In-situ simultaneous measurement of strain and temperature in automated fiber placement (AFP) using optical fiber Bragg grating (FBG) sensors

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Abstract There has been a tremendous growth of utilizing automated fiber placement (AFP) to manufacture highly precise components and large structures like fuselage panels and wing skins for high-end applications in aircrafts and next generation of spacecrafts. Consequently, in-situ identification of potential defects and strain level within the laminates is critical to ensure the quality and integrity of the final product. In this study, optical fiber Bragg grating sensors (FBGs) have been implemented as an on-line monitoring technique for simultaneous measurement of strain and temperature in AFP. In addition, it is also shown that, the embedded FBG sensors can remain within the laminate for continuous health monitoring after manufacturing process toward the identification of crack induced acoustic emissions.

Keywords Fiber Bragg gratings, automated fiber placement, acoustic emission, in-situ process monitoring

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Introduction

The capabilities of automated fiber placement (AFP) machine for making bespoke components along with increasing productivity have provided wide range of application for the AFP in comparison with the other manufacturing methods. Regardless of these advantages, producing defect free component using AFP is practically challenging. Structural health monitoring is required for two reasons; one for the designers to assess the strain level within the laminate structure and the other for the manufacturers to assess the quality of manufactured part.

Several studies have been conducted on application of strain gages on composite materials. It has been asserted that these types of sensors are very accurate for measuring residual stress within the thermoset composites. Parlevliet et al. have demonstrated how a strain gage was melt-embedded in the center of the surface plies of a unidirectional carbon fiber/PEEK laminate to measure the formation of residual stresses from thermal and crystallization effects. Daniel and Liber have studied the effect of laminate construction on residual stresses in graphite/polyimide composite using thermal resistance strain gages in which high temperature withstanding strain gage is placed between the plies and cured. The strain gages are then exposed to any deformation within the laminate during the curing process. Tsouvalis et al. highlighted that the strain gages are not reliable for thermoplastic composites due to their high processing temperature. It is mentioned that embedding strain gages inside the laminate as a foreign object will change the structural integrity of laminate and may leads to incorrect measurement.

So far, no work has been reported on in-situ and simultaneous measurement of strain and temperature during the lay-up process in AFP. The strain gages for this purpose can only be located underneath the substrate to avoid thickness variation between the plies and they cannot measure temperature. On the other hand, optical fiber Bragg grating sensors (FBGs) can be considered as a promising candidate for in-situ
structural health monitoring due to their localized and multiplexed sensing capabilities. These sensors are small in size, lightweight and can be easily embedded within the laminates without affecting its integrity for continuous health monitoring. Using them, parameters like stress, strain, temperature, natural frequencies, and cracks could be monitored in real time. Several studies have been conducted on the application of FBG sensors in composite structures.

In our recent experimental developments, the authors have successfully implemented the FBG sensors for real-time process monitoring and defect identification. In the first study, an array of two FBGs was embedded between the second and third plies of composite laminate consist of 10 plies. The sensors were then connected to the measurement system to measure the effects of stacking plies, recovering time and residual strain/temperature. The measured wavelength during the placement of remaining plies were also monitored and recorded in real time. In another experimental program, the application of optical FBG sensors for identifying misalignment defects within the laminate have also been demonstrated through the embedment of three different artificial defects within the laminate. It was found that depending on the type of defects in terms of material and size, three different changes in the wavelength profiles could be observed. These changes include the shape of wavelength profiles, the wavelength shifts and the slope of the wavelength profiles during the cooling process.

In these experiments, the combined effect of both consolidation pressure and curing temperature were measured for each lay-up as a wavelength change. However, the cross-sensitivity of FBGs to the strain and temperature is an issue that needs to be addressed. This will be a major step towards measuring residual stresses using FBGs. There are two available solutions for this purpose: one is to design a temperature insensitive sensor head by encapsulating one of the FBGs, whereas the other is using a configuration with sufficient degree of freedom to permit the simultaneous discrimination of strain and temperature. Several works have been conducted on this direction and a significant number of configurations have been proposed to discriminate these two parameters such as twisted FBGs and encapsulated FBG configurations.

