STRUCTURAL HEALTH MONITORING AND PROCESSING OF COMPOSITES USING PHOTONIC SENSING TECHNOLOGY

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ABSTRACT

The increasing use of composite materials in many advanced structures brings with it a need to establish inspection and monitoring regimes to ensure structural integrity and safe operation throughout the service life. This results in the fast-growing composite industry searching for a technologically and economically feasible structural health-monitoring method to identify and assess defects/cracks in advanced composite structures at a very early stage of development. Optical fibre based photonic sensing technologies are increasingly common for structural health monitoring (SHM) of composite structures. In this paper, this method is used to determine the processing defects in composites effectively. In the first part of this paper, an overview of SHM for a sandwich composite specimen is presented by performing static, dynamic and low velocity impact test. Processing defects measured using embedded fibre Bragg gratings (FBGs) during automated manufacturing process of glass prepreg based composite laminates form the second part of this paper. Utilizing FBG sensors in the Automated Tape Placement (ATP), method we have demonstrated that variable parameters such as roller pressure, temperature can be measured real-time and as well as the formation of residual stresses in the fabricated laminates.

1 INTRODUCTION

In recent decades, composite materials are widely being used in various engineering industries like aerospace, marine, aviation and civil for a number of structural applications due to their high specific strength and stiffness [1]. Although composites materials have higher strength in comparison to other types of materials, their excellent mechanical properties might be negatively affected due to the presence of any flaw, failure or damage in their structure during the manufacturing process or due to fatigue or foreign object impact. [2]. These barely visible impact damages (BVID) can cause a serious reduction in load-bearing capacity of the structure. Thus to ensure the integrity of structural composites and for early detection of failure and also to ensure safety during their operation, structural health monitoring solutions are desired.

There are several manufacturing methods for making composite laminates [3]. The Automated Tape Placement (ATP) is one of the advanced one in which several manufacturing stages like cutting the tapes, lay-up, curing and consolidation are merged together in a lay-up head. This machine consists of a placement head and a robotic arm which is being operated by computer assisted controller [4]. In this method, the incoming prepreg tape is bonded to a previously laid and consolidated laminate under heat and pressure locally applied to the interface. These methods have considerable potential for increasing productivity and efficient manufacturing of composite laminates by improving the quality and increasing lay-up speed [4]. However, the quality of fabricated laminate may be adversely affected
by the presence of any change in the variable parameters like roller pressure and curing temperature during the lay-up stage.

Currently different types of non-destructive techniques (NDT) like X-ray radiography, Ultrasonic C-scan and Neutron radiography are being used for structural health monitoring of composite structures [5]; however, due to the size and weight of these devices it is difficult to use them in operational service. On the other hand, the optical fibre sensors (OFS) can be considered as an alternative method for in-situ health monitoring of composite structures both during the manufacturing process and service life due to their small size, light weight, immunity to electromagnetic interference and most importantly due to the possibility of remote operation [6]. They can be easily embedded within the composite laminates without affecting their structural integrity for automatic and continuous health monitoring. These optical sensors have the capability of monitoring stress, strain, temperature, vibration, cracks and delamination in composite laminates [7]. Among different types of optical fibre sensors, FBG sensors have good linearity and resistance to harsh environment [8].

Several studies have been conducted on the application of FBGs in composite laminates. Murukeshan et al. [9] have used FBGs for on-line monitoring of curing process in CFRP laminates and to indicate interfacial debonding within the sandwich composites for foam core [10]. Farmand et al. have demonstrated short length multiplexed FBGs for strain measurements under fatigue and invariable loads [11].

This paper presents a detailed study on static, dynamic and low velocity impact characterisation of sandwich laminate composites embedded with FBG sensors and also demonstrate the capability of FBGs for on-line monitoring of lay-up process in the advanced robotic composites. These findings further support the idea of a state-of-the art structural health monitoring technique for the automated tape lay-up processing.

2 FIBRE BRAGG GRATING SENSORS

An elementary FBG consists of a short section of single mode optical fiber in which the core refractive index is modulated periodically by 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 the backward propagating core mode generating a refraction response. The wavelength of reflected light by periodic variation of the refractive index of the Bragg grating \( \lambda_G \), is given by [12],

\[
\lambda_G = 2n_{\text{eff}} \Lambda
\]

where \( n_{\text{eff}} \) is the effective refractive index of the core and \( \Lambda \) is the periodicity of the refractive index modulation. The basic principle of operation of any FBG-based sensor system is to monitor the shift in the reflected wavelength due to the changes in measurements such as strain and temperature. The wavelength shift, \( \Delta \lambda_S \), for the measurement of an applied uniform longitudinal strain, \( \Delta \varepsilon \), is given as,

\[
\Delta \lambda_S = \lambda_G (1 - \rho_\alpha) \Delta \varepsilon
\]

where \( \rho_\alpha \) is the photo elastic coefficient of the fiber. The typical strain sensitivity of FBG at 1550nm is about 1.2pm/\( \mu \varepsilon \). For FBG sensors embedded in composite laminates, the dynamic structural variations are transferred to the embedded fibre and the strain induced dynamic change in the peak reflected wavelength of the FBG is measured and correlated to the structural dynamics of the composite laminate.

