Damage assessment in hybrid laminates using an array of embedded fibre optic sensors

TSP Austin[*1], MM Singh[1], PJ Gregson[1], JP Dakin[2] and PM Powell[3]

[1] Department of Engineering Materials, University of Southampton, UK

[2] Optoelectronics Research Centre, University of Southampton, UK

[3] Structural Materials Centre, DERA, Farnborough, UK

ABSTRACT

Hybrid laminates typically consist of alternate layers of fibre-reinforced polymer and aluminium alloy. Developed primarily for fatigue critical aerospace applications, the hybrid laminates are orthotropic materials with lower density and higher strength compared to the aluminium alloy monolith. One of the damage mechanisms of particular interest is that of fatigue crack growth, which for hybrid laminates is a relatively complex process that includes a combination of delamination and fibre bridging. To facilitate the development of a unified model for both crack and damage growth processes, a remote sensing system, reliant upon fibre optic sensor technology, has been utilised to monitor strain within the composite layer. The fibre optic system, with capacity for sub microstrain resolution, combines time domain multiplexing with line switching to monitor continuously an array of Bragg grating sensors. Herein are detailed the findings from a study performed using an array of 40 sensors distributed across a small area of a test piece containing a fatigue crack initiated at a through-thickness fastener hole. Together with details of system operation, sensor measurements of the strain profiles associated with the developing delamination zone are reported.

Keywords: In-fibre Bragg gratings, hybrid laminates, fatigue crack growth, delamination

1. INTRODUCTION

Hybrid laminates consist of alternate fibre-reinforced plastic (FRP) and aluminium alloy laminae, examples include aramid-reinforced (ARALL) and carbon-fibre-reinforced (CARALL) aluminium laminate. These materials were developed primarily for aerospace applications, owing to their improved fatigue performance, combined with a high strength-to-weight ratio. From a structural integrity perspective the response of these materials to fatigue cracking about fastener holes is of particular interest. The failure mechanism is one of fatigue crack growth (FCG) confined to the alloy laminae, and delamination between composite and alloy layers in the vicinity of the crack[1-3]. Until recently, no quantitative description of the strain field developing within the FRP laminae has been possible. However, with the advent of fibre optic sensor technology, in-fibre Bragg gratings embedded within the matrix of the FRP provide a means for direct measurement of strain.

The technique has applications to any structure in which a matrix material with a relatively low setting temperature (less than 200°C), such as epoxy or concrete[4], is used. Fibre optic sensors are particularly suited to monitoring the structural integrity of polymers reinforced with glass or carbon fibres. They can readily be incorporated into the structure during the fabrication process and have been shown to have little effect on the overall mechanical performance of the composite. Indeed, a number of different types of sensor have been employed for a variety of tasks, from monitoring the cure process to vibration detection[5].

[*] Correspondence: Email: austin@soton.ac.uk; WWW: http://www.soton.ac.uk/~austin

Advantages offered by fibre optic sensors, when compared with interferometric or resistive strain gauge techniques, include the following:

- The strain at normally inaccessible sites within the body of a structure may be determined.
- In-fibre sensors facilitate surface measurement from complex 3-dimensional profiles.
- In-fibre sensors are relatively non-intrusive, and cause less stress concentration.
- The communication link shares a common fibre medium with the measurement system.
- Optical fibres offer resistance to harsh chemical environments.

Sensors may also be incorporated at defined locations which are known to be prone to damage, such as in regions of stress concentration, so that, by monitoring their output continuously or periodically, the onset and development of damage may be detected. The technique reported herein measures the strain over an area of the test piece, rather than at a single point, by embedding an array of in-fibre Bragg gratings at a specified location within the material, thus enabling the development of delamination damage in the laminate to be monitored.

2. SYSTEM OPERATION

Bragg gratings written into the waveguide reflect light of a characteristic wavelength, Figure 1. When the fibre experiences a strain, ε, the associated change in Bragg spacing causes the wavelength of reflected light to change by an amount proportional to $\varepsilon\lambda$, where λ is the wavelength of the light reflected from the unstrained grating.

