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ULTRASONIC TECHNIQUE FOR DAMAGE DETECTION IN COMPOSITE LAMINATES WITH AN EMBEDDED FBG SENSOR

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Abstract

Real-time structural health monitoring of composite structures with ultrasonic technique is presented in this paper. Ultrasonic Lamb wave, which is generated by a piezoelectric actuator, can propagate into a composite laminate. When delamination is developed inside the composite laminate, the propagation characteristics of the Lamb waves are altered. Delamination information can then be obtained from the signal received by an embedded fiber Bragg grating (FBG) sensor. A laser source is used in the signal acquisition unit because it enables a higher sensitivity of the system when compared to a broadband light source. In this study, glass fiber-reinforced epoxy composite (GF/EP) laminates with artificial delamination at different layers are fabricated. FBG sensors are embedded into the GF/EP laminates for the detection of ultrasonic Lamb wave. The velocity of Lamb wave in the GF/EP laminate is predicted and compared with experimental result. The waveforms of received signals change due to different sizes of the delamination region and the trend of the change of acquired signals with the growth of delamination size are examined.

INTRODUCTION

Delamination detection in fiber-reinforced plastics with the use of conventional nondestructive evaluation (NDE) techniques such as x-rays, thermography, eddy currents and ultrasonic C-scans has long been a subject of interest to researchers. This kind of composite materials offer the advantages of comparably high specific strength to weight ratio and excellent corrosion resistance, and hence have been widely adopted for advanced structures in aerospace, automobile and marine industries. Proper health monitoring for these materials is essential to ensure the integrity and reliability of the composite structures. In particular, ultrasonic Lamb wave, a guided elastic wave in plates with free parallel surfaces, shows a great potential for establishing novel nondestructive evaluation tools.

Piezoelectric lead zirconate titanate (PZT) is commonly used as an actuator and sensor for composite laminates for ultrasonic damage detection [1-3]. Recently, fiber Bragg grating (FBG) sensors have been proposed for measuring

Lamb wave in carbon fiber-reinforced polymer (CFRP) due to its immunity to electromagnetic interference [4, 5]. Besides, the FBG sensors have the advantages of small physical size, light weight, capability at high working temperature or environmentally unfavorable conditions, and can be easily multiplexed.

Previous research revealed that optical fibers embedded parallel to the reinforcing fiber direction would not induce significant effect in terms of the strength reduction to composite laminates [6]. In this paper, a hybrid actuator-sensor unit for damage detection in glass fiber-reinforced epoxy (GF/EP) composite laminate is presented. A PZT element and an embedded FBG sensor were used as Lamb wave generator and sensor, respectively. A tunable laser source was used in the sensing system. The acquired Lamb wave signals corresponding to different delamination sizes and locations are discussed. Since the propagation characteristics of Lamb wave are affected by the presence of damage in composite structures, their health condition can be potentially monitored in real-time through inspecting received signals from embedded FBG sensors.

THEORY

FBG Sensing Principle

FBG is a permanent periodic perturbation of refractive index in an optical fiber. It is fabricated by UV irradiation of the fiber with the 'phase mask' technique. When broadband light is transmitted through an FBG, a narrowband spectrum is reflected with a central wavelength called the Bragg wavelength, λ_B, which is given by

$$\lambda_B = 2n\Lambda , \qquad (1)$$

where n and Λ are the effective refractive index in the grating region and the grating period respectively [7]. Change of strain within the gauge length would alter the grating period and the effective mode index of refraction, resulting in a shift of the Bragg wavelength ($\Delta\lambda_B$). Under a controlled environment where the temperature effect is negligible, the Bragg wavelength shift in terms of the strain of the fiber within the gauge length is given as

$$\Delta\lambda_B = K\Delta\varepsilon , \qquad (2)$$

where K is the theoretical gauge constant.

FBG can be used as a sensor for detecting ultrasonic Lamb waves if the detection system is properly designed. The Lamb wave involved in ultrasound damage identification is usually generated in an ultrasonic frequency range of kilohertz or even megahertz, resulting in high speed strain change in the level of micro-strain. An optical spectrum analyzer (OSA) is unable to capture a dynamic Lamb wave appropriately. In order to solve this problem, a wavelength-intensity conversion technique is designed with the use of a tunable laser source.

