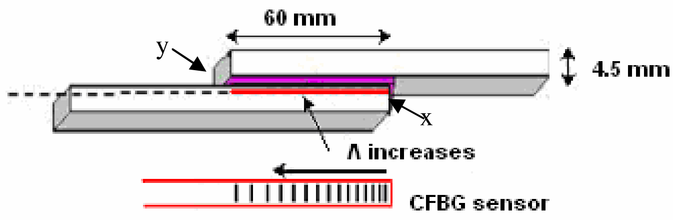
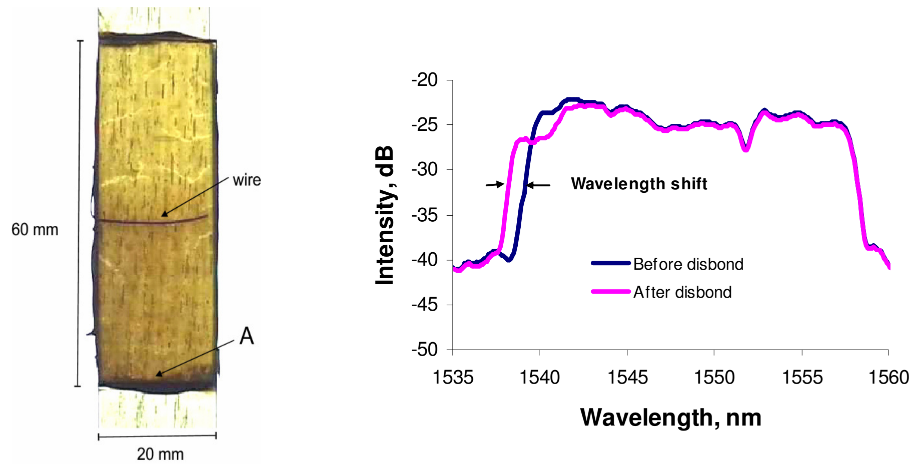


Figure 1. Schematic of a lap joint with a chirped FBG embedded in one adherend, with the low-wavelength end of the sensor adjacent to the adherend end.

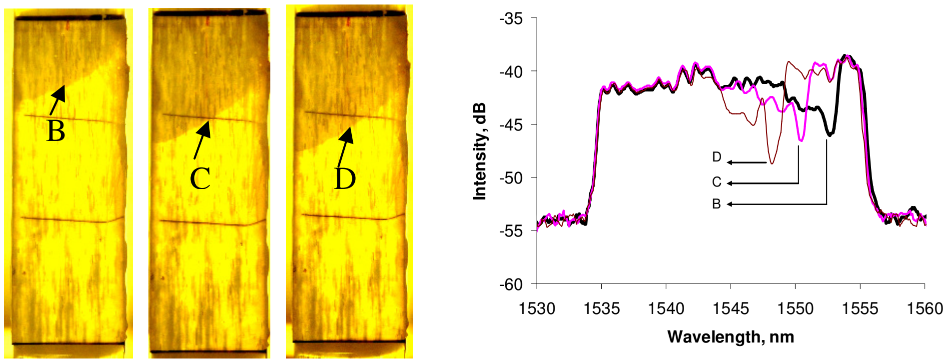
Figure 1 shows a schematic of a CFBG sensor embedded within one of the adherends of a composite/composite lap joint (in these experiments, transparent glass fibre reinforced plastic (GFRP) has been used). In this example, the sensor has been arranged so that the low-wavelength end is adjacent to the end of the adherend end at "x"; it should be noted that the sensor is embedded *within* the adherend and is not located within the adhesive bondline where it could initiate failure. During fatigue loading, disbonds initiate at the termination of the overlap of the adherends, and Figure 2(a) shows the initiation of such a disbond (at A, which corresponds to the adherend end at "x") after about 8000 fatigue cycles (further details can be found in [4]). As Figure 2(b) shows, comparison of the spectra taken under a small load both before and after disbond initiation (i.e. after 2000 and 8000 fatigue cycles, in this case) shows a shift of the low-wavelength end of the reflected spectrum to lower wavelengths as a consequence of the unloading of the end of the adherend due to disbond initiation.

