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A novel method of identifying damage types in carbon fiber-reinforced plastic cross-ply laminates based on acoustic emission detection using a fiber-optic sensor

Feng-ming Yu [a, *], Yoji Okabe [a], Qi Wu [a], Naoki Shigeta [b]

[a] Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505, Japan
[b] IHI Corporation, 229, Tonogaya, Mizuho-machi, Nishitama-gun, Tokyo 190-1297, Japan

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ABSTRACT

We applied a highly sensitive phase-shifted fiber-optic Bragg grating (PS-FBG) sensor with a broad bandwidth to acoustic emission (AE) detection in a composite material. Based on AE detection, this research proposed a novel method to identify damage types in carbon fiber-reinforced plastic (CFRP) laminates. Because the PS-FBG sensor measured pure dynamic strain, the detected AE signals had great physical reliability, which made elastic wave theory suitable for analysis of the signal. The analysis clarified the different characteristics of Lamb wave modes in three types of AEs caused by a transverse crack, delamination and fiber breakage. Additionally, the ratios of the amplitudes of the S_0 mode to the A_0 mode and the peak frequencies quantitatively evaluated the mode characteristics in the AE signals. Simultaneously using the two physical parameters, we identified the three types of damage among the AE signals detected in a three-point bending test. Furthermore, the finite element method-based AE wave propagation simulation agreed well with the identification results. Hence, the proposed identification method with the PS-FBG sensor has great physical reliability for evaluating damage in composite laminates.

1. Introduction

Acoustic emission (AE) detection is a non-destructive testing (NDT) method for evaluating damage processes in structural composites [1]. Recently, fiber-optic Bragg gratings (FBGs) have been applied to AE detection [2–5]. Because of their good flexibility and durability, immunity to electro-magnetic interference (EMI), and ability to be embedded in composites [6,7], FBGs have potential to extend the application of AE detection to structural health monitoring of composites [8,9].

In addition, FBG sensors have the advantage of adding high physical reliability to the AE detection results because the Bragg wavelength shift of FBGs is proportional to the change in the axial strain [10]. By demodulating the shift at a high frequency measurement [11], the dynamic strain caused by AE waves could be correctly detected using an FBG sensor. Since AE waves propagate as a Lamb wave in the plate-shaped structure [12–14], analyzing detected AE waveforms using a PS-FBG sensor based on elastic wave theory has great potential to identify damage types.

However, common FBG-based AE sensors had low sensitivity and limited frequency bandwidth [3,4]. To develop the sensor for strong performance for AE detection, Wu and Okabe [15] used a special type of FBG, phase-shifted FBGs (PS-FBG), for a balanced sensing system. Due to its high sensitivity and broad frequency bandwidth, that sensing system was able to clearly detect AE signals with small energy in CFRP laminates [16–18].

The purpose of this research is to establish a reliable method to identify damage types in CFRP laminates through analyzing the AE signals detected by the PS-FBG sensor on the basis of Lamb wave theory.

F. Yu et al. [18] extracted amplitude ratios of the S_0 and A_0 modes from AE signals detected using the PS-FBG sensor to quantitatively evaluate the occurrence of transverse cracks and delaminations in CFRP laminates. However, because only one parameter was used, the method was not sufficient to identify damage among all the AE events.

The aim of the present work was to improve the identification method by using an additional parameter with good physical

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* Corresponding author.
E-mail address: houmei@iis.u-tokyo.ac.jp (F.-m. Yu).

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reliability. Recently, Baker et al. [19] applied a PZT sensor to identify transverse cracks in CFRP laminates by combining mode behaviors with the peak frequency, which is also an important characteristic in wave propagation. Analysis of the peak frequency in AE signals is also suitable for the present paper. This was because the broad bandwidth [15] allows a PS-FBG sensor to examine AEs with different peak frequencies. Utilizing the peak frequency and the amplitude ratio simultaneously could improve the quantitative identification method involving the PS-FBG sensor.

The special configuration shown in Fig. 1 was applied to improve the identification method. In this configuration, the optical fiber without the PS-FBG was glued onto the structural plate. The segment of optical fiber between the adhesive and the PS-FBG was used as the AE propagation waveguide. The PS-FBG sensor detected the propagating AE in the waveguide. Existing research [4] proposed a similar configuration for a strain-insensitive FBG sensor. In the present paper, we called this special detection configuration a new adhesive method for remote AE measurement (ADRM).

In Section 3, AE detection using the ADRM configuration clarified the characteristics of Lamb wave modes in the AE signals caused by transverse cracks, delaminations and fiber breaks in CFRP laminates. To evaluate the mode characteristics quantitatively, the amplitude ratio and the peak frequency were extracted from the AE signals. Then, on the basis of these two parameters, we classified AE signals that had been detected using the PS-FBG sensor to identify the specified three types of damage among a number of detected events during a three-point bending test. Finally, the identification result was verified by finite element (FE) simulation of AE propagation.