Signal Acquisition

Fig. 1(a) shows the signal acquisition unit with the use of a tunable laser source. The wavelength of the laser source is tuned so that it falls onto the linear slope of the FBG reflection spectrum, i.e. 20-80% of the grating's maximum reflectivity (see Fig. 1(b)). When the FBG sensor is stretched, the Bragg wavelength shifts to the right and the light intensity increases. When the FBG sensor is compressed, the Bragg wavelength is shortened and the light intensity decreases. The changes of light intensity are recorded by a photo detector.

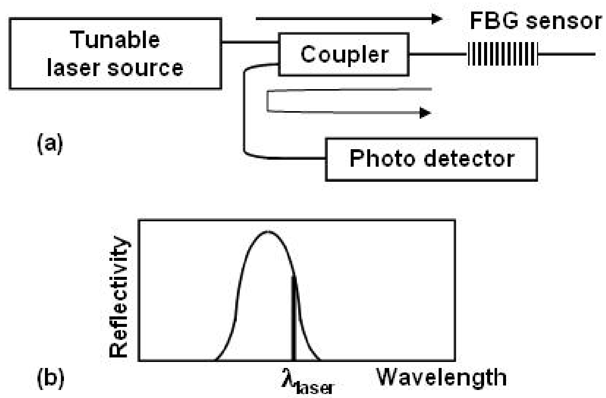

Figure 1. (a) Schematic diagram of the signal acquisition unit with a tunable laser source.
(b) Conversion of mechanical strain into light intensity.

Ultrasonic Lamb wave is used as a diagnostic signal in our study because it can propagate over a long distance with little attenuation. Lamb waves are described as symmetric or antisymmetric modes depending on the symmetry about the midplane of the particle displacement. One distinctive feature of Lamb wave is that its propagation velocity varies with the product of the excitation frequency and the thickness of the medium. Taking the limit of symmetric dispersion equation, a low frequency approximation of the fundamental symmetric (S_0) mode in a hypothetical isotropic plate can be obtained [8], and the velocity of S_0 mode can be written as:

$$V_{S0} = \sqrt{\frac{E}{2\rho(1-\nu^2)}} \ , \qquad (3)$$

where E, ρ and ν are the Young's modulus, density and Poisson's ratio of the material respectively.

EXPERIMENTS

Experimental set-up

Balanced type woven glass fiber-reinforced epoxy composite laminate samples were fabricated in our experiments. Single-mode acrylate coated FBGs with 10-mm gauge length were used as ultrasonic wave sensors. The FBG sensors were embedded between the 9^{th} and 10^{th} layers (counting from the bottom layer) of the composite plates during the fabrication process. The stacking sequence was $0°_9$/{OF}/$0°_1$, with {OF}denoting the position of the optical fiber. The coating and cladding diameters of the optical fibers were 250 μm and 125 μm respectively, with the coating removed at the grating region. Since the epoxy was highly susceptible to moisture in its liquid state, the laminate was cured under controlled temperature (20 °C) and humidity (55 %) for 24 hours. The consolidated laminate plates were then machined to form composite beams with the dimension of 440 mm x 25 mm x 2 mm. The mechanical properties of the laminate were obtained from a tensile test and listed in Table 1.

Table 1: Properties of GF/EP composite laminate

Young's modulus, E_{11}, E_{22} (GPa)	13.363
Shear modulus, G_{12} (GPa)	5.86
Poisson's ratio, ν_{12}	0.14
Density, ρ (kg/m^3)	1664.03

A PZT actuator (PI 151) having a diameter of 6.9 mm and thickness of 0.5 mm was attached to each sample with conductive silver epoxy. The locations of the PZT actuator and the FBG sensor on the composite beam are shown in

Fig. 2. The horizontal distance between the PZT actuator and the FBG sensor was 100 mm. The parameter L_D is the length of an artificial delamination created by putting a thin Teflon film between composite laminate, which was then removed after the curing process. In other words, L_D=0 for an intact composite beam.

