Development of Sensor Technology to Facilitate In-situ Measurement of Damage in Composite Materials for Spacecraft Applications

Mowlem M.C., Chambers A.R., Singh M.M.
Dakin J.

Materials Research Group, School of Engineering Sciences, University of Southampton, Highfield, Southampton. SO17 1BJ
Optoelectronics Research Centre, University of Southampton, Highfield, Southampton. SO17 1BJ

INTRODUCTION

CFRP is used in a variety of applications where its high strength to weight ratio and high specific modulus is advantageous. Impact damage can however significantly reduce the strength and the modulus of the material through the creation of areas of delamination, matrix cracking and fibre failure. Such impact damage is often hard to locate and its severity hard to assess. For applications in remote or inaccessible locations traditional methods of damage assessment are not feasible and therefore a method of assessment in-situ and in service is often required to predict the optimal reparation or replacement period. Such a technology is particularly relevant to spacecraft applications where reparation and replacement costs are prohibitive and where impacts are often sustained from micrometeoroid and space debris impingement.

Optic fibre Bragg gratings reflect light at a characteristic wavelength which is a function of sensor characteristics, strain and temperature. Changes in strain (or temperature), result in a wavelength shift of the order of 1.2 nm / $\mu\varepsilon$ and 10^{-2} nm / ^{o}C.[1]

Due to their small size (typically 9μm in diameter) optical fibres containing Bragg grating sensors can be included within the matrix of fibre reinforced plastics with little detriment to their physical properties. Each optical fibre line can contain a number of discrete grating based sensors with as little as 1mm separating each grating. The limit to sensor length is sub-millimetre. These sensors are well suited to CFRP condition monitoring.

At present the most significant barrier to the widespread application of this technology is the difficulty in accurately interrogating each grating based sensor to discern its characteristic wavelength at any time. Modifications made to an existing interrogation system to enable impact damage identification are detailed in this paper.

A Bragg grating based sensor array was placed in the CFRP structure to enable accurate strain profiling of the material pre-impact and post-impact. This strain information is related to the observed damage. Dynamic strain information (during impact events) has also been recorded. The importance of this data for the development of the sensor technology is discussed.

MODIFICATIONS TO INTERROGATION SYSTEM

The interrogation system used in these experiments was developed by H.Gieger [2] at the Optoelectronics Research Centre (ORC) and interrogates each grating in turn (time domain multiplexing (TDM)). To locate a peak, a point on either side of the reflected Gaussian is located. The wavelength domain filter employed (Acousto-Optic Tuneable Filer (AOTF)) has its centre wavelength toggled between these two points. If the reflected power at these wavelengths is identical then the peak is then located at the median of these two points. If this is not the case the difference between these reflected powers is used to generate an error signal which is fed back to move the centre wavelength of the AOTF to the correct position. The generation of this error signal requires that the phase of the AOTF toggling signal (signal1) and the signal passed to the error signal production electronics (signal2) is preserved at all times. This enables the correct reflected power value to be associated with the point on the side of the gaussian peak from which it originated. A modification made to the TDM interrogation system ensures the phase of these signals is preserved by generating signal 2 from signal 1 directly using Schmidt triggers [3]. This modification offers greater stability than previously achieved when the PC controlling the system generated signal 2.

A number of software changes were also completed to enable the system to be used to measure static strains accurately (using repeated averaging) and to enable the sampling speed to be increased to facilitate the observation of strain transients during impact. A maximum sampling frequency of 200Hz was achieved.

