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An experimental study on the effect of length and orientation of embedded FBG sensors on the signal properties under fatigue loading

Abstract: Fiber Bragg grating (FBG) sensors provide excellent capability for the structural health monitoring (SHM) of load-bearing structures by allowing for local internal strain measurements within structures. However, the integration of these sensors to composite materials is associated with several challenges that have to be addressed to have the correct strain measurement and in turn to perform reliable SHM. One of the most important issues is the presence of uneven strain fields around FBGs, which significantly affect the response of the sensors and hence the reliability of the acquired data. The uniformity of the strain fields around sensors is important for dependable data acquisition; however, to generate such a condition, tow width-to-FBG length relationship, optical fiber configuration with respect to reinforcement fiber orientation, and crack density resulting from fatigue loading are very important factors that have to be considered. In this paper, these issues are addressed by investigating the signal properties of FBG sensors with 1 and 10 mm lengths embedded within the composite specimens during the manufacturing process. After fatigue testing of the specimens, it is shown that 1-mm-long FBGs embedded in-line with adjacent reinforcement fibers with tow widths of ~2 mm provide much more reliable signals than 10-mm-long FBGs embedded perpendicular to adjacent tows.

Keywords: fatigue monitoring; fiber Bragg gratings; fiber optics; smart structures; structural health monitoring.

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1 Introduction

Currently, composite structures are built with high safety factors to account for the variability in constituent material and the lack of manufacturing repeatability, among other factors. They remain in service for a predetermined amount of time and discarded once they pass their predicted lifespan. These practices result in overbuilt/overweight structures that are discarded before they need to be. To overcome this situation, embedded fiber-optic sensors have been investigated for structural health monitoring (SHM).

A type of fiber-optic sensor called fiber Bragg grating (FBG) can be embedded within the composite material during manufacturing and used to monitor the fatigue loads induced in the structure. This gives the operator real-time knowledge of the condition of the structure during operation, allowing the composite structures to be built with a lower safety factor and operated until they must be replaced. FBGs can be used for the remaining useful life determination of composites and curing monitoring of polymer resins [1–3].

Many researchers have investigated the use of embedded or surface-mounted FBG sensors for damage detection in composites in real time [4–10]. In several of these works, the focus was on the investigation of the response of the fiber-optic sensors to transverse cracks and delaminations formed in the proximity of sensors due to either static or fatigue loading conditions. The spectrum responses of the long-gauge sensors are used to obtain quantitative information regarding the crack density [5, 6], crack locations [7], and delamination length [8, 9]. Moreover, the spectrum responses of sensors were modeled analytically and a rather satisfactory correlation with the experimental response was reported [5–7, 9]. Moreover, FBG sensing systems were developed for ultrasound detection within structures [11, 12] and their SHM capability was examined for damage detection of impact-damaged cross-ply carbon fiber-reinforced polymer [12]. In other works, FBG sensors with different lengths (i.e., 5–10 mm long) are embedded in a neat epoxy specimen having a region with uneven strain fields created either by a pre-notch [13] or varying the width of the sample smoothly [14] in the FBG sensor location. The results of these works have indicated that long gauge-length FBGs are vulnerable to uneven strain fields, thereby experiencing peak distortions and splitting in the reflected spectrum.

A major challenge with embedded FBGs in composite materials operated under fatigue lies in obtaining a clear and accurate signal. Matrix cracking and the orientation of adjacent reinforcement fibers may cause uneven strain fields in the grating resulting in peak splitting, which causes an offset in the reading obtained from the sensor. With proper FBG selection and reinforcement fiber orientation, these problems might be reduced or even eliminated. In this work, it is demonstrated that long FBG sensors (i.e., 10 mm) embedded inside fiber-reinforced composite specimens being subjected to uniaxial fatigue loading in the sensor direction can show distortion and splitting in the reflected spectrum and can even experience intermittent loss of the signal, although they are not initially and particularly positioned nearby the nonhomogeneous strain field. This intermittent loss of signal might be attributed to the formation of damage in the composite that creates dynamically varying strain fields in the proximity of the FBG sensor. It is further shown that short gauge-length FBGs (i.e., 1 mm) are much more immune to such strain fields and their spectrum is less likely to be distorted by the uneven strain distribution, hence leading to much more reliable strain measurement than the long FBG sensors as their spectrum is largely intact. Moreover, this work investigates the reasons causing the peak splitting of FBG sensors once embedded into composite structures subjected to fatigue loading and proposes a few important and practical factors (i.e., the tow width should be greater than the length of the FBG, the optical fiber should be aligned with the direction of the adjacent reinforcement fibers, and ideally the crack density should be equal to or greater than the FBG length) that need to be taken into account to circumvent its occurrence. This work is structured as follows. Section 2 provides a concise background and theory on FBG sensors. Section 3 introduces the experimental methodology. Section 4 proceeds with the results and discussion followed by the conclusions in Section 5.