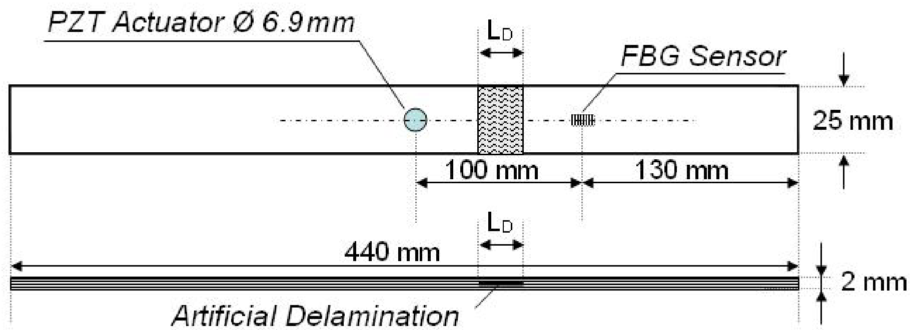

Figure 2. Locations of PZT actuator and FBG sensor on the GF/EP composite beam.

A 3-cycle tone burst modulated by the Hanning window function at the central frequency of 300 kHz was generated by a Hioki 7075 waveform generator. The signal was then amplified by a piezo linear amplifier (Piezo Systems) and transmitted to the PZT actuator as the diagnostic signal shown in Fig. 3. The velocity of S_0 wave mode predicted with Eq. (3) is 2862 m/s.

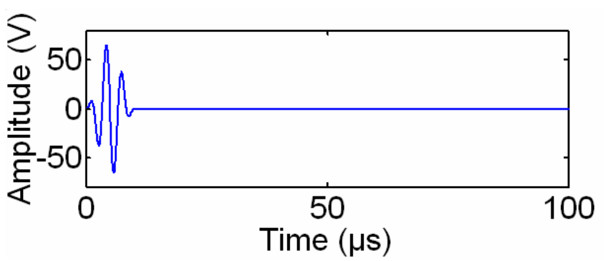

Figure 3. Input waveform to PZT actuator.

Results and discussions

Detection of delamination in a GF/EP composite beam with an embedded FBG sensor is presented in this section. The FBG sensing scheme described in section 2.2 was set up to measure the ultrasonic signal. First, an artificial delamination of 20-mm was created in the GF/EP composite beam by inserting a thin Teflon film between two laminate layers during the fabrication process. Two different cases were studied. In case 1, the Teflon film was inserted between the 5th and 6th layers measured from the bottom, while in case 2 the Teflon film was inserted between the 8th and 9th layers. In other words, the stacking sequence of the two cases are $0°_5$/{T}/$0°_4$/{OF}/$0°_1$ and $0°_8$/{T}/$0°_1$/{OF}/$0°_1$, where {OF} and {T} denote the position of the optical fiber and the delamination respectively.

When delamination is developed in a composite laminate, the Lamb wave propagation properties are changed. Fig. 4(a) compares the response from the intact GF/EP composite beam (dotted line) with that from the delaminated beam (solid line) in case 1. The captured signal was averaged by 200 waveforms to avoid random noise and technical error. The arrival time of S_0 mode was approximately 32 μs, which is a little faster than the predicted value of 35 μs. This is probably due to the assumption of an isotropic plate in the prediction model (Eq. (3)). The S_0 mode could be easily identified as it arrived first, followed by the A_0 mode (fundamental antisymmetric mode) and subsequent reflected modes. In Fig. 4(b), the delamination occurred between the 8th and 9th layers in case 2, and the response of the delaminated beam (solid line) was compared with that from the intact beam (dotted line). The delaminated beam in case 2 produced a much higher deviated signal than the delaminated beam in case 1. It is believed that the delamination closer to the top surface can be identified more easily.