In this paper, we attempt towards the measurement of strain, temperature, and acoustic emissions in composite laminates using FBG by conducting two experimental approaches. In the first part of this experimental study, a method for discrimination of strain and temperature is introduced and implemented. Since the aim of this study is to measure both temperature and strain, the encapsulated option was discarded. Embedding the twisted configuration is also challenging due to the securing issues, wrinkling effects and thickness variation between the plies which could have negative influence on the structural integrity of the laminate. Instead, new sensing head based on an angled FBG related to the straight one was utilized. In this way, thermal sensitivity of FBGs remains similar while different strain sensitivity can be obtained.

In the second part, the AFP sample with embedded FBG sensor is demonstrated for its capability to measure acoustic emissions in a composite laminate. Thus, using one set of embedded FBG sensor, both in-situ manufacturing process parameters and ex-situ structural health monitoring parameters can be measured.

Background and operating principle

In-situ automated fiber placement (AFP)

The AFP lay-up is an advanced manufacturing method for making composite components in which several manufacturing stages are incorporated in the placement head, Figure 1. The machine includes compaction roller, heating system, and a robotic arm, which is computer controlled. During the placement process, an incoming tape is delivered to compaction roller while temperature is being introduced through a heat source to the laminate. In this study, a hot gas torch (HGT) is used as heat source which delivers high temperature nitrogen around the tape at the nip point. A number of parameters influence the quality of laminated composite manufacturing using the AFP machine include HGT temperature, hot gas flow rate, consolidation pressure, ply orientation, and lay-up speed/deposition rate.

![Figure 1 Automated fiber placement (AFP) machine with the thermoset head (left) and thermoplastic head (right); (Photo courtesy: UNSW Sydney)](image_url)
Operation principle of an FBG and acoustic emission measurement system

An elementary fiber Bragg grating comprises a short section of single-mode optical fiber in which the core refractive index is modulated periodically using an intense optical interference pattern, typically at UV wavelengths. This periodic index modulated structure enables the light to be coupled from the forward propagating core mode into backward propagating core mode generating a reflection response. The wavelength of light reflected by periodic variations of the refractive index of the Bragg grating (Figure 2), having a central wavelength $\lambda_B$ is given by:

$$\lambda_B = 2n_{\text{eff}} \Lambda \tag{1}$$

where $\Lambda$ is the grating period and $n_{\text{eff}}$ is effective refractive index of the core fiber.

The basic principle of operation of any FBG-based sensor system is to monitor the shift in the reflected wavelength due to changes in measurements such as strain and temperature. A typical commercial FBG interrogation system can be used to measure the wavelength shift. Such systems typically will have a wavelength resolution of 1–5 pm.

Similarly, when an acoustic wave impinges on an optical fiber with an FBG the refractive index of the fiber and the FBG period are modulated due to acoustic wave induced mechanical strain in the fiber through the elasto-optic effect. The dynamic wavelength shift, corresponding to the acoustic signal induced strain $\Delta \varepsilon(z, t)$ can be written as:

$$\Delta \lambda_B(z, t) = \lambda_B \left(1 - \rho_e \right) \Delta \varepsilon(z, t) \tag{2}$$

where $\rho_e$ is the photo elastic coefficient of the fiber.

Conventional FBG interrogation systems are relatively slow and the strain sensitivity is not sufficient to measure the AE induced events. Therefore, an AE FBG interrogation system will typically need sub micro wavelength resolution and high frequency measurement capability.

Simultaneous measurement of strain and temperature in AFP composites

In this experiment, a new sensing configuration based on an angled FBG (15º) related to the straight one was utilized. In this scheme, the angled and straight FBGs will have different strain sensitivities due to their orientation with the composite.
laminates, while their temperature sensitivities are assumed to be the same. The angle between the FBG sensors was set as 15° so that the FBG sensors stay within the width of the prepreg tape used. As the FBG sensors have different sensitivities, strain ($\Delta \varepsilon$) and temperature ($\Delta T$) at the vicinity of the FBG sensors can be calculated using the well-known characterization matrix as shown below.