2 Background and theory

FBGs are becoming increasingly popular for many applications due to their advantages such as their size, immunity to electromagnetic interference, multiplexing potential, and absolute reading. They have been used to measure properties such as displacement, strain, temperature, pressure, humidity, and radiation dose, among others. An FBG is a segment of a single-mode optical fiber core with a periodically varying refractive index in the axial (longitudinal) direction [15]. It allows a broad band of light to pass while reflecting a narrow band centered on a wavelength known as the Bragg wavelength λ_B. The reflected wavelength is a function of the grating pitch Λ (i.e., spacing between the refractive index variations) and the average refractive index n. An FBG satisfies the Bragg condition as

$$\lambda_B = 2n\Lambda \tag{1}$$

The change in spacing of the periodic refractive index modulation is a function of both strain and temperature. If an FBG sensor is under a mechanical load or temperature variation, the spacing and average refractive index will change, therefore causing a shift in the Bragg wavelength:

$$\frac{\Delta\lambda}{\lambda_B} = (1-p_e)\varepsilon + (\alpha+\xi)\Delta T \tag{2}$$

where $\Delta\lambda$ is change in the wavelength, p_e is the photoelastic coefficient, and α and ξ are the thermal expansion and thermo-optic coefficient of fibers, respectively. ε is the strain and ΔT represents the temperature change in the sensor [15].

The fatigue behavior of composites is a complex phenomenon due to various types of damage that can occur (fiber fracture, matrix cracking, fiber buckling, fiber-matrix interface failure, delamination, etc.) and interact with each other [16]. Research has shown that the damage process in fiber-reinforced composites under fatigue loading is progressive and a combination of various damage modes. The composite goes through three phases. The first phase is characterized by a sharp, nonlinear decrease in stiffness attributed to a rapid interconnection of matrix cracking initiated by shrinkage stresses, degree of resin cure, voids, and fiber discontinuities. The second phase is characterized by a gradual, linear decrease in stiffness attributed to matrix cracking leading to crack propagation, fiber debonding, and delamination. The final stage shows a sharp nonlinear decrease eventually resulting in a sudden fiber failure [17].

The signal from a typical embedded FBG under an even strain field is shown in Figure 1A. As observed, a narrow, clean, symmetric peak is reflected back from an

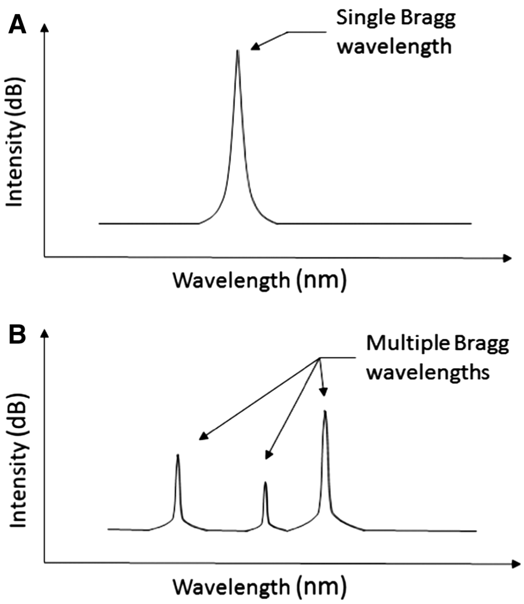

Figure 1: Schematics for reflected FBG spectrum from even strain field (A) and peak splitting resulting from uneven strain field (B).

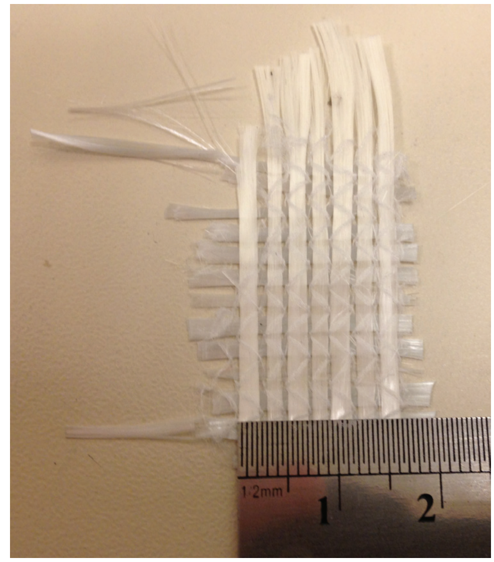

Figure 2: Fabric tow width (~2 mm).

