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FBG-based real-time evaluation of transverse cracking in cross-ply laminates

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ABSTRACT

Transverse cracking is one of the most common initial failure modes of composites and has detrimental effects on the structural integrity. In this paper a novel real-time non-destructive testing method is proposed to evaluate the transverse cracking in cross-ply laminates. The FBG sensors were embedded in the cross-ply specimens $[0_2/90_n]_s$ and $[90_n/0_2]_s$, $n = 2,3,4$, at the interface along the fiber direction. The Digital Image Correlation measurement was applied in the tensile testing to determine the density of the transverse cracks. The FBG spectrum was distorted as the crack density increased and its width at a quarter of the peak $w_{1/4}$ showed a high correlation with the crack density. A numerical method based on spectrum reconstruction using the Transfer Matrix Method was then introduced to investigate the relations between spectrum distortion and transverse cracking. The reconstructed spectrum has an accurate reproduction of the reflective spectrum of FBG. The results demonstrate that the spectrum distortion attributes to the non-uniform distributions of the longitudinal strain due to the transverse cracks and $w_{1/4}$ can be applied as an effective indicator to evaluate the transverse crack density. The demodulation method using the FBG spectrum can be used to real-time detect the internal transverse cracks of composites.

1. Introduction

Composite is damage susceptible and involves distinct damage modes, such as interfacial debonding, matrix crack, fiber break, inter-laminar delamination. Among them, transverse cracking is one of the most common initial failures in composite structures and has detrimental effects on the structure integrity [1]. Chamis and Sullivan [2] have shown that the transverse cracks could sharply decrease the longitudinal compressive strength and intralaminar shear strength. Zubillaga et al. [3] investigated the process of transverse cracking under off-axis loading and noted that the cracks would introduce subsequent delaminations in composite laminates. The understanding of transverse crack initiation and propagation is the foundation of structural durability and damage tolerance evaluation for composites.

Two approaches are primarily used to evaluate the matrix crack evolution, which are based on the experimental investigation [4,5] and the development of the damage models [6,7]. To reach a more intuitive and reliable evaluation, several traditional experimental methods have been conducted to estimate the process of transverse cracking including both destructive and non-destructive methods, such as the optical microscope [8], scanning electron microscope, X-ray radiographic inspection [9]. However, these methods are always time-consuming and involve a lot of specimen handling. In order to improve the service efficiency and ensure the structural reliability, several in-situ methods have been proposed to detect the potential damages, i.e., transverse cracks. Yang et al. [10] applied ultrasound infrared thermography method to detect the matrix cracks in aerospace composites and they pointed out that the method was sensitive to closed cracks rather than open cracks. Selvakumaran et al. [11] and Abry et al. [12] characterized the transverse cracks with electrical potential change and their results indicated that the electrical potential measurement was limited for laminates with low conductivity. Scholey and Wilcox [13] also paved a new in-situ technique to quantitative the matrix cracks by acoustic emissions, but the acoustic signals were often vulnerable to environmental interference. Moreover, full-field measurement methods [14,15] have been proven to be feasible to detect the cracks on-line, such as Digital Image Correlation (DIC) method. The nature of these methods is to estimate cracks through displacement, strain or abnormal temperature changes. However, using an optical method only the surface cracks could be detected, while the laminates may sustain internal damages, including delamination and cracking. To the author's best

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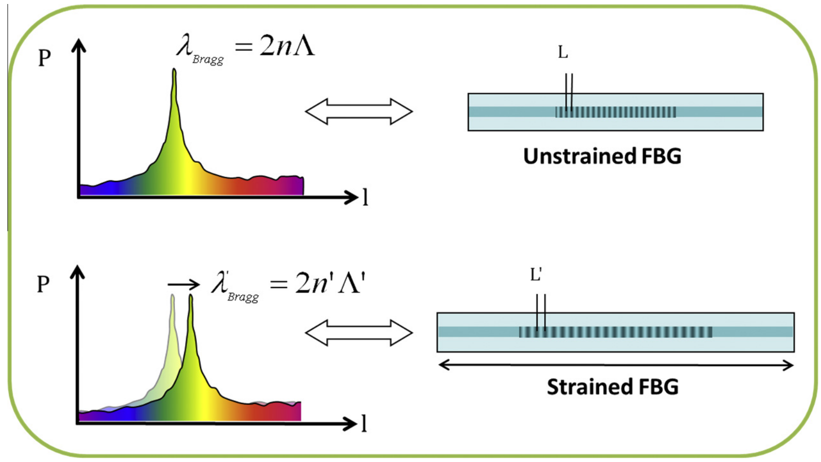

Fig. 1. The working principle of a FBG sensor.