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = \frac{1}{D} \begin{bmatrix} K_{22} & -K_{21} \\ -K_{21} & K_{11} \end{bmatrix} \begin{bmatrix} \Delta \lambda_{FBG1} \\ \Delta \lambda_{FBG2} \end{bmatrix}$$  \hspace{1cm} (3)

$$D = K_{11}K_{22} - K_{12}K_{21}.$$  \hspace{1cm} (4)

where $\Delta T$, $\Delta \varepsilon$, and $\Delta \lambda$ are in degree centigrade ($^\circ$C), microstrain ($\mu$ε) and nanometres (nm), respectively. Also, $K_1$ and $K_2$ are strain and thermal sensitivities of FBGs.

The strain and thermal sensitivity of the free space FBGs in the normal conditions are 1.2 pm/$\mu$ε and 10 pm/$^\circ$C, respectively. However, in this case as the FBGs are embedded inside the composites, the sensitivities to strain could be different from that of the free space one.

Therefore, to measure the true strain sensitivity of the FBG sensors, the sample with the embedded FBGs (including straight and angled FBGs with peak reflected wavelength of 1549.6 and 1554.5 nm, respectively) was setup on the tensile test machine (Instron 3369) to apply uniform loading at constant strain. The longitudinal extensometer was attached to the middle of the specimen and the FBGs were connected to the interrogator system (Figure 3(a)). The tensile test machine was setup under strain control and the specimen was strained up to 750 $\mu$ε at the constant rate of 0.5 mm/min. The reflected wavelength was measured using a commercial FBG interrogator system (IMON-256, Ibsen Photonics) routinely. Then, the strain sensitivity of both FBGs were obtained from the experimental slope ($K_{11}: 1.16$ pm/$\mu$ε, $K_{22}: 1.9$ pm/$\mu$ε), in which, the strain sensitivity of angled FBG is higher than the straight one (Figure 3(b)). It should be noted that, the reflection spectrum of the FBG before embedding and after embedding is obtained for both the straight and angled FBGs. There were no spectral broadening observed for the angled one after embedding. However, if a wider angle was set between the FBGs, there would be a possibility of strain gradient across the FBG and could result in spectral broadening, but with a small angle as in this experiment this was minimal and did not have any impact on the peak detection algorithm used in the interrogation system. As such, it is considered that $K_{12}$ is same in all the scenarios considered in this experiment. The thermal sensitivity of FBGs ($K_{11}, K_{22}$) in this new configuration are assume to be dependent only on the thermal expansion coefficient of the fiber and are independent of sensing head geometry, and thus it is assumed to the same as that of the free space sensitivity.

### Experimental program

#### Sample preparation

Two samples were manufactured using AFP for in-situ simultaneous strain and temperature study. A sample containing 10 plies of unidirectional prepreg CF/PEEK (AS4/APC2) supplied by Cytec were laid using Automated Dynamics AFP machine. The material properties of prepreg tape including density, module of elasticity, shear modulus, and Poisson’s ratio are 1570 kg/m$^3$, 138 GPa, 5 GPa, and 0.28, respectively. The prepreg had a fiber volume fraction of 60%. The tapes were laid down unidirectional (0/0) to each other and have a thickness of 0.15 mm and 12.7 mm width. The prepreg plies are processed simply by heating and cooling cycle.

The polyimide coated FBG sensors utilized for this experiment were able to withstand a temperature to 350 $^\circ$C. In this experiment, the HGT temperature was set to 750 $^\circ$C which delivers around 320 $^\circ$C to the tapes. The sensors were embedded between the second and third plies with the angle of 15° related to each other as shown in Figure 4(a). The straight and angled FBGs have peak reflected wavelength of 1549.6 and 1554.5 nm, respectively, with 10 mm long and reflectivity
Experimental setup

Strain and temperature measurement

The experimental setup shown in Figure 5 was used for discrimination of strain and temperature during the lay-up process in AFP using photonic technologies. First, two plies of CF/PEEK thermoplastic prepreg tapes were laid down on a substrate. As described in the previous section, the FBGs were placed, aligned, and secured on the top of the second ply. They were then connected to measurement systems including a commercial FBG interrogator, fiber optic circulator and broadband optical source. The spectral variation of the reflected signals from the FBGs were monitored for each ply during the entire fabrication process. The heat source using the hot gas torch (HGT) induced a temperature of 750 °C (~320 °C to the tapes). The force of 180 N is applied through the consolidation roller, which is made of stainless steel and has 10 mm diameter. The lay-up speed/deposition rate was set to 76 mm/s.