FBG. When the FBG is subjected to an uneven strain field, various portions of the FBG are under different magnitudes of strain and therefore reflect a wavelength at the corresponding length. It is almost as though the FBG acts as a number of smaller FBGs. This can result in the reflection of more than one Bragg wavelength as in Figure 1B. This is known as peak splitting. From multiple reflected peaks, it is not possible to determine the average strain by simply tracking the peak wavelength, which is the standard technique used by most FBG interrogation systems. When embedded within a composite, a typical FBG with 10 mm length is exposed to a variation of strain magnitude due to the composition of the composite (stiff fibers and a compliant matrix). This results in the aforementioned situation of an uneven strain field, which causes the peak to split whereby a typical interrogation system can no longer detect the peak signal. The use of a shorter FBG, 1 mm in length that is aligned with the reinforcement fibers in the composite, has the potential to experience a less uneven strain field and therefore produce an acceptable signal possessing more reliable physical information.

3 Experimental investigations

To investigate the potential benefits of a shorter FBG and factors affecting the quality of acquired signals from a longer FBG, a number of experiments have been performed. Both 10- and 1-mm-long FBGs have been embedded in a glass fiber/epoxy composite and subjected to fatigue loading until failure. During loading, the signal from the FBG is monitored. After failure, the specimens are sectioned to acquire the relevant cross-sections that were polished and examined under an optical microscope.

3.1 Materials and sensors

The laminate selected for this research is $[(0/90)_6]_S$ and $[(90/0)_6]_S$, glass fiber with epoxy resin. The fiber used is LT300 E10A 0/90 biaxial E-glass stitched fabric (manufactured by METYX Composites, Istanbul, Turkey) with 161 gsm in the 0° orientation and 142 gsm in the 90° orientation, summing to 313 gsm total. The selected resin is Araldite LY 564 epoxy resin with XB 3403 hardener produced by Huntsman Corporation. The panels undergo an initial cure at 65°C for 24 h with a post-cure at 80°C for 24 h. Figure 2 shows a sample of the fabric with a ruler overlaid for reference. The tow width is measured to be approximately 2 mm. The FBG sensors used in this work are from FiberLogix, UK. They have a center wavelength of 1555 or 1540 nm and lengths of either 10 or 1 mm.

3.2 Fatigue specimen preparation

A number of processing methods exist for composite materials. One method that is particularly suitable to produce composite parts satisfying stringent specifications of the aircraft industry is the resin transfer molding (RTM)

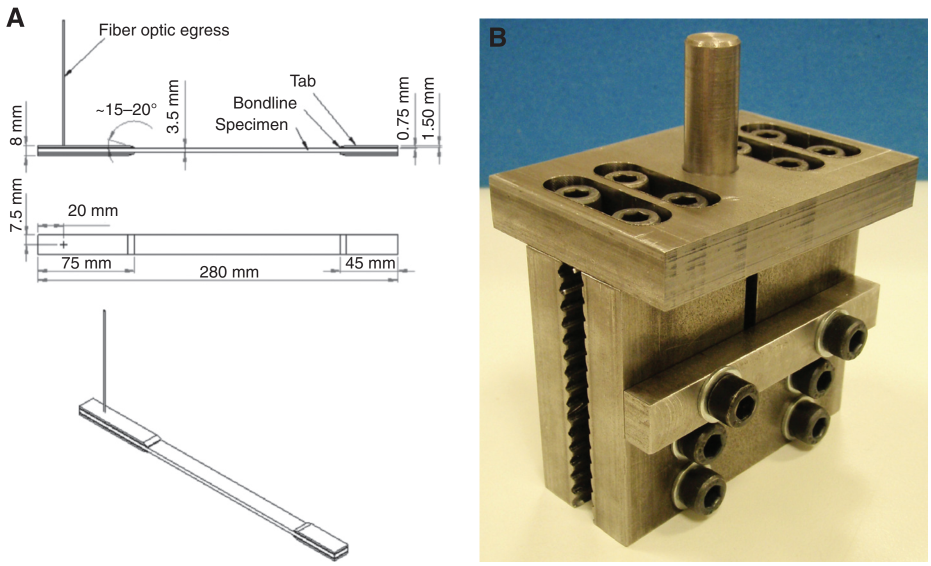

Figure 3: Drawing of test specimens (A) and gripping fixture (B).

