OPTIMIZATION AND STRAIN MEASUREMENT OF FBG SENSORS EMBEDDED IN CARBON COMPOSITES

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ABSTRACT

This paper focuses on the development of a laminate containing optical sensors using a novel cure process and the detection of the load distribution in a structure. An array of Fiber Bragg Grating (FBG) sensors embedded in a carbon laminate has been manufactured using an out of autoclave process, called the Quickstep process, which permits shortening of cure time. The internal strain changes of FBG sensors were observed during the manufacturing process and static loading test. The sensors remain stable during manufacturing process and the temperature responses of sensors prove that the cure process was suitable. Embedded FBGs show the promising static loading sensitivity and repeatability.

1. INTRODUCTION

Recent intensive developments in sensing technologies have enabled significant advances to be made in the development of smart structures, particularly in the aerospace industry, civil engineering and the marine sector [1]. Early detection of damage and long term monitoring in some critical areas can help improve the safety and the maintenance cost will be reduced by using smart materials. Various sensing technologies including optical fiber sensors, piezoelectric sensors, strain gauge, carbon nanotube, eddy current sensor arrays, MEMS (Micro-Electro-Mechanical Systems) and shape memory alloys have been successfully employed [2-3]. In this study, Fiber Bragg Grating (FBG) optical sensor was chosen for the strain and temperature monitoring of carbon composites during manufacturing process and static loading test. FBG optical sensor is considered as one of potential materials for smart structure because of their good corrosion resistance, long term stability, electrical immunity, minimal size and lightweight compared to metallic sensors [4].

The objectives of this study were to:
(1) Find out the suitability of the Quickstep technique for the processing of a large scale of the laminate containing optical FBG sensors;
(2) Ensure the stability, sensibility and repeatability of the embedding sensors;
(3) Maximise the FBG sensors' utilisations such as monitoring the cure process and detecting the load distribution in a laminate to determine the final wing structure loads.

As an out-of-autoclave manufacture of advanced composite materials, the Quickstep process utilizes a fluid-heated, balanced-pressure, floating mould for the curing, partial curing and joining of composite materials. The technique utilises a Heat Transfer Fluid (HTF) to apply heat and pressure to the uncured component during the process. The laminate stack is assembled on a single-sided tool using conventional lay-up, sealed in a vacuum bag and then installed in a low pressure chamber containing a glycol-based HTF. The tool and laminate are supported between two flexible membranes in the pressure chamber [5]. With Quickstep, fast heating and cooling can be achieved due to the good heat transfer between the HTF and the component. Consequently, a significant reduction in the overall process cycle time and manufacturing cost are possible in comparison with typical manufacturing technologies such as Resin Transfer Moulding (RTM), Resin Film Infusion (RFI), Vacuum Assisted Resin Transfer Moulding (VARTM) and autoclave process. Furthermore, the monitoring of the inner temperature of the composites and observation of resin flow of prepreg during cure cycle are possible using embedded sensors as the Quickstep pressure chamber is processed in open manner.

2. EXPERIMENTS

MTM 45-1 unidirectional carbon epoxy prepreg tape (10K, Advanced Composites Group, UK) was used which may be initially cured at temperatures as low as 80°C allowing lower cost tooling. A laminate of 800 x 800 mm^2 was prepared by stacking 24 plies of prepreg with multiple orientation [[0/+45/90/-45]s]2, debulking every ply for 15 mins. An array of FBGs which contains four strain sensors and one temperature sensor with a grating length approximately 4 mm was embedded in an optimal position during lay-up. Figure 1 shows the positions of BG1 to BG5 and the division of the laminate into 16 sections for static load testing. The laminate containing the FBGs was vacuum bagged overnight before the curing operation. The stability of the FBG sensors was observed during both vacuum bagging and curing; the intensity power of the FBGs decreases slightly during the vacuum bagging process but there was no wavelength shift. An optical spectrum interrogator (W4-5, Smart Fibers Ltd) combined with Smartsoft W4 was used to detect the changes in parameters. The laminate was cured under vacuum pressure using the Quickstep QS5 production machine (Quickstep Technologies Pty Ltd) at 80°C for 30 mins (1st dwell), 130°C for 120 mins (2nd dwell) then followed by 180°C for 120 mins (3rd dwell). Non-destructive static loading test has been completed by applying a mass at 16 different positions of the laminate for 20 seconds.