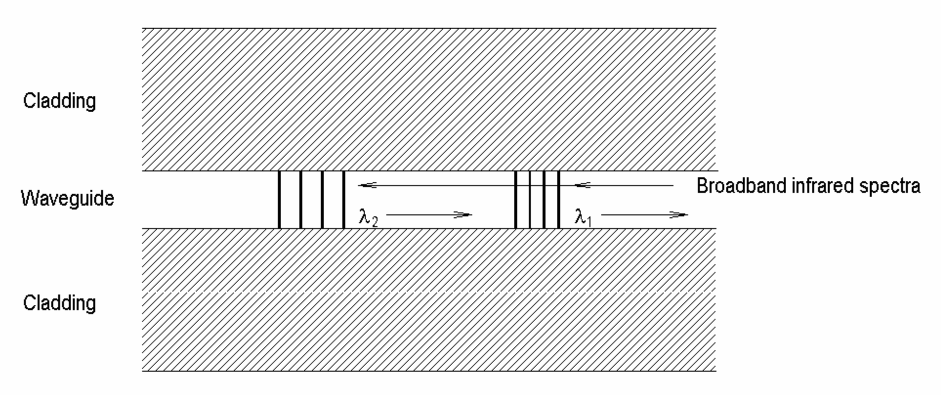

Figure 1. Illustration of in-fibre Bragg gratings.

Extensive research into Bragg grating sensors has been undertaken at the Optoelectronics Research Centre at the University of Southampton[6-8]. The results described in this paper derive from a system developed to sample data from an array of gratings in real time, by means of time-division multiplexing (TDM) employing low-speed, sequential polling[9]. The array of 40 sensors consisted of 8 gratings along each of five separate fibre optic lines.

The gratings on each line had 8 different peak reflective wavelengths in the spectral region between 1520 nm and 1580 nm, such that there was a fixed wavelength separation between each. The gratings were written by traversing a 100 mW UV beam from a CW argon ion laser, operating at 244 nm, across a phase mask held lightly against each fibre in turn, so that each line incorporated an ostensibly identical set of gratings. To increase the sensitivity to UV-induced refractive index modulation (the photorefractive effect necessary to form Bragg gratings) the germania-doped, high-boron optical fibres were hydrogenated before the gratings were written[10].

The multiplexed system for interrogation of the peak reflective wavelengths of the gratings was based on a broadband source (1550 nm ELED) and an acousto-optic tunable filter (AOTF). A block diagram of the interrogation system is given in Figure 2. Further details of this system have been reported elsewhere[11-15]. Light from the ELED source illuminates all the gratings in the selected line, whilst the AOTF acts as an electrically-tunable narrowband optical filter. The light reflected by the gratings was filtered by the AOTF and detected by an optical receiver. A software controlled coarse scan was performed to identify the 8 gratings, followed by a fine scan and lock-in procedure whereby the system tracked the wavelength of each grating in turn. In the lock-in mode, a feedback loop was enabled; the voltage controlled oscillator (VCO) was driven by a square wave which initiated a frequency-shift keying (FSK) of the RF drive signal to the AOTF. This toggled the centre wavelength of the AOTF between two wavelengths, within the bandwidth of the selected grating. When the optical power at these two wavelengths was not equal, an error signal was generated. The feedback loop used the error signal to tune the mean AOTF wavelength to match the grating wavelength. The mean optical frequency of the AOTF is directly proportional to the mean driving RF frequency. This RF frequency was measured and recorded. Changes in the grating wavelength were thereby detected as (inverse) changes in the mean AOTF drive frequency, which allowed a direct calculation of the strain experienced by the grating.