technique. RTM can produce high-quality near net-shape parts with high fiber volume fractions, two high-quality surfaces, and little postprocessing in a fully contained system that eliminates human operator exposure to chemicals and reduces the chance of human error. For these reasons, RTM has been selected to produce the specimens for this study. A sophisticated laboratory-scale apparatus was designed and built with the ability of embedding fiber optics into the composite component. This apparatus is used to produce flat panels that are 620×320×3.5 mm, which are processed into specimens for fatigue testing. All specimens have fiber optics embedded in the mid-plane of the laminate. Depending on the configuration of the laminate $[(0/90)_6]_S$ or $[(90/0)_6]_S$, the FBG is perpendicular to or in-line with the glass fibers, respectively. This proves to be an important detail in terms of data collection as discussed later. A tabbing material composed of 1.5-mm-thick, plain weave E-glass fabric/epoxy with ~20° angle on one edge is bonded with West System 105 epoxy and 205 hardener thickened with milled glass fiber with a bond-line thickness of 0.7 mm. The panels are cut into specimens using a water-cooled diamond blade saw and the edges of specimens are polished by sandpapers with up to 400 grit. The final dimensions of the fatigue specimens are 280×15×3.5 mm with a 160-mm gauge length. The length of the specimen is aligned with the 0° fiber orientation. Figure 3A shows a drawing of the specimens. A special fixture is required to grip the specimen such that the fiber-optic ingress location is not under load. The fixture consists of three steel plates, a bar, and a pin. Two plates are clamped across either side of the specimen with bolts. One plate has a slot that allows the fiber to egress from the composite. The plates are screwed into the third plate that has a cylindrical pin that interfaces with the machine grips. A stiffening bar is located across the slot to reduce detection when the bolts are tightened. Figure 3B shows this fixture.

3.3 Fatigue loading

Many challenges lie in the area of fatigue testing of composite materials. They exhibit different characteristics from metallic materials that become apparent during fatigue testing. One such difference between metallic and composite materials is their heat conduction. Autogeneous heating becomes a major concern during fatigue testing of glass fiber-reinforced composites, as the built-up heat is not conducted to the environment as it is with metallic materials. The fatigue properties of composite materials are especially sensitive to heat. ASTM standard D3479 states that a temperature increase of 10°C has demonstrated measurable property degradation. Generally, a fatigue loading frequency of 1–4 Hz for glass fiber has been used with no or negligible heating [18]. This results in a lower testing frequency, which in turn results in extended time to perform an adequate test study. All fatigue tests were conducted with tension-tension sinusoidal load at 4 Hz. Fatigue loading was applied under a displacement-controlled mode with maximum displacement corresponding to a constant amplitude strain of 0.4 and 0.5 times the ultimate strain of the material. The maximum and minimum loads and displacement are recorded from the MTS software. The minimum stress on the specimens is 27.6 MPa, whereas the maximum load is determined as a fraction of the maximum stress of 318.75 MPa (0.4 or 0.5 depending on the test). The magnitude of the minimum load was selected based on the value used by Natarajan and Gangarao [17] in a similar fatigue study to prevent the generation of compressive loads. To determine the displacement amplitude to obtain the desired strain, a simple calibration procedure is performed: the specimen is loaded into the machine and a load that will produce the desired amount of stress is slowly applied and released and then applied and released a second time. When the specimen is unloaded, there is a residual displacement sensed by the linear variable differential transformer. This is due to the wedge grips tightening and the specimen slipping slightly before the full clamping force is realized. To account for this nonlinear phenomenon, the zero-offset/residual displacement value is subtracted from the maximum displacement on the second loading cycle. The peak of the FBG was interrogated with a Micron Optics SM230 interrogator at a rate of 100 Hz.

3.4 Microscopic inspection

To prepare samples for microscopic inspection, sections were cut from the full-sized specimen after having been subjected to fatigue testing. Initially, three small samples were cut perpendicular to the loading direction from the center of each fatigue test specimen using a water-cooled circular diamond saw. To investigate the cracks located along the fiber direction, samples are also cut parallel to the loading direction such that the optical fiber is as close as possible to the cut surface. All cut surfaces were polished on a rotating lap by progressive abrasion using finer and finer grits of silicon carbide sand paper and then investigated under an optical microscope with dark- and bright-field reflected light mode.