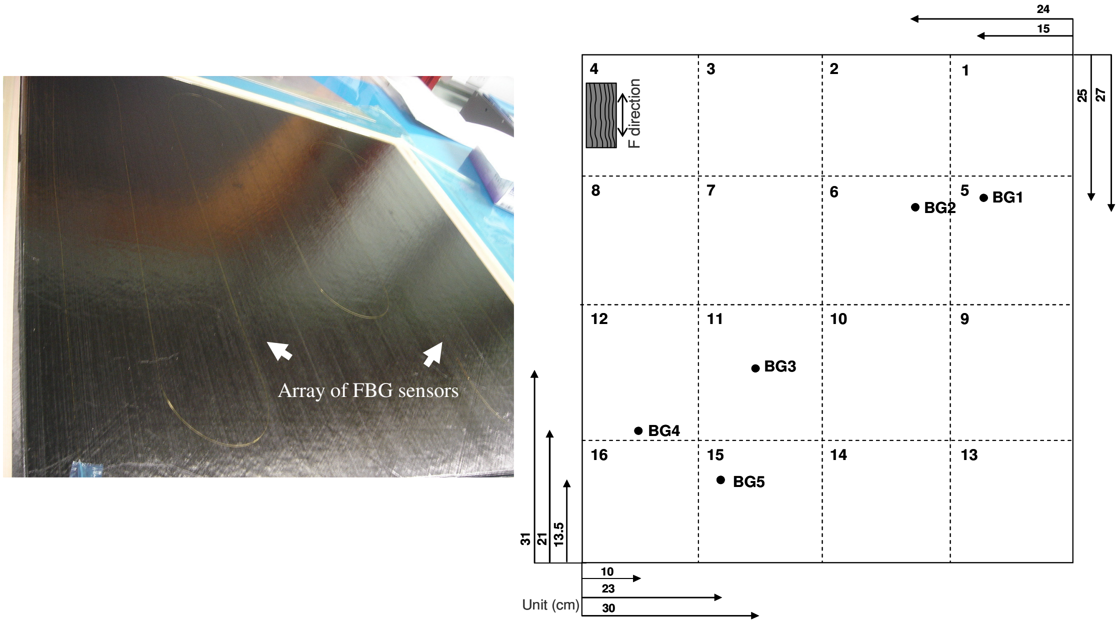


Figure 1. (a) Embedding an array of FBGs during lay-up; (b) positions of BG1, BG2, BG3, BG4 and BG5.

3. RESULTS

The FBGs have a periodic variation in the refractive index along the short length of a single-mode optical fiber. When broadband light is launched into the sensor, a narrow band of light is reflected. The reflection of the light at a specific narrowband wavelength is called the Bragg wavelength and given as Equ. (1).

$$\lambda = 2n\Lambda \qquad (1)$$

Where, n is the average refractive index of the fiber core and Λ is the average grating period.