Acoustic emission measurement

To measure the acoustic emission within the laminate FAESense system from Redondo Optics Ltd was used. The maximum measurement frequency capability of the system is up to 1.16 MHz and the system can interrogate FBGs with greater than 70%. A very thin layer of super glue was used to fix the fibers on to the second ply, highlighted with an orange circle in Figure 4(b), without having any adverse impact on the FBG. The main purpose of this is to make sure that the FBG stays in place during the lay-up procedure. Typically, the superglue meltdowns/evaporates at high temperature, it is assumed that the superglue has not affected the structural integrity of the laminate. It may be noted that, after placing the third and last plies, the orientation of optical fibers double-checked to ensure the angle between the FBGs remains 15° as shown in Figure 4(c). This confirms that the 15° angle is retained during and after processing.

In order to check the capability of FBG towards the acoustic emission signature measurements, another set of samples with embedded FBG were fabricated using 10 plies of unidirectional prepreg glass fiber/Nylon (TC910) supplied by Cytec. The prepregs consist of Nylon-based thermoplastic resin system and unidirectional glass fibers with fiber volume fraction of 60%. The other material properties of prepreg tape including density, module of elasticity, shear modulus and Poisson’s ratio are 1730 kg/m³, 30 GPa, 11.53 MPa, and 0.3, respectively. The tapes were laid down unidirectional (0/0) to each other and have a thickness of 0.25 mm and 6.35 mm width.
FBGs were recorded as a wavelength (Figure 7(a)–(b)). Although the FBGs were secured between the second and third plies using super glue, after laying the third ply the orientation of the angled FBG was double-checked to see whether it remains at the same orientation or not (Figure 4(c)). Then, the reflected wavelengths were recorded during the lay-up of remaining plies.

With the measurement of the wavelength changes (Δλ_{FBG1} and Δλ_{FBG2}) for each lay-up from both straight and angled FBGs (Figure 7) and substituting them in the Equations (3) and (4), the values for change in strain (Δε) and temperature (ΔT) were obtained at the position of FBG sensors, as shown in Figure 8.

The results show that, with the increase in number of stacked plies, lower thermal effect is experienced by the FBGs (Figure 8(a)). This could be attributed to the fact that the presence of material (ply/plies) between the heat source and the FBGs. On the other hand, with the increase in number of stacked plies strain values measured using the FBGs varied from 428 to 551 με and was fluctuating as seen in Figure 8(b) with an increasing trend. This investigation is the first step towards the proof of concept for simultaneous measurement of strain and temperature. Though the possibility of simultaneous strain and temperature are measured, further experiments will be needed to validate and demonstrate the accuracy of the measured strain and temperature values.

**Experiments results and discussions**

In this experimental work, as mentioned previously, the attempt was towards the simultaneous measurement of strain and temperature and also assessing the capability of FBGs to measure acoustic emissions in a composite laminate.

### Wavelength measurement during the lay-up process for strain and temperature analysis

With the start of placement of the third ply above FBGs, the lay-up process was monitored and the reflected signals from the FBGs were recorded as a wavelength (Figure 7(a)–(b)). Although the FBGs were secured between the second and third plies using super glue, after laying the third ply the orientation of the angled FBG was double-checked to see whether it remains at the same orientation or not (Figure 4(c)). Then, the reflected wavelengths were recorded during the lay-up of remaining plies.

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obtained from the demonstrated experimentation to detect acoustic emission in composite laminates show that the embedded FBG can measure the acoustic signal frequency and amplitude. The frequencies detected by the FBG are very close to those generated by function generator and tuning forks. The obtained data and the corresponding frequency