4 Results and discussion

FBG data were recorded during testing and the specimens were inspected under a microscope after failure to determine the crack density. The effects of the different FBG lengths and orientations are very evident in the collected data. Essentially, with a 1-mm-long FBG that is oriented in-line with adjacent reinforcement fibers, there are no lost data (data recorded as 0 due to a lost signal). Figure 4 shows the data collected from a specimen with a 10-mm-long FBG embedded perpendicular to adjacent reinforcement fibers. Initially, there is no loss of signal as can be seen in the first 8 s in Figure 4A. This continues for the initial 5% of the cycles before data points are regularly lost. As can be seen in Figure 4B, data points are successfully recorded during lower loading (troughs), with a few exceptions, but are lost (and recorded as 0) intermittently during higher loading (peaks). The intermittent nature of the signal loss at later cycles can be attributed to the dynamically varying strain fields due to the formation of defects in the vicinity of the FBG sensor. Under certain combinations of uneven strain state, the FBG spectrum is split whereby the interrogation algorithm can no longer detect the Bragg wavelength, thus leading to intermittent data loss.

Figure 5 shows the data collected from a specimen with a 1-mm-long FBG embedded in-line with the reinforcement fiber. It can be seen that the data points are recorded at virtually every time step from the initial cycles (Figure 5A) up to failure (Figure 5B).

To further illustrate the reliability of 1-mm-long FBG sensor under high cycle fatigue experiment, the spectrum of the FBG sensor is recorded at different durations of experiment (Figure 6). One may note that the FBG sensor holds its integrity for the entire duration of the test and does not show any noticeable degradation or peak splitting, which clearly points out the reliability and accuracy of measurement for the entire duration of the test.

After failure, the specimens were sectioned, polished, and examined under a microscope. The density of matrix cracking was measured to correlate the effect of the crack spacing and FBG length.

Figures 7A and 7B are microscopic images of the cross-section of fatigue tested specimens where the cross-section is parallel to the loading direction or the length of fiber optic cable and a number of cracks can clearly be observed thereon. The average crack density was measured to be approximately 1.1 mm. The interaction between the fiber optic and the composite was also inspected to determine if the FBG was debonding inside the laminate, which may be contributing to the loss of the signal. Figure 8 shows a cross-section of the embedded fiber optic. It appears that there is no detrimental interaction between the FBG and the composite and hence no debonding between them. As one may note from this figure, the fiber-optic sensor is surrounded by three different regions, namely, reinforcing fibers parallel (region 1) and perpendicular (region 2) to the fiber optic and matrix (region 3). This case might further contribute to the development of uneven strain distribution around the FBG. However, the sinusoidal wavelength change and the FBG spectrum data

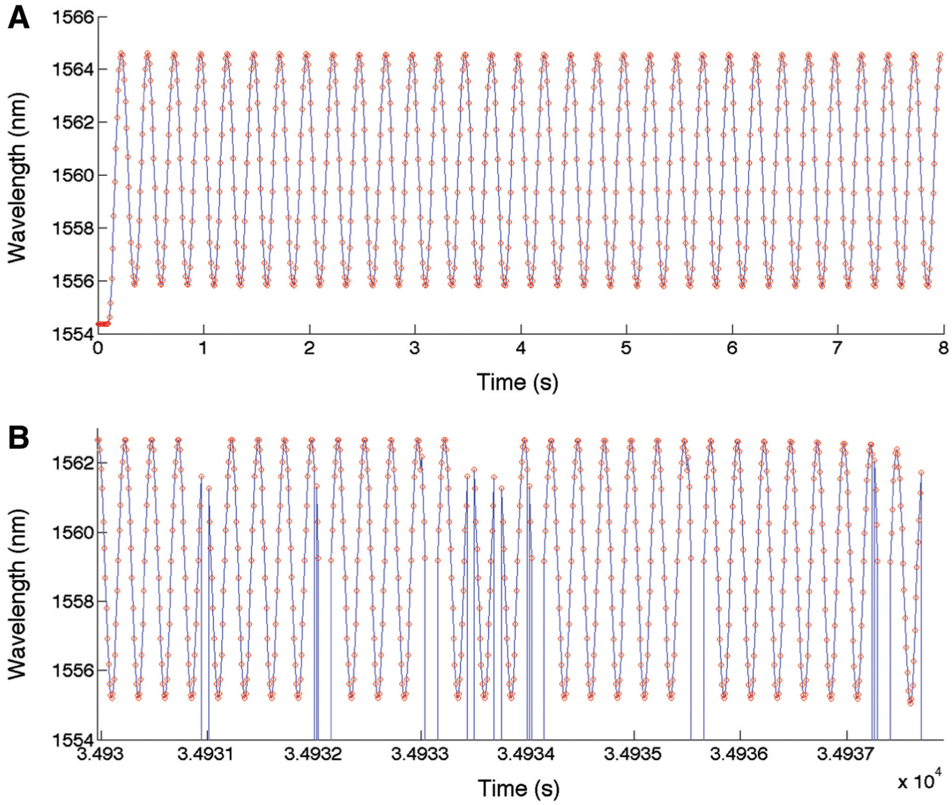

Figure 4: Cyclic variation of wavelength of 10-mm-long FBG: (A) initial 8 s and (B) final 8 s.