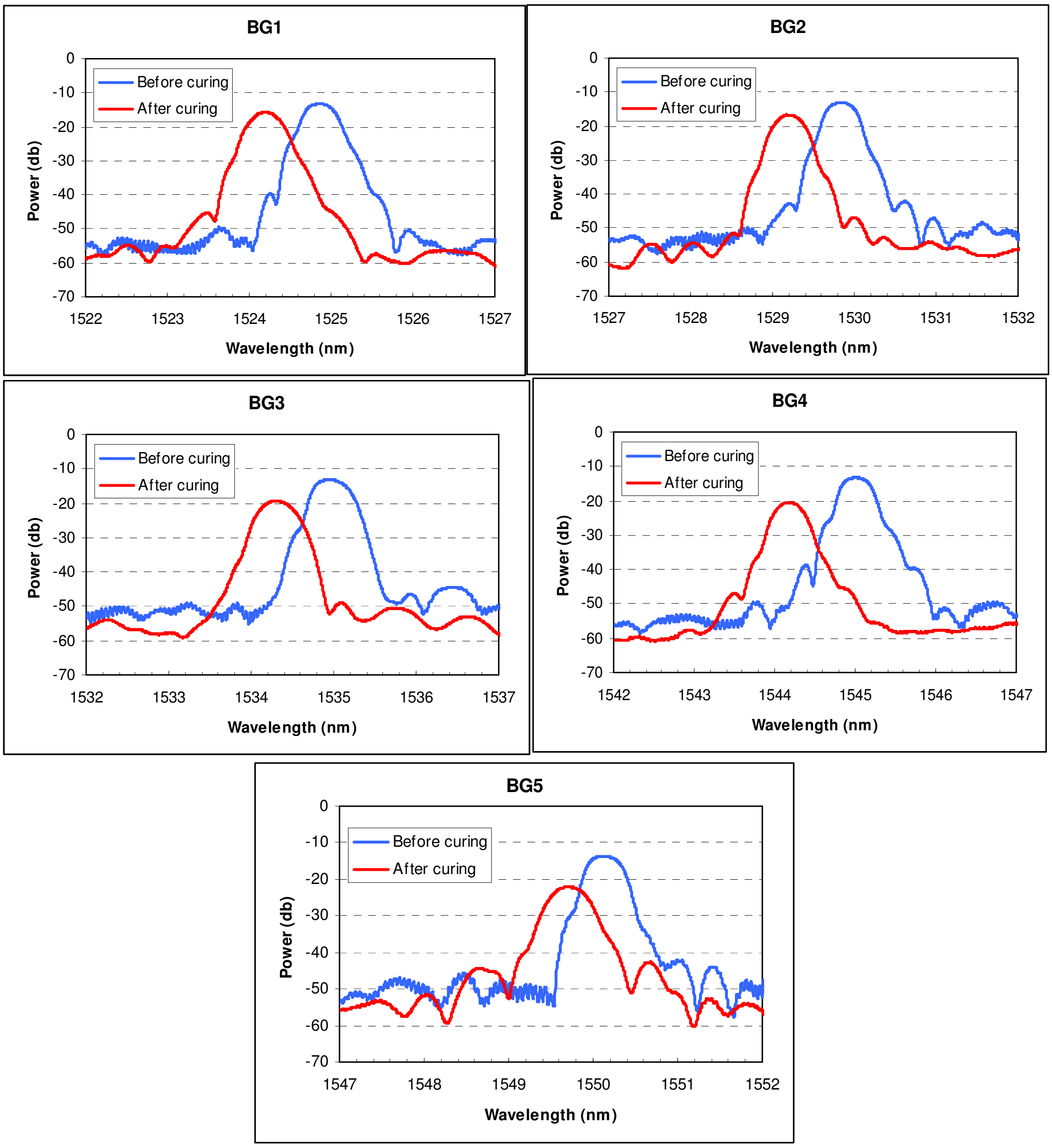


Figure 2: Five Bragg Grating sensors output as a function of wavelength before and after manufacturing process

The wavelength λ is known to change linearly depending on the strain and temperature applied to the sensor. The wavelength shifts can be used for measuring strain and temperature. An optical spectrum interrogator detects the changes in parameters and transforms them into readable information. The residual stress and strain can be calculated using the wavelength shift and load monitoring of inhomogeneous materials can be also achieved [6-7]. The reflection spectra of an array of gratings BG1 to BG5 before and after manufacturing process are compared in Figure 2. The optical sensors were stable during the manufacturing process but the wavelength shifts were observed after curing. Temperature influences the behaviour of the FBG as a result of the linear thermal expansion of the grating, as well as the change in its refractive index as given in Equ. (2).

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\Delta T \qquad (2)$$

Where, α, ξ and ΔT are the thermal expansion coefficient, thermal optic coefficient and temperature shift, respectively.