![Fibre Bragg Grating](image)
3 SHM OF SANDWICH COMPOSITE LAMINATE- CASE STUDY 1

3.1 Sample preparation

A sandwich composite sample was manufactured using hand lay-up method. Three plies of carbon fabrics (CF200) used together with vinyl ester resin (SPV6014-NUPLEX) for each facing. The plies are unidirectional to each other (0°/0°) with thickness of 0.33 mm. A foam core (Divinycell-H80) with thickness of 8 mm and density of 80 kg/m³ was place between the facings. The FBG used for these experiments has 10 mm long with a peak reflected wavelength of 1556.5 nm and a reflectivity greater than 70% and it was embedded between second and third plies of top facing. In order to provide uniform compression to the laminate a custom made press is used that leads to correct geometrical dimension after curing. The final dimension of the cured sample after machining was 280 mm x 50 mm x 10 mm.

3.2 Static strength characterisation of carbon-fibre-foam sandwich composite laminate

In case of static loading to estimate the strain distribution in the sandwich composite laminate, finite element analysis was carried out using ANSYS. Simulation of a uniform three point bending model is considered for the analysis where the two cylindrical supports are placed at both ends and the transverse load is applied at the centre of the specimen. The load range was selected from 100 N to 800 N. For the 800 N load a maximum strain of 1047.6 με is experienced in the middle region of the FBG. In order to validate experimentally, the flexural strength of the sandwich sample with embedded FBG is also carried out using an Instron three-point bending fixture to apply static loading. Transverse loads up to 800 N were applied at the rate of 5mm/min under displacement control. The strain experienced within the sandwich composite laminate is measured by the embedded FBG is shown in figure 2. In order to verify the FBGs results they are compared with analytical, numerical and strain gauge results.

![Figure 2. Comparison of measured strain using FBG with analytical and numerical results.](image)

3.3 Dynamic characterization of sandwich composite laminates

The dynamic characterization of sandwich composite embedded with FBG is carried out using the experimental setup shown in figure 3(a). In this cantilever configuration the end of specimen is-

![Figure 3. (a) Experimental setup; (b) Corresponding FFT spectra.](image)
clamped over the length of 20 mm. The specimen then is excited by tapping the free end and the dynamic optical wavelength change that corresponds to the sandwich laminate vibration is recorded by the FBG in the time and frequency domain. The maximum recorded wavelength change is approximately ±0.0045 nm, which corresponds to a strain change of ±3.75 µε and is dampened to zero in 0.2 seconds. In the FFT response, only one major frequency peak is visible, 88.32 Hz, which corresponds to the 1st natural frequency of the laminate, figure 3(b) [13].

3.4 Low velocity impact characterization of sandwich composite laminates

The impact resistance is one of the main parameters for composite designer to consider. Mainly for the sandwich composites which are consist of weak core. Several measurement techniques have been introduced and utilized to study impact characteristics of sandwich composites [14, 15]; however, in this test, induced-impact strain and damage progress within the sandwich specimen is measured with embedded FBG sensor using high velocity and high energy impact test machine (CEAST 9350). The change in the spectral shape of the FBG response and the wavelength change due to residual strain provided information on the depth of structural damage due to the impact.

The specimen was subjected to low velocity impacts from 5 to 10 J at an impact velocity of 1.35 m/s in the first run with an increase of 0.1 m/s for the other runs respectively. The test was stopped after six run, when the cracks developed in the laminate. These cracks are due to the shear failure of the foam as are inclined at about 45° starting at the top surface of the foam to the bottom, figure 4(b). The measured wavelength shift for the FBG sensor within the specimen due to impact forces are shown in figure 4(a). As witnessed, during the impact events a rapid strain increase was measured by the FBG sensor except for the fifth run. This inconsistency might be due to displacement of the specimen or a small drift in the impact’s location.

Another issue which should be considered is the increase of dissipated energy per strike with the increasing number of strikes. This is due to the reduction in sample stiffness and increase in damage accumulation. In order to measure the damage progress within the specimen the reflected wavelength of the FBG sensor was measured before and after the impacts and their full width half maximum (FWHM) before and after the impact was measured and is shown in figure 5 (a). A change in FWHM can provide an insight to the change in strain gradient within the FBG region, which conveys how the cracks are developing within the specimen. It can be seen in figure 5 (a) that there is an overall upward trend in the FWHM of the reflected spectrum of the FBG as the number of impact increases. A summary of the impact force and the impact induced strain measured by the embedded FBG is also given in table 1. The formation of residual strain after the impact force is also studied. The residual strength of a sandwich composite is directly related to the size and depth of the impact damage [16]. Therefore, in order to have a better understanding, prediction and monitoring of the localized failure of sandwich composites, the residual strain information was obtained from the FBG data. From the FBG...
response, the residual wavelength change ($\Delta \lambda$) for each hit was obtained and is demonstrated in figure 5 (b). As the impact force increases the residual wavelength change also increases by a small amount and the cumulative residual $\Delta \lambda$ is found to be increasing linearly as the number of impacts rises. The impact forces have resulted in sudden negative shift of wavelength (region A) and gradual increase of wavelength (region B), shown in figure 4. The gradual damping of the wavelength response is an indication of formation of residual stress. As seen in figure 4, the damping time (region B) for each run is different which might be due to the intensity of applied force or effects of accumulated damage within the specimen.