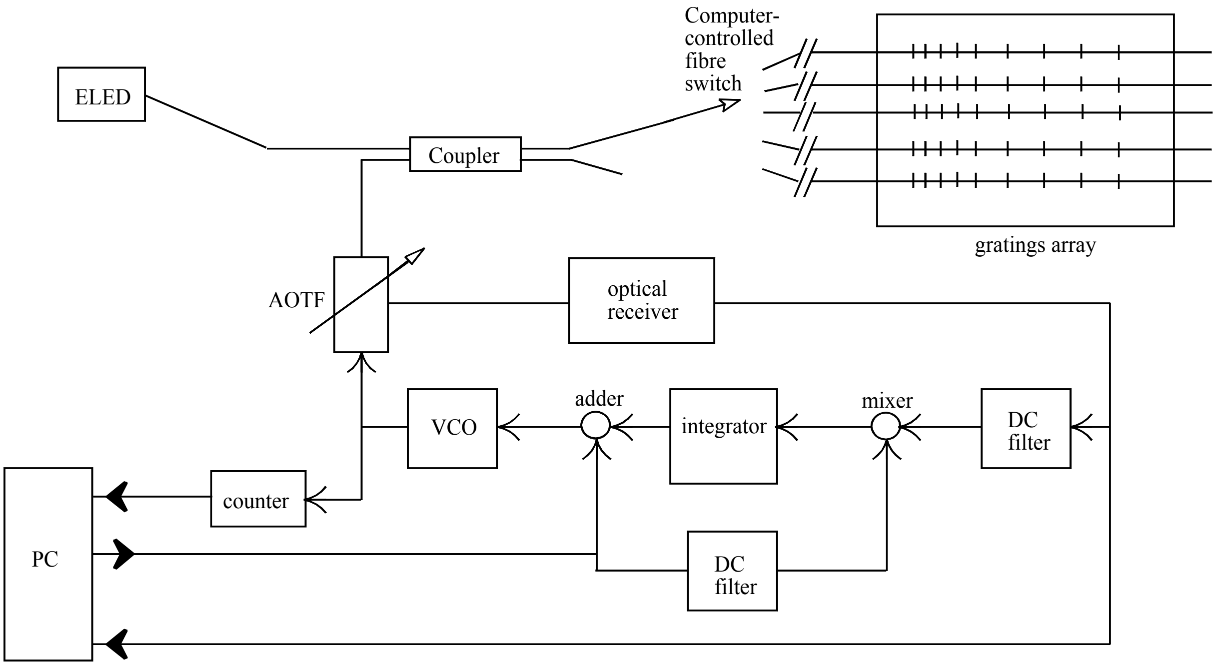

Figure 2. Schematic diagram of the Bragg grating interrogation system.

Each line was interrogated in turn. A computer-controlled monomode (DICOM Inc.) fibre switch was employed to select the fibre line to be monitored, by polling each in turn. To account for changes in the AOTF mean frequency due to temperature, a reference grating line, of a type similar to the gratings embedded in the test panel (but maintained free of stress and held at a constant temperature) was simultaneously interrogated. This was also selected at intervals by the fibre switch. The whole interrogation and data logging system was controlled using a personal computer (PC), in such a way that strain data were collected at intervals of 200 seconds over the period of the test. For the purposes of the current investigation the strain amplitude was of particular interest, so that only the maximum and minimum strain levels during each cycle were logged. To monitor the entire array required a total period of approximately 90 seconds which, when compared with the much longer duration of the complete FCG test (typically about 7 days), generated an essentially instantaneous record of strain.

The eight gratings were distributed over a length of 20 mm. The five lines were equally spaced at 5 mm intervals, so that the array occupied a 20 x 20 mm square area (Figure 3). Thus, the sensor array occupied a defined area of the test piece, adjacent to the expected path of crack propagation along the line XX, extending from approximately the midpoint of the expected final crack.

3. EXPERIMENTAL PROCEDURE

The test piece consisted of a panel made from four carbon-fibre-reinforced epoxy plies (913C HTA) of total thickness 0.5 mm, sandwiched between two 0.48 mm thick 8090 aluminium-lithium alloy skins. The FRP laminae were unidirectional, with the carbon fibres aligned with the loading axis. Both the rolling direction of the alloy skins and the embedded optical fibres lay parallel to this longitudinal axis. The panels were cured in an autoclave for one hour at 100 psi and 120°C. A hole of diameter 6.35 mm was drilled at the centre of the panel to simulate a stress concentration point, such as a fastener hole, as illustrated in Figure 3.

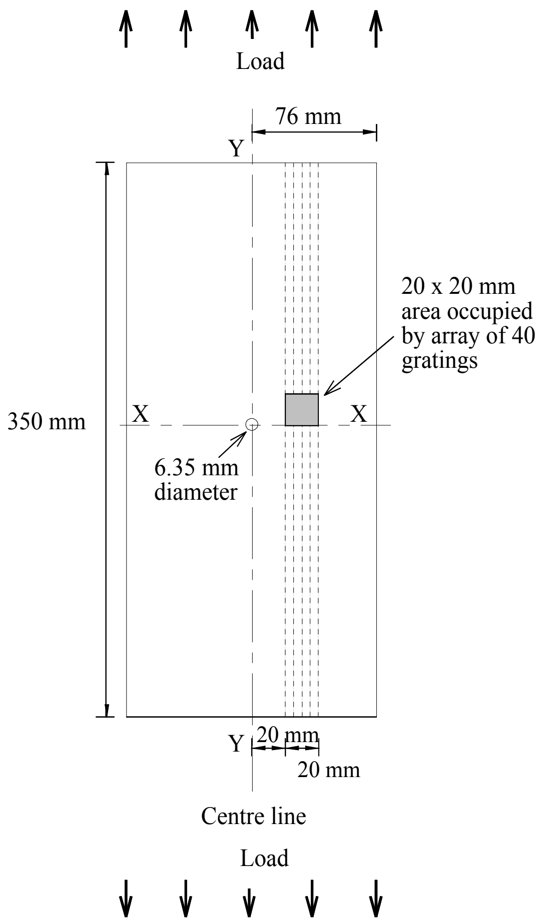

Figure 3. Panel configuration (M(T)[16]) with embedded optical fibres (broken lines).