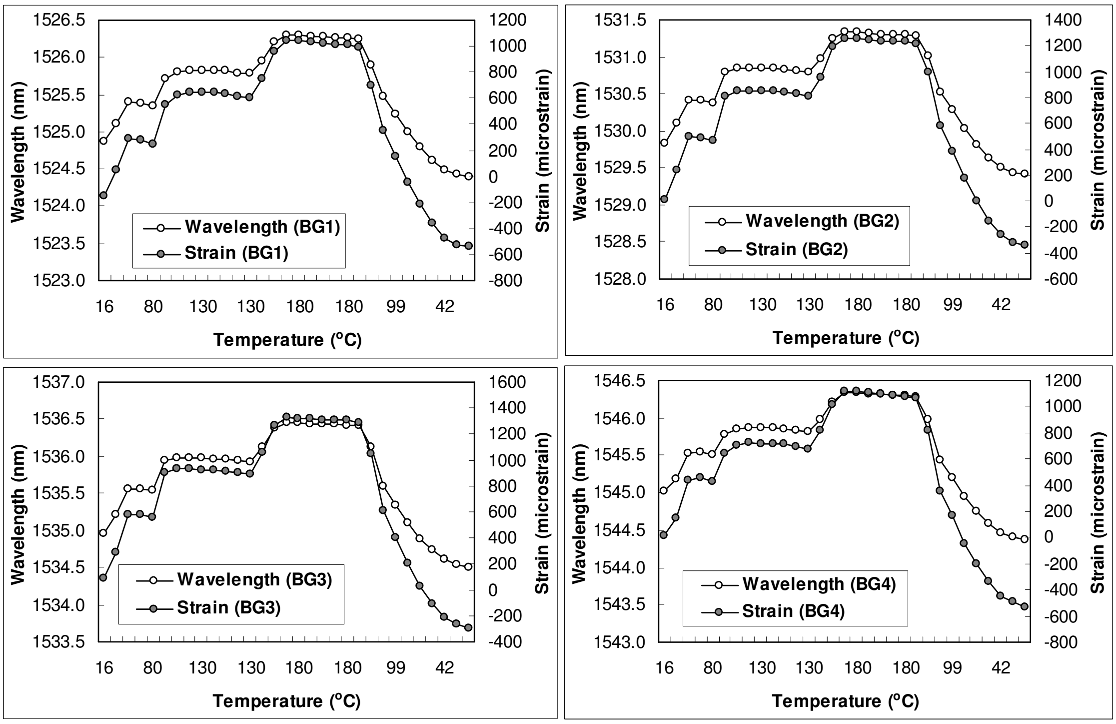


Figure 3: Evaluation of the Bragg wavelength of BG1 to BG4 during the cure cycle.

Change in the refractive index is the main factor and both coefficients are constant over a wide temperature range. When a grating is heated the material expands and the refractive index also increases. The temperature coefficient of BGs is calculated from the wavelength shift of BGs; the temperature sensitivity of the FBGs was found to be 0.007~ 0.01 (10 pm) nm/°C. The evaluation of the Bragg wavelength of BGs with temperature during the cure process is shown in Figure 3. The shift in the Bragg wavelength $\Delta\lambda_B$ with applied microstrain $\Delta\mu\varepsilon$ and change in temperature ΔT for silica fiber is given in Equ (3).

$$\frac{\Delta\lambda_B}{\lambda_B} \approx 0.78\times10^{-6}\Delta\mu\varepsilon + 6.67\times10^{-6}\Delta T \qquad (3)$$

The sensitivity and repeatability of the BGs have been studied via non-destructive static loading test. When a load is applied, the grating is strained leading to a change of the Bragg spacing (Λ). This results in a change of the reflected wavelength and offers a robust measurement of strain. The real time stress and strain responses of BGs were recorded while the loading mass was increased. Figure 4 shows the strain response of the BGs when 10 kg of mass (20 cm diameter) was applied at section 1 to 16 of the laminate. All sensors show good repeatability during loading test. Strong responses were observed at section 5, 6, 11, 12 and 15 where the sensors are located and the sensitive areas are shown in Figure 5.

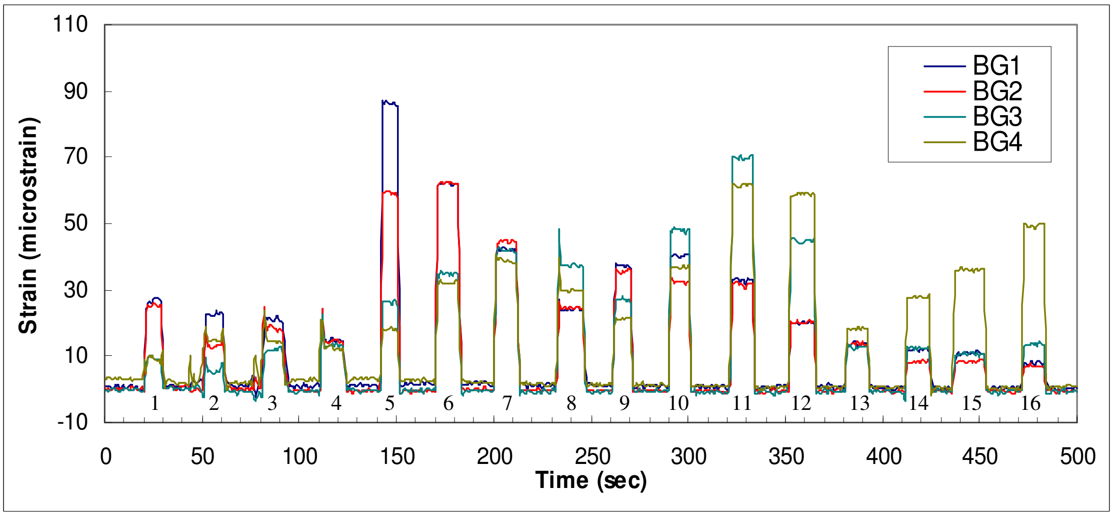
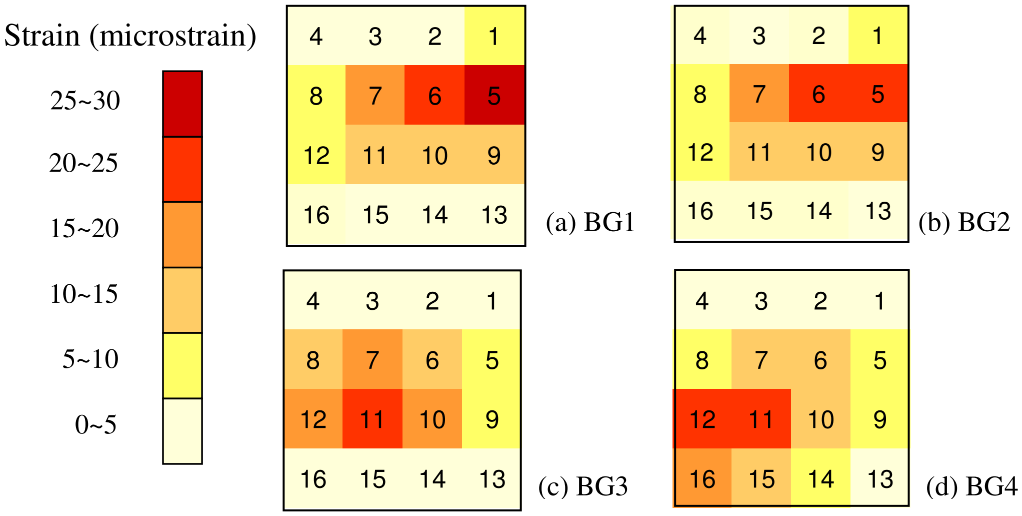