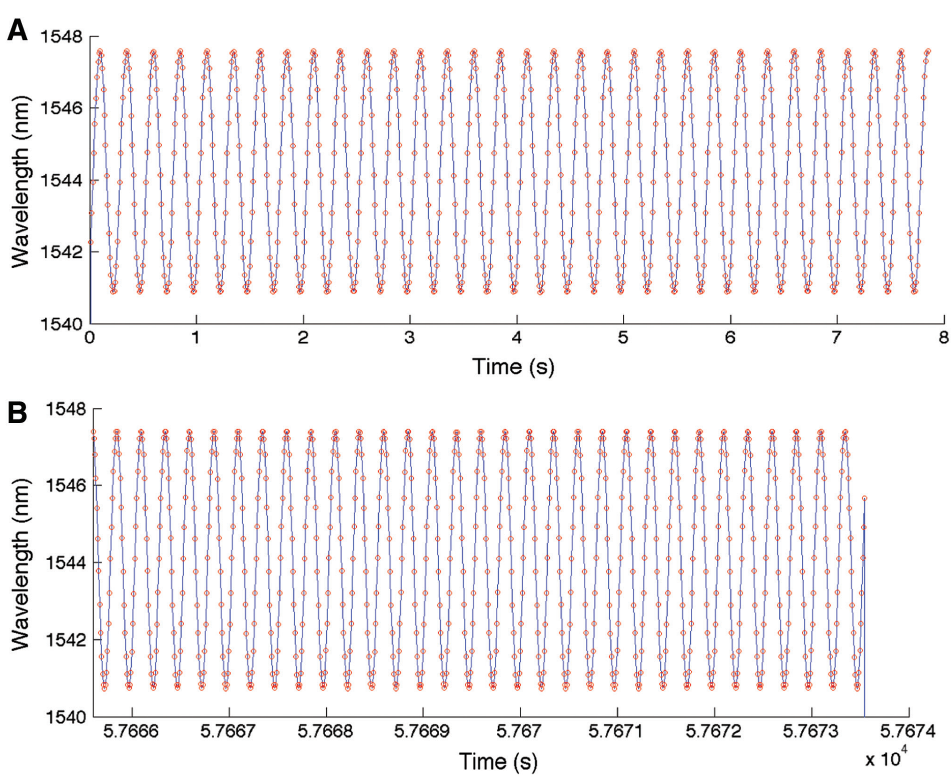

Figure 5: Cyclic variation of wavelength of 1-mm-long FBG: (A) initial 8 s and (B) final 8 s.