The sample was cyclically loaded with a raised sinusoidal waveform at a frequency of 10 Hz in a servo-hydraulic machine. The peak-to peak load amplitude, ΔP, was 25.2 kN, and the load ratio, R, was 0.1. Crack length and load-line displacement were logged continuously using pulsed direct current potential drop (DCPD) and clip gauge methods respectively. The optical fibre strain data were logged simultaneously. The test was interrupted at intervals, and a ‘dry’ ultrasonic C-scanner used to record the delamination zone, whilst the panel remained housed in the test facility.

4. RESULTS

A selection of the data acquired are given in Figures 4 and 5. The dynamic strain amplitude measured along fibre optic line #1, situated 20 mm from the longitudinal axis YY, is shown in Figure 4 as a function of the number of fatigue cycles. The data associated with gratings at 1, 2, 3, 4 and 6 mm are identified, a sequence that, although not marked on the figure, continues logically for the remaining three gratings at 8, 12 and 20 mm. Broken lines indicate the stage of the FCG study at which the delamination zone profiles were recorded.

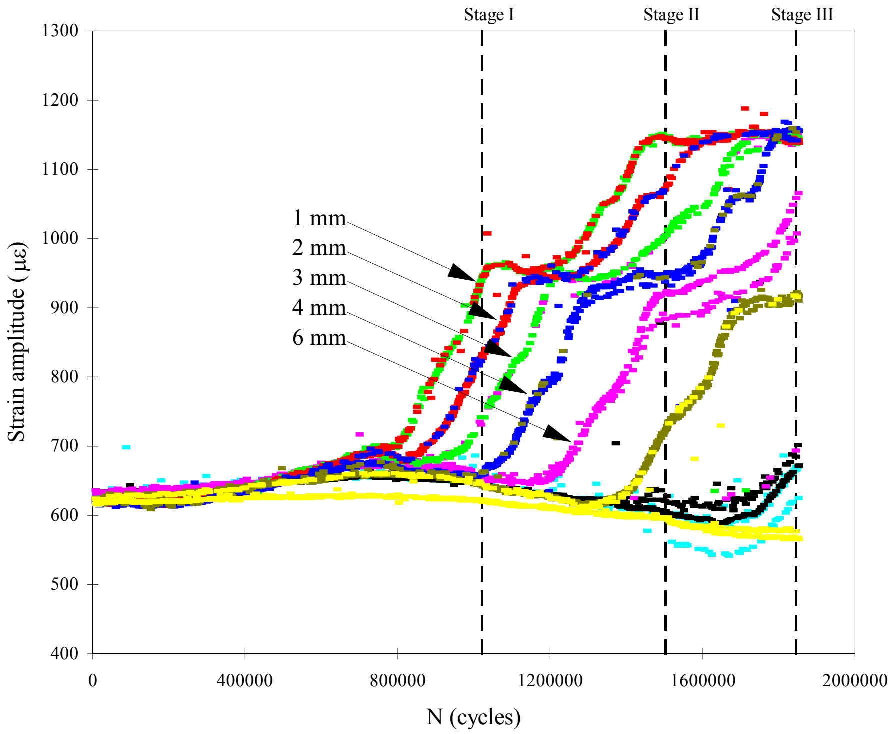

Figure 4. Dynamic strain amplitude measured along XX = 20 mm (Line #1).

Figure 5 details these profiles for the delamination in interfacial layer I, which denotes the interface between the aluminium alloy skin on one side (the front) of the panel and the composite core. The relative positions of the optical fibres and their gratings are also shown. Although shown as a single point, the gratings have a finite length: the four closest to the axis labelled XX were all 0.6 mm in length, the two furthest away were 2.0 mm and the remaining two were 1.0 mm long.