2. Experimental setup

2.1. AE data acquisition equipment

The PS-FBG balanced sensing system was used to detect the AEs generated from microcracking in the CFRP laminates. The electrical output of the PS-FBG sensing system was amplified by preamplifiers (MISTRAS, 0/2/4) and then recorded by an AE data acquisition system (Physical Acoustics, PCI-2). The sampling rate was set to 10 MHz. For comparison with the PS-FBG sensor, AEs were also detected using broad bandwidth PZT sensors (NF Co., AE-900M), from 0.3 MHz to 1.5 MHz, with a diameter of 5 mm and a height of 3.2 mm.

2.2. Specimen preparation

A T700S/2500 (Toray Inc.) prepreg system was used in the fabrication. Cross-ply CFRP laminates in a $[90_2/0_2]_S$ configuration were manufactured in a pressclave under a vacuum environment with a stage heating and by continued heating up to the maximum temperature of 130 °C in approximately 2 h. The manufactured specimen was used in the three-point bending test. Cross-sectional surfaces of the specimens were polished to observe the damage occurring during the test. For the mechanical properties of this type of laminate, we referred to existing research [18] in the following calculations of the dispersion curve and simulations.

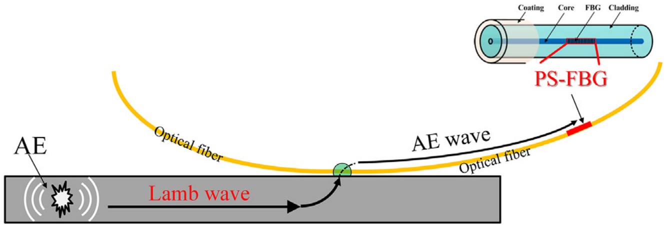

Fig. 1. The sensing configuration of a PS-FBG sensor using the new adhesive method for remote AE measurement (ADRM).

3. Characteristics of AE signals due to different damage types

As shown in Fig. 2, a three-point bending test was implemented to generate damage in the $[90_2/0_2]_S$ coupon specimen ($L \times W \times H = 180 \times 20 \times 1.2$ mm^3). The PS-FBG sensor was glued by the ADRM configuration to detect AEs generated during the bending test. The adhesive point was located 50 mm away from the loading pin. The distance between the PS-FBG and the adhesive point was 200 mm. Furthermore, as a reference to qualitatively verify that the S_0 and A_0 mode components were separated from the AE waves detected by the PS-FBG sensor, the two broad bandwidth PZT sensors were glued near the adhesive point but on two opposite surfaces [20].

The threshold of the channel connected with the PS-FBG sensor in the acquisition system was 75 dB, and the threshold of the channels connected with PZT sensors was 55 dB. These thresholds were high enough to eliminate the noise generated by friction between the loading pin and specimen and the noise caused by the feedback control of the PS-FBG balanced sensing system [21]. During post-processing, the AE signals were filtered over a frequency range from 150 kHz to 2 MHz to obtain the A_0 and S_0 modes clearly.

After the three-point bending test, the cross-sectional surface of the specimen was examined under a microscope. As shown in Fig. 3, the three-point bending test generated three types of damage in the CFRP laminates including transverse crack, delamination and fiber break. Based on the AE detection using the PS-FBG sensor, this research attempted to identify the three types of damage.

3.1. AE signals of transverse crack and delamination

After the first AE event, a transverse crack was identified under a microscope. The corresponding AE signals are shown in Fig. 4. A continuous wavelet transform (CWT) was applied to the AE signals to identify the modes that were included in the received wave. Fig. 4 (a) and (b) show the AE signals detected by the PS-FBG sensor and by one of the two PZT sensors located near the adhesive, respectively. The S_0 and A_0 modes were qualitatively identified on the basis of the dispersive characteristics [18]. The separation between the two modes in Fig. 4 (b) was verified by comparison with the calculated addition and subtraction of AE signals detected by the two PZT sensors [20]. The modes in Fig. 4 (a) had the same characteristics as those in Fig. 4 (b), with a delay in the arrival time resulting from the increase in propagation length caused by the optical fiber waveguide.

The amplitude of the A_0 mode in Fig. 4 (a) was found to be larger than that of the S_0 mode. To quantitatively evaluate this wave characteristic, we calculated the ratio of the peak amplitude of the S_0 mode to that of the A_0 mode. This ratio was defined as the E/F

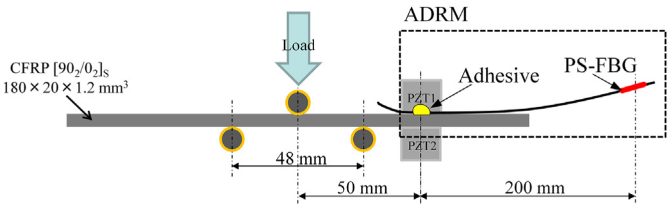

Fig. 2. Experimental setup of the three point bending test.