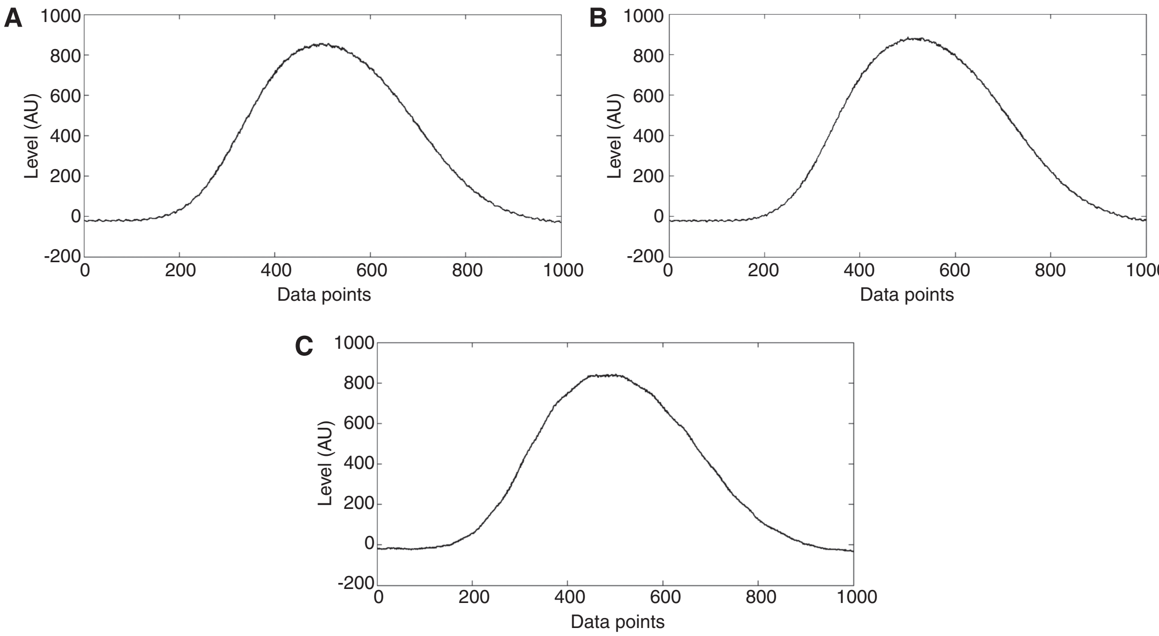

Figure 6: Spectrum of the 1-mm-long FBG sensor: (A) before the fatigue experiment has started, (B) at 3×10^6 cycles, and (C) at nearly 4×10^6 cycles.

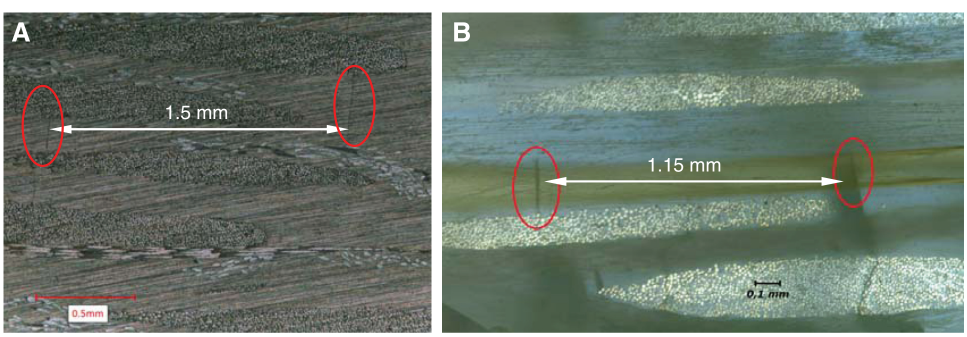

Figure 7: Microscopic images of the cross-section of fatigue tested specimens where the cross-section is parallel to the loading direction or the length of fiber optic cable. A number of transverse cracks, and two transverse cracks just above the fiber optic cable can clearly be seen in (A) and (B) respectively.

show that 1-mm-long FBGs are not prone to uneven strain distribution, which can normally cause peak splitting; hence, they can easily provide local strain data reliably.

The difficulty in embedding FBG sensors in composite materials having inherent local nonuniform strain distributions lies in ensuring that sensors are under an even strain field. Three important main factors influence the consistency of the field, thereby enabling FBGs to reliably monitor strain during fatigue loading. The first factor is the relationship between FBG length and tow width. In a composite made with noncrimp fiber (NCF) material, tows (bundles of fiber) are stitched together to make up a fabric. Once the composite is processed, the regions between the tows are resin rich compared to those regions within the tows. The stiffness of the resin-rich areas is less than within the tow, as there is only resin and no glass fiber to increase the stiffness. This results in an uneven strain field across a number of tows when a load is applied. In the material used in the study, the tow width is on the order of 2 mm. This is greater than the length of the 1-mm-long FBGs and less than the length of 10-mm-long FBGs. At most, a 1-mm-long FBG will experience one resin-rich area, whereas a 10-mm-long FBG will experience four resin-rich areas. The more excessive variation in strain seen in a longer FBG results in a broader reflection spectrum and, in some cases, causes a loss of the ability to track the peak wavelength. Figure 9A describes this configuration and shows the relative sizes of FBGs and tow width. In line with the concept of maintaining an even strain field by reducing the number of tows that cross an

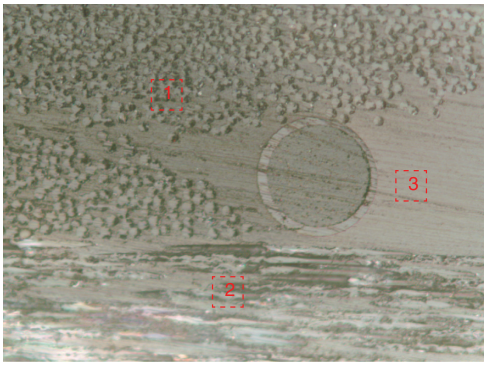

Figure 8: Microscopic image of the cross-section of an embedded optical fiber.

FBG, the reinforcement fiber orientation also plays an important role. If the fiber optic is embedded in-line with the reinforcements that it is in contact, it will experience a less uneven strain field. Figure 9A and 9B show the two possible optical fiber/fiber reinforcement orientations. The experimental results show that optical fibers oriented in-line with the reinforcement (Figure 9B) had a sharper reflected spectrum and were therefore more reliable.

