DAMAGE TYPE IDENTIFICATION BASED ON ACOUSTIC EMISSION DETECTION USING A FIBER-OPTIC SENSOR IN CARBON FIBER REINFORCED PLASTIC LAMINATES

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Abstract

Recently, the authors have developed a high sensitive fiber-optic ultrasonic sensing system with phase-shifted fiber Bragg grating (PS-FBG) and employed it for AE detection in composite materials. This research proposed a novel method to identify the damage types in carbon fiber reinforced plastic (CFRP) laminates from the AE signals detected by this system. As the PS-FBG sensor was highly sensitive to the normal strain over a broad bandwidth, the physical quantity of AE signals is much clearer than that of conventional AE sensors. Hence, the signals could be analysed based on a Lamb wave theory to quantitatively identify the damage types in the CFRP laminates.

The relative amplitude ratio between the two Lamb wave modes of S0 mode and A0 mode included in the AE signal was obtained after the modes were separated by a time-frequency analysis. Especially, we figured out that the peak frequencies of AE signals had a correlation with the modes. And then, from the actual AE signals detected by PS-FBG sensor under three point bending test, the characteristics of the amplitude ratio of the two modes and the peak frequency were clarified for identification of the three types of microscopic damages: transverse crack, delamination and fiber breaking. Hence, we believe that AE detection using PS-FBG has a great potential for evaluating the damage progress in the CFRP laminates based on the theory of Lamb wave.

Keywords: Optical Fiber Sensor, Composite Material, Guided Wave

1. Introduction

Acoustic emission (AE) detection is a non-destructive testing (NDT) method for evaluating damage processes in structural composites. Recently, fiber-optic Bragg gratings (FBGs) have been applied to AE detection [1-3]. Because of their good flexibility and durability, immunity to electro-magnetic interference (EMI), and ability to be embedded in composites, FBGs have potential for extending the application of AE detection to the structural health monitoring of composites [4, 5].

In particular, Wu and Okabe [6] 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 suitable for AE detection in CFRP laminates [7-9]. In this research, we attempted to find a reliable method to identify damage types in CFRP laminates based on AE detection using the PS-FBG sensor.

Because the PS-FBG sensor detects only the axial strain over a broad bandwidth, the detection results possess a high physical reliability. In addition, AE propagates as a Lamb wave in the plate-shaped structure [10, 11]. Hence, the elastic wave theory was applied to studying the detected AEs in this research.

F. Yu et al. [9] extracted amplitude ratios of the S0 and A0 modes from AE signals to quantitatively evaluate the occurrence of transverse cracks and delaminations in CFRP laminates.
laminates. However, because only one parameter was used, the method was not sufficient to identify damage among the amount of AE events.

The aim of the present paper was to improve the identification method by additionally using another parameter with highly physical reliability. As an important characteristic in wave propagation, the peak frequency of AE attracted our attention. This was because the broad bandwidth [6] allows a PS-FBG sensor to examine AE signals with different peak frequencies. Utilizing the peak frequency and the amplitude ratio simultaneously could improve the quantitative identification method involving the PS-FBG sensor.

A special configuration shown in Figure 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. The existing research [3] 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).

The damage identification method proposed in the present paper depends on correct responses to the $S_0$ mode and $A_0$ mode included in AE. However, the ADRM is different from the normal detection configuration. Hence, first, we studied sensing characteristics of PS-FBG sensor in the special configuration. Then, using the ADRM configuration, we 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. In the section 4, on the basis of the clarified characteristics of Lamb wave modes and peak frequency in the AE signals, we identified the three types of damage among a number of AE events detected under a three-point bending test. Finally, the identification result was verified by finite element (FE) simulation of AE propagation.

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


Characteristics of Lamb wave modes included in the AE signals or the ultrasonic waveforms are useful for studying properties of damages in the CFRP laminates. In the normal adhesive method, the PS-FBG sensor was glued directly on the plate surface in order to accurately detect the dynamic strain caused by the AE or ultrasonic wave at the adhesive point. Conversely, in the ADRM configuration, waves propagated through the waveguide of the optical fiber from the adhesive point to the PS-FBG. The wave propagation in the optical fiber could influence the detection of the Lamb wave modes. Hence, the experiment was conducted to investigate the sensing characteristics of PS-FBG sensor in the ADRM configuration.