EXPERIMENTAL METHOD

An array of forty Bragg grating strain sensors was embedded in the centre of a 4 ply unidirectional CFRP (913HTA) laminate structure with a 0.6 fibre / volume fraction. The laminate was cured at 130 ^{o}C in an autoclave and had a thickness of 0.5mm. These panels originally formed the central element of Carbon fibre Reinforced Aluminium laminates (CARALL) used for fatigue assessment by MM Singh et al. [4]. Three panels were investigated, one with both Aluminium layers (8090 (0.45mm)) removed (panel C), the others with one skin removed (panels 8h13 and 8H9). Although materials structures such as these are not used extensively in spacecraft applications it was felt that they would provide adequate test specimens to demonstrate this impact damage assessment technology. The gratings were etched onto five optical fibre lines at 1,2,3,4,6,8,12 and 20 mm from the central x-axis (transverse axis) of the test panels. The lines were placed at 20,25,30,35 and 40mm from the centre of the panels parallel to the y-axis (longitudinal axis).

Impinging particles were produced by an air rifle, which produced an impact velocity of 225ms with a 0.0005kg, 4.5mm diameter particle (11.8 J impact). Impact location was varied for each panel and repeated until a residual strain was observed. Panel C required 2 impacts before residual strains were observed.

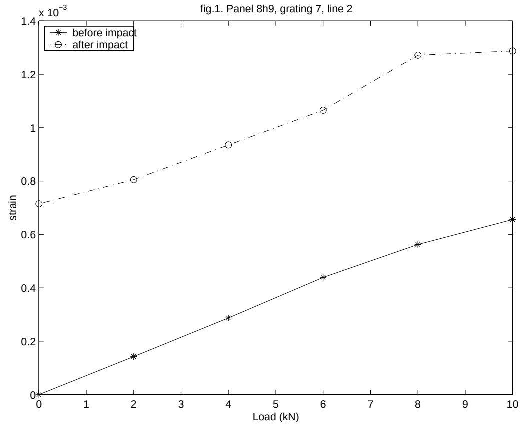
Each panel was loaded to 10kN in 2kN increments in a servo-hydraulic machine with all strain sensor outputs recorded at each load both before and after impact. Strain information was also recorded during an impact event at the maximum sampling rate of 200Hz.

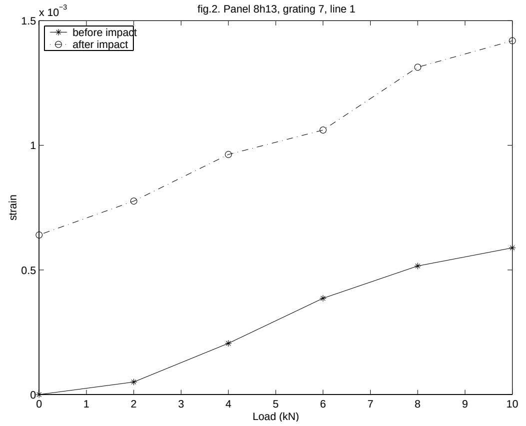
High speed digital photography (40500 frames/s) was used to examine the damage mechanisms and put any dynamic strain information into context.

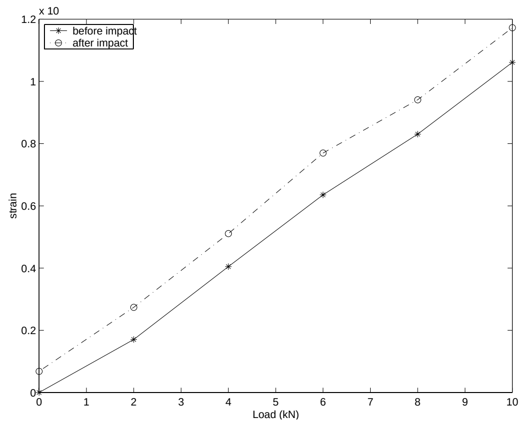
RESULTS AND DISCUSSION

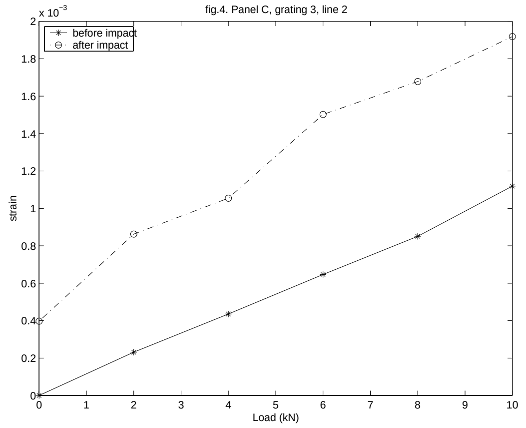
After each impact on panel C a 3.5mm width of the material was removed (fibre and matrix failure) along the length of the panel. A region of visible delamination was also created 1mm either side of this void. The 2nd impact which resulted in residual strains was located 4mm from the first optical fibre in the transverse direction and adjacent to the third Bragg grating in the longitudinal direction.