Table 1
Parameters of the FBG sensors.

FBG parameter	Data
Grating length L	10 mm
Initial period Λ_0	525.68–532.53 nm
Mode effective index of refraction n_{eff}	1.46
Mean index variation Δn_{max}	0.00025
Photoelastic constant of core P_{11}	0.121
Photoelastic constant of cladding P_{12}	0.270
Poisson's ratio v	0.17
Refractive index distribution coefficient m	1

knowledge, very few reliable methods have so far been addressed on real-time detection of the internal transverse cracks.

As one of the promising sensing techniques for Structural Health Monitoring (SHM), optical fiber sensing system has become the forefront of the in-situ non destructive testing (NDT) techniques [16]. A Fiber Bragg Grating (FBG) sensor is a wavelength encoding fiber sensor which makes it self-referencing and easy to integrate distributed measurement system. Due to their small size, FBGs can be embedded in composite laminates without altering the structural integrity [17]. FBGs have been integrated into composite laminates to collect the internal information, such as strain and temperature. Papantoniou et al. [18] and Pereira et al. [19] demonstrated the good strain sensibility of embedded FBGs using mechanical tests. Ryu et al. [20] applied multi-channeled built-in FBGs to monitor the strain data of a composite wing box during buckling. Karalekas et al. [21] investigated the process-induced residual stress with the strain data obtained using embedded FBGs. Shrestha et al. [22] developed a 1-D FBG array to monitor the impact loads of composite wings. As the common solution of these papers, the FBG spectrum was demodulated by the center wavelength change which considers the uniform strain along the fiber grating. However, very little effort has been paid to study the reflective spectral shape information which relates to the strain distribution and structural damage. Ussorio et al. [23] reported the spectrum change of FBG embedded in GFRP during tensile testing and it was supposed that this phenomenon was related to the appearance of transverse cracks. Mulle et al. [24] also observed the similar change of FBGs bonded to laminates during static loading but no more explanation was given. To the authors' best knowl-

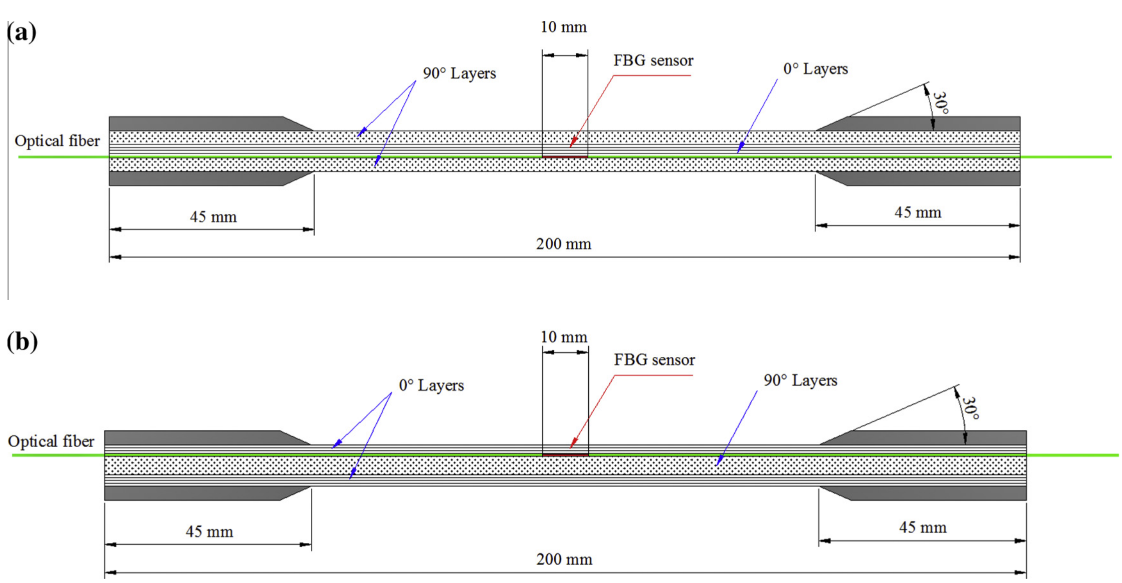

Fig. 2. Embedding of an FBG sensor into CFRP laminates: (a) $[90_n/0_2]_s$; (b) $[0_2/90_n]_s$.