In the experiment, we used piezo actuator-type macro fiber composite (MFC) to generate a three-cycle sinusoidal wave with a hamming window in an aluminum plate. In the ADRM configurations, the adhesive point was located 20 cm away from the MFC, and the PS-FBG
A sensor was located 40 and 60 cm away from the MFC to detect the ultrasonic wave, resulting in ADRM(40-20) and ADRM(60-20) configurations, respectively. In addition, normal adhesive methods with distances of 20 and 40 cm between the MFC and PS-FBG, respectively, were also used as references. They resulted in AD(20) and AD(40) configurations, respectively.

PS-FBG sensors in the different detection configurations were used to receive the input signals with central frequency of 150, 300 and 450 kHz, respectively. The responses of PS-FBG were modulated by the high sensitive balanced sensing system [6]. Figure 2 shows the results. On the basis of the theoretical dispersive curve of arrival time against frequency, the A0 and S0 modes were separated in detection results corresponding to the AD(40) and AD(20) at each frequency. Referring to the results in AD(20), it was observed that wave components having the same characteristics as that of the S0 and A0 modes also appeared in the ADRM(40-20) and ADRM(60-20).

The results indicated that the waveforms detected by using the ADRM configuration could reflect the characteristics of the Lamb waves at the adhesive point. In comparing with the results corresponding the ADRM(40-20) and ADRM(60-20), we determined that detected wave components propagated in the waveguide of optical fiber without distortion. Hence, PS-FBG sensor in the ADRM configuration have a feasible remote sensing of the A0 and S0 modes included in the original AE wave propagating from AE source to the adhesive point.

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<th>Central frequency: 150 kHz</th>
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Fig. 2 Comparison between the response of PS-FBG sensor in the common adhesive method (AD(40) and AD(20)) and ADRM configuration (ADRM(40-20) and ADRM(60-20)) to the ultrasonic wave with center frequency of 150 kHz (from (a) to (d)), 300 kHz (from (e) to (h)) and 450 kHz (from (i) to (l)).
3. The Characteristics of AE Signals Due to Different Damages

A three-point bending test was implemented to generate damage in the \([0_{2}/0_{2}]_{S}\) coupon specimen (LxWxH= 180x20x1.2 mm³). A T700S/2500 (Toray Inc.) system was used in the fabrication of the laminate. We glued the PS-FBG sensor in the ADRM configuration on the plate 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 verify that the S₀ and A₀ 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 [9].

The threshold of the channel connected with the PS-FBG and with PZT sensors were set to eliminate the noise generated by friction between the loading pin and specimen. During postprocessing, we filtered the AE signals over a frequency range from 150 kHz to 2 MHz to obtain the A₀ and S₀ modes clearly.

As the first step, after each AE event, the cross-sectional surface of the specimen was examined under a microscope to identify the corresponding damage. We detected three types of AE signals and showed them in the Figure 3 (a), (b) and (c). We applied a continuous wavelet transform (CWT) to the AE signals to identify the modes that were included in the received wave.

![Fig. 3 Continuous wavelet transformation (CWT) results for waves detected by the PS-FBG sensor in the ADRM configuration: AE generated by (a) transverse crack, (b) delamination and (c) fiber break.](image)

By observing the cross-sectional surface, we identified that the Figure 3 (a) and (b) were generated by transverse crack and delamination, respectively. Based on the dispersive characteristics [9], we qualitatively identified the S₀ and A₀ modes in them. The separations on the two modes were also verified by adding and subtracting the two AE signals detected by the PZT sensor pair. The amplitude of the A₀ mode in Figure 3 (a) was found to be larger than that of the S₀ mode. To quantitatively evaluate this wave characteristic, we calculated the ratio of the peak amplitude of the S₀ mode to that of the A₀ mode. This ratio was defined as the E/F ratio. In this research, the peak amplitudes were obtained from the CWT results. The E/F ratio obtained from Figure 3 (a) was 0.59.