Figure 5. (a) Change in FWHM of the reflected spectrum of the FBG sensor with impacts; (b) Change in residual $\Delta \lambda$ of the FBG sensor after impacts.

<table>
<thead>
<tr>
<th>Impact</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (J)</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Strain (E)</td>
<td>0.578</td>
<td>1.498</td>
<td>2.042</td>
<td>2.324</td>
<td>2.048</td>
<td>2.488</td>
</tr>
</tbody>
</table>

Table 1. Strain and wavelength change measured by FBG.

4 MONITORING OF PROCESSING DEFECTS USING EMBEDDED FBG SENSORS-CASE STUDY 2

4.1 ATP Method

The automated tape placement (ATP) method is one of the advanced manufacturing technologies for making highly precise composite structures in the aerospace industry. Several manufacturing stages like cutting tapes, curing and consolidating are merged together which increased the productivity of this method over the traditional methods [4]. Though, utilizing this method has resulted in improvement of composite laminate quality through better compaction but issues like improper consolidation or imprecise tow placement leads to presence of defects in the components manufactured using this method. The aim of this study, at the first, is to check the capability of FBG sensors for on-line monitoring of composite lay-up using the ATP process.

4.2 Sample preparation and Experimental setup

In this experimental program, eleven plies of unidirectional prepreg glass fibre/HDPE (Cytec TC930), with HDT of ~121°C, were used to fabricate a composite laminate. The tapes have 100 mm long and 6.35 mm with thickness of 0.27 mm, with prepreg density of tapes as 1550 kg/m$^3$. The prepregs are processed simply by heating and cooling cycle and they were placed on top of each other using automated tape placement machine. The FBGs used in this experiment have 10 mm long with peak reflected wavelength of 1545.5nm and 1555nm respectively.

The experimental setup using AFPT robotic head for ATP process and on-line monitoring is shown in figure 6 (a). After placement and consolidation of first and second plies, optical fibre with array of two FBGs was placed on the second ply. Then, the FBG sensors were connected to the measurement system which was discussed in section 3.2. Finally, during the placement of the subsequent plies the FBG reflected signals were monitored and recorded. The process parameters in this experiment
including lay-up speed, consolidation pressure and curing temperature are 10 mm/sec, 450 N and 210 °C respectively.

4.3 Results and Discussion

The results obtained from the two embedded FBGs for each lay-up are shown in figure 7. The maximum wavelength change for both FBGs is observed in the first lay-up. Then, in the subsequent runs, it is reduces gradually. This means that by increasing the number of stacked plies the wavelength reduces. The changes in the FBGs’ wavelength are due to the effect of both pressure and heat which are applied during the tape lay-up. A comparison of the FBGs responds in figure 6 (b) reveal that the process parameters of ATP machine, including heat and pressure, for each lay-up remain particularly constant. Another important observation in this experiment is to monitor residual stresses after consolidation due to the information available from FBG sensors. It can be seen in Figure 7 that applying heat and pressure leads to sudden increase in the wavelengths and removing them result in the gradual reduction of wavelength. This phenomenon indicates formation of residual stresses which might be due to different thermal expansion of fibre and matrix or due to the shrinkage in the tape’s material after consolidation. In this study, the exact effects of pressure and temperature could not be investigated by the FBG sensor; however, the obtained results further support the idea that FBG sensors could be reliable candidate for online monitoring of lay-up process in advanced manufacturing methods like ATP.

5 CONCLUSION

In this paper, optical fibre Bragg grating sensors were implemented for on-line health monitoring of sandwich and laminated composites during and after manufacturing. In the first study, carbon fibre-foam sandwich composite with embedded FBG was fabricated and static, dynamic and low velocity
impact characterization was performed. From the results of static loading it was found that sandwich composites exhibit foam relaxation but its impact on strain measurement accuracy is negligible. The dynamic test characterization of the sandwich composite was also revealed that the fundamental frequency measured by the embedded FBG matches with that of the ones estimated previously using numerical and traditional accelerometer method. Finally by conducting the impact test, damage progress within the specimen was measured via measuring FWHM before and after impacts which give better understanding of the change in the strain gradient within the FBG region. In the second study, a glass-fibre laminate composite with embedded FBG sensors was fabricated using automated tape placement method. The lay-up process conditions were monitored for each lay-up at the FBGs’ position. Taken together, these results indicate that optical FBG sensors can be utilized as a reliable candidate for structural health monitoring of composite materials not only during the service life of composite structures but also during the fabrication process of advanced composites.

REFERENCES