Figure 4: Strain response when 10kg of mass was applied at positions 1 to 16 of the laminate.



(a) BG1

(b) BG2

(c) BG3

(d) BG4

Figure 5: Sensitivity of BGs when 10 kg of mass was applied through the strain evaluation.

The smart structures should be able to endure thousands of load cycles over the structures’ lifetime without failing. Various mass from 0.02 to 13kg were applied at site 6 (most sensitive area) for 20 seconds and the mean values of strain are shown in Figure 6. From this test, a maximum static force can be estimated since the BGs can be typically strained up to 3000 microstrain before they overlap in wavelength.

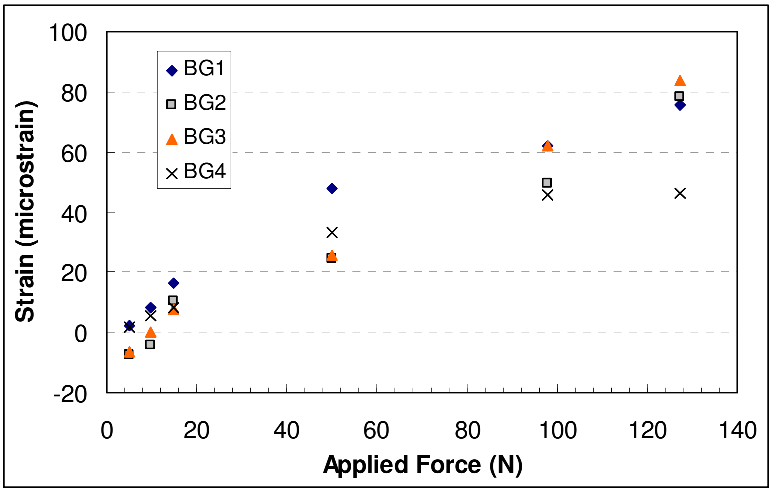


Figure 6: Strain responses of the BGs when various mass were applied at BG1, BG2, BG3 and BG4 respectively.

6. CONCLUSIONS AND FUTHUR WORK

An array of Fiber Bragg Grating (FBG) sensors embedded in a carbon laminate has been manufactured using the Quickstep process. The temperature dependent FBG response during the manufacturing process has been discussed and internal strain changes during static loading test were observed. The sensors show a promising loading sensitivity and a maximum static force can be estimated before the sensors overlap in wavelength.

The local impact tests will be undertaken to make correlations between the variations of global static parameters and the extent of damage in structures. The BGs might response in microsecond when the impacts occur but they might show limited sensitivity when damage occurs in small areas at long distance from the sensors. Non-destructive observations using C-scan and Omniscan will be carried out after impact test.

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