In the Figure 3 (b), the AE signal corresponding to the event of delamination also clearly showed the separated wave mode components corresponding to the A₀ and S₀ modes. Comparing with the Figure 3 (a), Figure 3 (b) indicated that the amplitude of S₀ was larger than that of A₀ in the AE generated by delamination. The E/F ratio obtained from the result was 1.35.

Because of the broad bandwidth of the PS-FBG sensor, it was determined that not only the E/F ratio but also the peak frequency of AE was useful for identifying damage types in the CFRP laminates. The peak frequency corresponding to the AE of the transverse crack was 0.29 MHz, obtained from CWT results shown in Figure 3 (a). In contrast, the AE shown in Figure 3 (b) generated by the delamination had a higher peak frequency of 0.80 MHz.
The results also revealed that the peak frequency was directly related to the relative amplitude of \(A_0\) and \(S_0\) modes in the AEs, i.e., an AE had a lower peak frequency when the \(A_0\) mode was larger and an AE had a higher peak frequency when the \(S_0\) mode was larger. That was because the \(A_0\) mode dominated in the low frequency field of the AE wave, but the \(S_0\) mode was present in the relatively high frequency field [9, 10]. For example, the \(A_0\) mode was larger than the \(S_0\) mode in Figure 3 (a) and the peak frequency belongs to the \(A_0\) mode in the AE generated by the transverse crack. In contrast, the peak frequency of the AE caused by delamination belongs to the larger \(S_0\) mode in Figure 3 (b).

Figure 3 (c) shows one more type of AE detected using the PS-FBG sensor. We also found that the \(S_0\) and \(A_0\) modes appeared in the corresponding CWT result. However, the amplitude of the \(S_0\) mode was much larger than that of the \(A_0\) mode. The E/F ratio obtained from Figure 3 (c) was 6.2. Because of the strong \(S_0\) mode, the AE signal shown in Figure 3 (c) had a maximum peak frequency of 0.89 MHz. Because of these characteristics, we believe that this AE was generated by another type of damage.

Previous research [9] has determined that the \(S_0\) mode dominates in AEs caused by sources whose orientation is parallel to a plate surface and located close to the neutral plane in the thickness direction. Only damage in the 0-degree ply of \([90_2/0_2]_S\) could possibly satisfy those conditions. Hence, we inferred that the AE shown in Figure 3 (c) was generated by a fiber break.

In this section, we studied three types of AEs based on Lamb wave theory. The E/F ratio and the peak frequency obtained from CWT were helpful to quantitatively evaluate the characteristics of AE waves. In the next section, we attempt to use both of the parameters simultaneously to develop a reliable damage identification method.

4. Damage Type Identification Based on E/F Ratio and Peak Frequency

We conducted another three-point bending test for a specimen with the same laminate configuration \([90_2/0_2]_S\). As a result, 34 AE events were detected using the PS-FBG sensor in the ADRM configuration. E/F ratios and peak frequencies were calculated from CWT results of the AEs.

The E/F ratios and peak frequencies obtained from all of the AE events are shown in Figure 4 (a) and (b), respectively. However, both sets of results indicated that it was difficult to identify the three types of AE using a single parameter. Based on the analysis in section 3, we could identify that an AE with an E/F ratio of over 4.0 in Figure 4 (a) had been generated by fiber breakage. However, the differences between the other E/F ratios were too small to distinguish between AEs generated by a transverse crack or delamination. On the other hand, the peak frequencies in Figure 4 (b) separated into two groups. We identified the AEs with low peak frequencies as being generated by transverse cracks. However, it was still difficult to distinguish a fiber break from a delamination because of their similar peak frequency.

![Fig. 4 Damage identification on the basis of a single physical parameter: (a) E/F ratios and (b) peak frequency.](image-url)
Hence, we utilized the two parameters, E/F ratio and peak frequency, simultaneously to build a new damage identification method. First, every AE event was expressed as a vector consisting of the peak frequency and E/F ratio, which was plotted as one point in a 2-D space. Then, we applied a pattern recognition method—hierarchical clustering—that was based on the minimum distance between all of the points, to classify the AEs. As a result, three clusters of AE events corresponding to three types of damages were clearly determined in Figure 5. On the basis of the AE signal characteristics clarified in section 3, we identified the events in clusters 1, 2 and 3 as having been generated by fiber breaks, delaminations and transverse cracks, respectively.