An example of changes in the reflected spectra as a consequence of disbond growth is shown in Figure 3 for a slightly different situation. In this case, the disbond is growing from the overlap end at "y", so that disbond growth is adjacent to the high-wavelength end of the sensor (Figure 3(a)); it should be noted that the sensor length is 60 mm which is the same as the overlap length of the joint. As a consequence of the disbond, load is shed onto the adherend which contains the embedded sensor, producing a characteristic dip in the reflected spectra which moves progressively from high to low wavelengths as the disbond grows (see Figure 3(b)). The dip in the spectra is a consequence of the enhanced local strain in the adherend containing the embedded sensor as a consequence of the disbond (it should be recalled that these spectra are taken with the joint under a small load). The intensity of the reflected spectrum of a chirped grating is related to the local density of the grating period; hence, a decrease in the density of the grating period local to the disbond front (due to a local *increase* in the grating spacing because of the enhanced local strain in the adherend containing the embedded sensor) leads to a local decrease in reflected intensity, and consequently a dip in the spectrum. As the disbond grows, the characteristic dip in the reflected spectrum moves to lower wavelengths, following the position of the disbond front.



(a) (b)

Figure 2. (a) Disbond initiation at A; (b) comparison of reflected spectra both before and after disbond initiation (the wire is used to produce a uniform adhesive thickness).

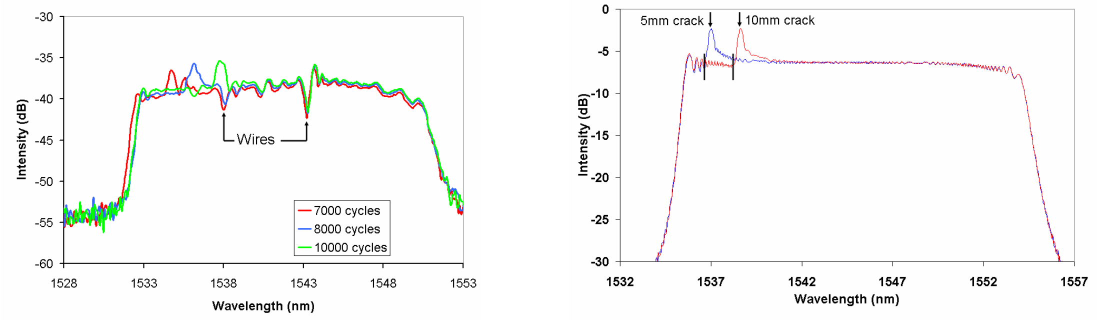


(a) (b)

Figure. 3. (a) Progressive growth of a disbond in a transparent composite/composite joint (after 34,000, 44,000 and 51,000 cycles); (b) movement in the position of a dip in the reflected spectrum as the disbond grows.

An example of monitoring the growth of disbonds in a metal/composite bonded joint is shown in Figure 4 (see [5] for further details). The CFBG sensor is again embedded within the composite adherend and extends the full 60 mm joint overlap length (the composite adherend is bonded to an aluminium adherend). As the disbond grows, the position of the disbond front can be tracked, this time by the movement of a peak in the reflected spectrum, as shown in Figure 4(a) which shows spectra for three disbond lengths. The peak in the spectrum is due to an increase in the intensity of reflected light at particular wavelengths. The gratings in the locality of the disbond front are relaxed (as a consequence of the disbonding) and reflect at longer wavelengths, the same wavelengths as those reflected by gratings still within the compressed GFRP just ahead of the disbond front (note that the GFRP adherend is compressed because of the mismatch in the coefficients of thermal expansion between the aluminium and the GFRP; the adhesive bond between the adherends is fabricated at a temperature of 120^{0}C). The increase in the density of gratings with the same period causes the increase in reflected intensity. Figure 4(b) shows examples of predicted reflected spectra for the aluminium/GFRP joint (for disbonds of 5 mm and 10 mm in length) based on a finite-element analysis of the joint and the use of commercial software for predicting FBG spectra (OptiGrating).

Figure 5 shows an example of the agreement between direct measurements of the position of the disbond front from photographs (note that the composite material used is transparent GFRP) and measurements obtained using the CFBG sensor technique (in this case, for composite/composite specimens). In general, the CFBG sensor technique can locate the position of the disbond front to within about 2 mm. This accuracy depends both upon the position of the CFBG sensor in relation to the adhesive bondline and on the materials used to produce the bonded joint.



(a) (b)

Figure 4. (a) Example of the monitoring of disbond growth in an aluminium/GFRP adhesive joint, showing changes in the spectra for increasing cycle numbers (7000, 8000 and 10,000); (b) predictions of reflected spectra for disbonds with lengths of 5 mm and 10 mm

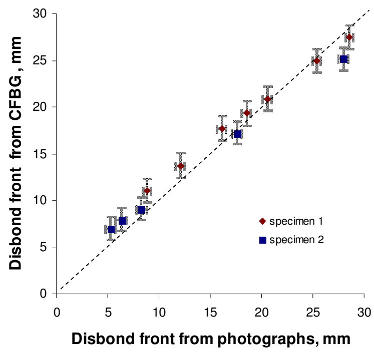


Figure 5. Example of the relationship between CFBG measurements of the disbond front position and measurements obtained from photographs.

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