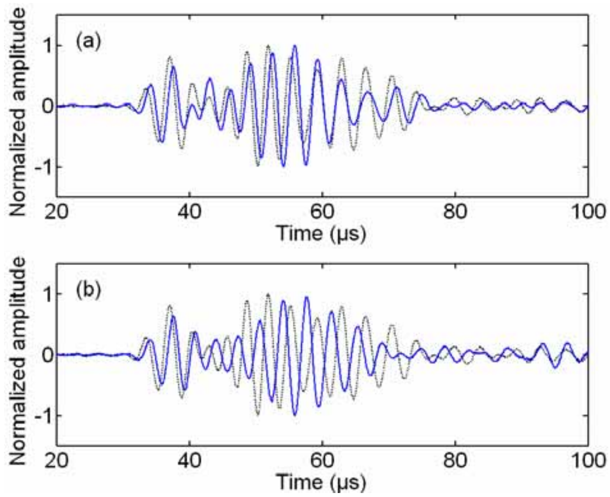

Figure 4. Sampled signals in GF/EP composite beams when L_D = 20 mm.
(a) Case 1 (b) Case 2. Dotted line: intact composite beam; solid line: delaminated composite beam.

In another set of experiments, normalized responses from composite beams with different delamination sizes were studied. Figs. 5(a), (b), (c) and (d) show the responses corresponding to the intact beam, and delaminated beams with L_D equals to 20 mm, 30 mm and 40 mm respectively.

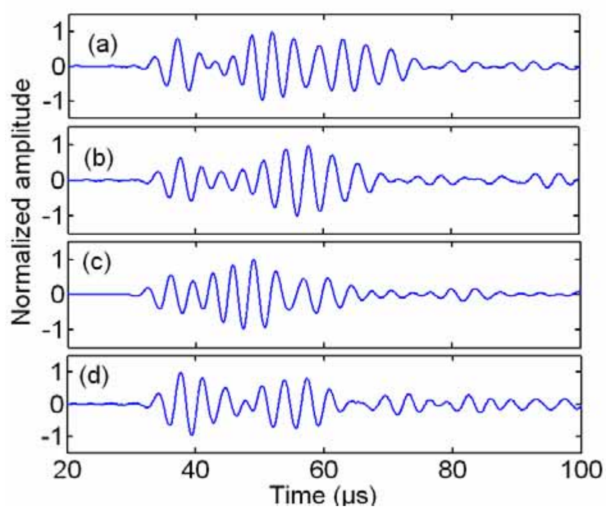

Figure 5. Sampled signals in composite beams with different delamination lengths.
(a) L_D = 0; (b) L_D = 20 mm; (c) L_D = 30 mm; (d) L_D = 40 mm.

The arrival times of S_0 mode in the four cases were similar, but the waveforms changed. In Fig. 5(b), an “accelerated” wave mode caused by the delamination interfered with A_0 mode, and together they formed the second wave packet. When L_D=30 mm, the velocity of the accelerated mode increased, and it appeared between the S_0 and A_0 modes. Finally, in Fig. 5(c), when L_D=40 mm, the accelerated wave combined with the S_0 mode and formed the first wave packet. The phenomenon can be explained as follows: when there was a delamination, the A_0 mode was separated into two waves that traveled in layers $[0]_2$ and layers $[0]_8$ with different velocities. The two waves combined after they passed through the delaminated area. As the delamination area grew, the velocity of this accelerated mode also increased. The accelerated mode interfered with the S_0 mode and A_0 mode, so new waveforms were observed.

SUMMARY

Damage detection in GF/EP composite laminate using embedded FBG as the sensor for ultrasonic Lamb wave is presented. Since the phase velocity of Lamb wave is dependent on the stiffness of the laminate, Lamb wave modes travel faster in CFRP than in GF/EP laminate. Nevertheless, it has been demonstrated that the detection technique is still promising in GF/EP laminate.

Experiments were conducted with GF/EP composite laminate. A laser source was used in the signal acquisition unit. Normalized responses detected by the FBG sensors from delaminated beams were compared to that of an intact beam. Delamination that was located closer to the surface of the beam could be detected more easily. Furthermore, when there was delamination in the composite beam, a new wave mode was observed. The velocity of this wave mode increased with the growth in delamination length. The feasibility of this non-destructive evaluation of damage in GF/EP laminate has been established in this paper. Further investigation into the waveforms corresponding to different delamination sizes and locations should be conducted in order to draw a more precise conclusion on the characterization of damage in GF/EP composite laminate.

ACKNOWLEDGEMENT

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