The crack density plays a similar role to tow width in maintaining a consistent strain field. When a crack in the composite develops, the region around the crack experiences a different strain field than the intact composite. Thus, the formation of multiple cracks in the vicinity of an FBG can create uneven strain fields along the sensor length. The crack density in our specimens that were examined under an optical microscope is approximately 1.1 mm. This is slightly larger than the 1-mm-long FBGs. On average, the 1-mm-long FBGs will experience one crack, whereas the 10-mm-long FBGs could experience nine cracks leading to a higher probability of exposure to such uneven strain fields. This reinforces the fact that the 1-mm-long FBGs produced better data than the 10-mm-long FBGs.

In addition to the three main factors influencing the measured signal accuracy, namely, tow width-to-FBG length relationship, optical fiber and adjacent reinforcement fiber orientation, and crack density resulting from fatigue loading, other factors such as edge delamination and composite thickness might also influence the measurement accuracy of the signal. The edge delamination is triggered by interlaminar stresses occurring in the proximity of free edges because of layer-wise difference in elastic properties. The current lamination structures are selected given its ease for manufacturability and also placing the FBG sensor perpendicular and parallel to tow directions achieved by the stacking sequences of $[(0/90)_6]_S$ and $[(90/0)_6]_S$, respectively. Out of these two stacking configurations, $[(90/0)_6]_S$ configuration is expected to carry a smaller edge delamination risk than $[(0/90)_6]_S$. However, it should be borne in mind that the regular distribution of interlocked layers can reduce the edge delamination hazard. In our experiments, we have not observed any edge delamination that can alter the signal behavior. Moreover, noting that the FBG sensors are positioned away from the free edges, the edge effects (if existing) are not prominent to affect our measurements. If the FBG sensor is to be placed nearby the edges, a possible occurrence of edge delamination should be considered, which can be reduced by optimizing the ply angles as elaborated in detail in Ref. [19]. Another important factor that needs to be taken into account might be the thickness of the laminate. If the laminate thickness is comparable to the diameter of the optic cable and thus the FBG sensor, the signal quality of the FBG sensor might be altered under fatigue loading. It is noted that, in our another work, a 1-mm-long FBG sensor embedded into the midplane of 2.26 to 2.21-mm-thick symmetric composite laminates having six layers of either unidirectional glass (600 Tex, 283 g/m^2) or carbon fibers (800 Tex 12K, 300 g/m^2) gives a reliable signal when subjected uniaxial static tensile loading. However, the fatigue behavior of short FBGs in thin laminate is not investigated within the scope of this work and will be examined in our further studies.

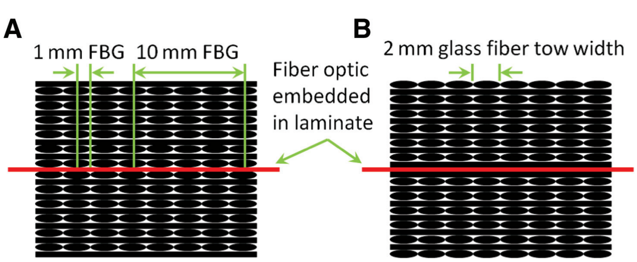

Figure 9: Schematics of an embedded FBG. (A) $[0/90]_{6S}$ with fiber optic in 0° direction. (B) $[90/0]_{6S}$ with fiber optic in 0° direction.

5 Conclusions

When an FBG is under an uneven strain field, the reflected spectrum will broaden and eventually split into a number of peaks. This results in either a loss of signal or an inaccurate signal due to a peak shift caused by the split. To embed FBGs in an even strain field, three factors should be kept in mind: (i) tow width-to-FBG length relationship, (ii) optical fiber and adjacent reinforcement fiber orientation, and (iii) crack density resulting from fatigue loading. The tow width should be greater than the length of the FBG, so that it only experiences one region of uneven strain (the resin-rich area between the tows). The optical fiber should be aligned with the direction of the adjacent reinforcement fibers. This further reduces the uneven strain field found between the tows. Ideally, the crack density should be equal to or greater than the FBG length. Cracked regions have different strain levels in the local vicinity compared to the intact region and therefore contribute to an uneven strain field in a similar manner to the resin-rich regions between tows. Experimental results show that the signal from a 1-mm-long FBG embedded in-line with adjacent reinforcement fiber within a NCF material with tow widths of ~2 mm and a 1.1 mm crack density after fatigue testing is much more reliable than a 10-mm-long FBG embedded perpendicular to adjacent tows.

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