![Fig. 5 Damage identification based on utilizing the E/F ratios and the peak frequency simultaneously.](image)

From the classification result, we were able to obtain a quantitative damage identification standard in the laminates [90/0]_S based on AE detection using a PS-FBG sensor in the ADRM configuration. When AE signals were filtered using a band filter from 150 kHz to 2 MHz, AE signals generated by transverse cracks had E/F ratios below 1, in the peak frequency range of 180 kHz to 390 kHz. The AE signals with E/F ratio from 1 to 3, corresponding to delamination events, had a peak frequency between 410 kHz and 900 kHz. The AEs caused by a fiber break had a distinctly large E/F ratio (over 4) in the peak frequency range of 750 kHz to 900 kHz. Quantitative damage identification was made much clearer by combining the E/F ratio and peak frequency, in comparison with using only one of the two physical parameters. In particular, we used a pattern recognition method to classify the signals, so this method also has great potential for identifying damage among a large amount of AE events.

5. Validation by FEM

To show the physical reliability of the identification method, we conducted a 2-D finite element (FE) analysis using LS-DYNA to validate the identification result. In this simulation, we mainly examined the E/F ratio of AEs caused by transverse cracks and delaminations. In this research, the AE sources were simulated as dipole sources of body force with a cosine bell shape and rise time of 0.2 μs. As an AE source, the source orientation of a transverse crack is along the in-plane direction. Delamination has a source orientation along the out-of-plane direction. [10] In addition, as shown in Figure 6, it was found by examination of the cross-section that transverse cracks only happened in the 90-degree-ply. Hence, to simulate transverse cracks in the cross-ply laminate with a thickness of 1.2 mm, the three dipole sources in the in-plane direction were located 0.6, 0.5 and 0.4 mm away from the neutral axis of the plate model, respectively. In contrast, delaminations happened after transverse cracks grew to reach the interface between the 90-degree-ply and the 0-degree-ply. Hence, delamination was simulated
by locating the out-of-plane dipole source 0.3 mm away from the neutral axis. In the three-point bending test, all of the damage appeared around the loading point in the bottom ply opposite to the loading surface. Hence, we put the adhesive point 50 mm away from the sources in the longitudinal direction. Because the PS-FBG was only sensitive to the normal strain, the outputs were the strain waves along the axial direction in the shell element of the optical fiber model 200 mm away from the adhesive.

![Schematic of the damage (input sources)](image)

Signal processing was applied to the simulated strain wave in the same way as the experimental data. We obtained the E/F ratios from the simulated strain wave to evaluate the characteristics of Lamb wave modes quantitatively. They were showed in Figure 7. This result indicated that source positions close to the neutral axis increased the E/F ratios. In particular, all of the E/F ratios corresponding to the simulated transverse cracks were below 1 and smaller than those obtained from the simulation result for delamination. The results calculated from the physical model were able to validate the difference between the E/F ratios extracted from the AEs caused by transverse cracks and those caused by delaminations.

6. Conclusions

Using experiment, we verified that ADRM configuration enable us to detect AE wave correctly. Then, AE detection was conducted under three-point bending test. In this research, using quantitative physical parameters, i.e., E/F ratio and peak frequency, obtained from AEs on the basis of Lamb wave theory, we developed a method to identify damage types in a CFRP laminate. The identification method had good physical reliability because the PS-FBG sensor detected the pure normal dynamic strain caused by AE over a broad frequency bandwidth. In addition, because of the ADRM configuration, the characteristics of the Lamb wave modes were clearly observable even in small coupon specimens and were evaluated correctly using the two quantitative identification parameters. The two AE parameters of E/F ratio and peak frequency enable us to apply a machine learning tool to the identification of damage types within a large number of AE signals. Furthermore, owing to the firm physical background of the method, the identification results could also be verified by FE simulation of wave propagation. Hence, we believe that the new method proposed in this research could be used as an NDT method with great physical reliability for identifying and evaluating damage types in composites.
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Reference