Panels 8h13 and 8h9 exhibited much less damage to the carbon layer. A 4mm hole was produced in both panels with 8-10mm long parallel cracks extending from both sides of the tangent of the impact whole in the longitudinal orientation. The aluminium layer at the rear of the specimen exhibited a 30mm diameter heavily deformed region (completely delaminated from the carbon layer) with a rupture resulting in a 15mm crack through which the particle had escaped. The impact for panel 8h9 was located 29mm from the first optic line and parallel with the last grating in each line. The impact on panel 8H13 was 9mm from the first optic line and 15mm from the first grating (i.e. parallel to a line between the penultimate and last grating) in the longitudinal direction.







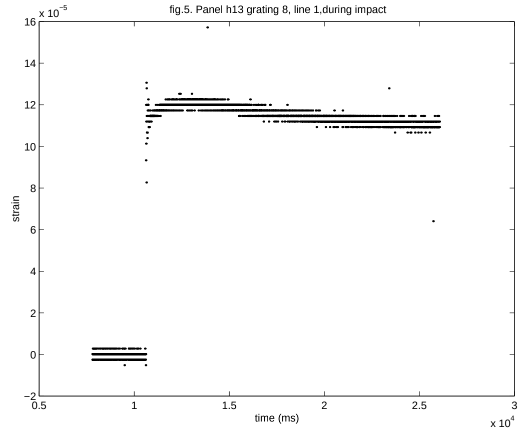


The damage observed was consistent with the differing properties afforded by the two types of test specimen. Whilst the addition of the aluminium layer greatly increased the strength of the material particularly in the transverse direction the increase in ductility which this configuration offered resulted in more energy absorption and hence damage.

Similarly the strain sensor readings were consistent with the observed damage for all of the panels. The residual strain observed by all sensors in both 8h9 (fig.1.) and 8h13 (fig.2.) were larger than those recorded by any of the sensors in panel C (fig.3.).

This is consistent with the stresses induced by the plastic deformation of the 8090 aluminium layer present in panels 8h9 and 8h13. A variation in residual strain can also be seen with location for each panel. A full analysis of the expected residual strain field is yet to be completed but many of the results appear consistent with the expectation that residual strains are greater closest to each impact (compare fig.3. with fig.4.). There is little appreciable change in stiffness observed due to the impact damage created.

Detailed strain transient information is limited due to the relatively low sampling rate of the interrogation system. Fig.5. shows the transient response of grating 8 on the first line of the sensor array during the impact of the panel. The creation of a large residual strain can clearly be seen. However, tracing of the immediate post impact transient is limited although some post impact vibration is detected. Post impact vibration at approximately 3kHz was observed using a high-speed digital camera. A longer time-constant variation was also observed post-impact. This is probably due to the heating and cooling of the aluminium post impact, which creates thermal strain. This effect is not due to the heating of the sensor directly and was much smaller for panel C.



Conclusion

Bragg grating strain sensors have been shown to be capable of providing distributed strain sensing for CFRP laminates that can enable in situ and in-service health monitoring. The interrogation technology developed by H.Gieger [2] has been successfully adapted for use for impact damage assessment. Despite its relatively low sampling rate both dynamic and residual strain information can be ascertained for a given impact. Dynamic and residual strain information has been shown to vary with material properties and with relative impact location. Future research will be directed towards improving the information gathered and relating this to observed damage to allow calibration of the sensor.

Acknowledgements

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