Acoustic emission (AE) analysis

Thus far, a typical FBG sensor has been used in composite structures for structural health monitoring through prediction of wavelength change. In this experiment, the same FBG is used towards the detection of acoustic emission signatures in laminated composites manufactured using AFP. The results obtained from the demonstrated experimentation to detect acoustic emission in composite laminates show that the embedded FBG can measure the acoustic signal frequency and amplitude. The frequencies detected by the FBG are very close to those generated by function generator and tuning forks. The obtained data and the corresponding frequency
The predictions with the finite element were then compared with the experimental findings from the FBGs. In the model, a composite laminate with the same dimension (width and thickness) as one that was made for experiment is simulated and the material properties including thermal conductivities for different temperature are applied. Extremely fine mesh with size of 0.15 mm used in the direction of the mass flow (approximately 0.4 million elements). The mass flow was assumed uniform and defined as 76 mm/s using APDL command, same as the lay-up speed. The heat flux was adjusted so as to match the nip-point temperature used in the experimental work (320ºC) and applied to the length of 10 mm of both incoming tape and substrate.

Convection loads were applied to the all surfaces exposed the ambient environment including the entire bottom surface of substrate, a portion of outer layer of the incoming tape (~15 mm), and the areas with the length of 2 mm on either side of the heating zone on the both substrate and incoming tape, Figure 11(a).

The measured temperatures between the plies through FEA simulation are depicted graphically in Figure 11(b). The results obtained from the FEA are used as an input for strain analysis, which is described in the following section. However, further research and analysis in the FEA is required to predict the dynamic temperature at different plies accurately.

Another computational analysis was also adopted to understand the induced strain due to the combined effect of load and temperature during the lay-up process in AFP and was performed on commercial finite element software, ABAQUS/CAE 14.6-1.

In this model, a composite laminate consist of nine plies was simulated using conventional shell method. The mesh size of 0.5 mm was employed, generating 3520 elements in each layer. In order to simulate the contact area between the roller and tapes, the top surface of composite shell was divided into 20 regions (0.5 mm width) and to each one-step allocated. Then, temperature and load were applied for each step from one side to the other side as shown in Figure 12.

**Computational approach for strain and temperature measurement**

The computation approach for the processing characterization is carried out using the commercial finite element analysis (FEA), ANSYS Workbench 15. The predictions with the finite element were then compared with the experimental findings from the FBGs. In the model, a composite laminate with the same dimension (width and thickness) as one that was made for experiment is simulated and the material properties including thermal conductivities for different temperature are applied. Extremely fine mesh with size of 0.15 mm used in the direction of the mass flow (approximately 0.4 million elements). The mass flow was assumed uniform and defined as 76 mm/s using APDL command, same as the lay-up speed. The heat flux was adjusted so as to match the nip-point temperature used in the experimental work (320ºC) and applied to the length of 10 mm of both incoming tape and substrate.

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The displacement and rotation of the bottom surface ($U_x = UR_x = UR_y = 0$) and the left edge ($U_y = U = UR_x = 0$) of laminate are fully constrained. The load and temperature are same as those, which were set in the experiment applied to each step. For instance, as shown in Figure 12, when the load of 180 N and temperature 320 °C are applied to the step 10 (the values, which were set on the AFP machine as described in Section Strain and temperature measurement), the load in other steps is reset to zero, similarly the temperature in subsequent steps is reset to zero while for the previous steps, the temperature values are modified. The modified values for temperature are obtained from the heat flux simulation (Figure 11). Finally, the strain components at integration points were measured. The strain values corresponding to the direction of FBG sensors for lay-up 4 to lay-up 10 are presented in the Table 1. The FEA model shows only a small increase in the strain levels compared to the overall mean increasing trend measured by the FBG sensors (Figure 8(b)). To further validate the results more in-depth and accurate experimental and simulation results will need to be carried out, which is currently ongoing.

**Conclusion**

In this paper, we have demonstrated a FBG configuration with different strain sensitivities as an on-line monitoring technique for simultaneous measurement of strain and temperature in AFP. The measured strain and temperature values were in the expected range. The measured strain data are validated using FEA and are in close agreement. However, further experiment and FEA will need to be performed to completely validate the strain and temperature data, and the results from this paper, provides a direction to this research area. Moreover, the potential of FBG-based acoustic emission measurement technique is also demonstrated for ex-situ monitoring solutions. These results indicate that the structural health of laminated composites during in service life of composites can be monitored by measuring the acoustic emission using FBG sensing systems.

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**Disclosure statement**

No potential conflict of interest was reported by the authors.

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