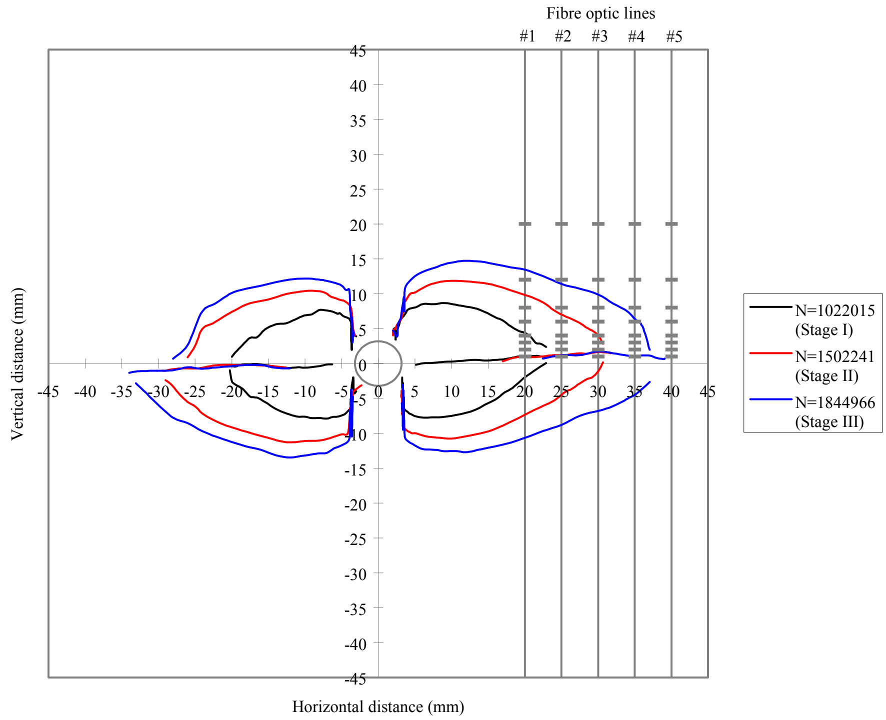

Figure 5. Development of the delamination zones in interfacial layer I.

5. DISCUSSION

The use of a broadband source and the frequency-agile nature of the AOTF makes the interrogation system suitable for dynamic tracking of a number of sensors over a range of wavelengths. The inclusion of a computer controlled switch and voltage controlled oscillator (VCO) for driving the AOTF means that an entry level personal computer (PC) fitted with a data acquisition card can be used for data logging. The period of interrogation may be varied, as can the sampling rate, allowing the same system to be used to record both static and dynamic loading conditions. In the reported work, the test frequency was 10 Hz and the sampling rate approximately 200 Hz. Using a higher power source (e.g. fibre source) to increase the signal to noise ratio, and hence facilitate an increased sampling rate, it is expected that events occurring at frequencies up to 1 kHz may be detected. Work is currently in progress to extend the system to detect high velocity impact events.

The Bragg gratings were closely spaced in these trials, since the area of interest was confined to the vicinity of the crack. Gratings may, however, be written at any desired spacing, provided the fibre attenuation is not too great. The number of gratings on each line may be varied, and plans for future research include the incorporation of a further eight gratings in the 1300 nm range, giving a total of sixteen Bragg gratings on a single optical fibre.

As the crack propagated in the aluminium alloy skins of the panel, the skins became separated from the CFRP core over a well-defined area. The development of these delamination zones on either side of the centre hole with continued fatigue cycling is depicted in Figure 5. The observed changes in strain amplitude can be related to progressive delamination, the rapid increase in strain amplitude occurring when the adjacent aluminium alloy became debonded from the composite. The effect of the delamination is a reduction in stiffness, and hence an increase in strain amplitude. The strain amplitude reached a saturation at approximately 1150 microstrain when the grating was wholly within the debonded region, that is, when delamination had occurred on both sides of the panel. The delamination process was, however, asymmetric and in the case of data reported herein, the ultrasonic C-scan measurements showed that the growth of the debonded region was more rapid in interfacial layer I than in layer II (between the rear skin and the composite core). The delay between the two growth rates gave rise to the intermediate plateau at about 900 microstrain in the strain amplitude trace.

Also of interest is the way in which the underlying strain amplitude appears to attain a maximum immediately prior to the onset of delamination and the associated steep rise in strain amplitude. It is suggested that this phenomenon relates to the region of stress concentration ahead of the crack tip; the strain measurements indicating a degree of stress transfer between the two components of the CARALL laminate.

The strain data compare well with finite element models of the fatigue damage development, in which the bridging of the crack flanks by unbroken carbon fibres has been taken into account. Further numerical simulations of FCG, incorporating fibre optic strain measurements, are in progress.

6. CONCLUSION

An array of in-fibre Bragg gratings has been demonstrated to monitor satisfactorily the progress of delamination damage within a hybrid laminate subjected to fatigue loading. The interrogation system enabled a direct measurement of the strain field in the vicinity of the crack as a function of time, and the results obtained have enhanced our understanding of the complex failure mechanisms which characterise hybrid laminate FCG.

ACKNOWLEDGEMENTS

This investigation was carried out for DERA under an EMR agreement. The support of the Ministry of Defence and the Department of Trade and Industry is gratefully acknowledged. The authors wish to thank L. Reekie, M. Cole and M. Durkin for their assistance in provision of in-fibre gratings during the course of the work.

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