Nondestructive Evaluation of Holed CFRP Laminates by a New Technique to Visualize Propagation of Ultrasonic Waves*

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Abstract

This study investigated damage detection in holed CFRP laminates by using a newly developed technique for visualizing ultrasonic waves. This technique provided a moving diagram of propagating waves with non-contact scanning by a pulsed laser. Its measurement scheme overcame the difficulties of sensitivity in conventional methods and enabled us to observe ultrasonic waves on CFRP laminates. We observed two types of ultrasonic waves propagating on the CFRP laminate in the measured snapshots. These waves were identified as the S_0 and the A_0 Lamb modes by the dispersion curves, confirming the validity of the visualization technique for composite laminates. Furthermore, ply cracks and delamination, as well as the damage during manufacturing, were observed near the hole in the loaded specimens, and we successfully visualized the Lamb waves scattered by the delamination. The region of wave scattering agreed with the damage observed by soft X-ray radiography. These inspection results demonstrated the usefulness of the visualization technique in inspecting composite laminates.

Key words: Nondestructive Inspection, Ultrasonic Inspection, Composite Material, Stress Concentration, Delamination, Image Processing.

1. Introduction

Carbon fiber reinforced plastics (CFRP) have superior mechanical properties of specific strength and specific modulus compared to conventional structural materials. Therefore, CFRP has been applied to the primary load-bearing structures of aircraft. CFRP is also a promising structural material for automobiles to help resolve environmental issues. However, these structures have many stress-concentrated regions such as fastener holes. The stress concentrations induce complex damage states that concurrently include ply cracks and delamination⁽¹⁾⁻⁽³⁾. The accumulation of the damage causes the loss of structural stability due to reduced stiffness and also becomes the source of damage extension. Accordingly, nondestructive testing (NDT) for composite materials is essential to ensure structural reliability.

Ultrasonic testing is widely used in NDT of the composite structures; a manual

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inspection is generally performed by engineers moving slowly around the structure. However, this can be time-consuming, troublesome, and even dangerous. Moreover, the received signals are difficult to interpret, particularly for a complex-shaped component, and the test results consequently depend on the skill of the inspecting engineer. This testing method often leads to overlooking or false detection of damage as well as serious misjudgments in damage size or location. Although ultrasonic C-scans have also been used for inspections, they are unsuited for in-service inspection because of their large size and requirement for water-immersion. Structural health-monitoring (SHM), which constantly inspects the condition (e.g., strain, temperature, and damage state) has been intensely investigated to overcome these difficulties ⁽⁴⁾⁽⁵⁾. Among various SHM techniques, fiber-optic-based methods have been studied in detail ⁽⁶⁾⁻⁽⁹⁾, and many systems have just entered the research stage or are under development. However, in many of these techniques, the system installation is difficult for existing structures. Acoustic-emission-based systems have also been developed ⁽¹⁰⁾⁻⁽¹⁵⁾. Although the location of the source (the crack initiation source) can be identified from the detected signals, these systems may provide little information about the complex damage pattern in composite laminates.

Systems that visualize the propagation of ultrasonic waves can be strong candidates for NDT, since interpretation of the received signal becomes easy. In addition, damage can be detected directly from wave scattering observed in two-dimensional images. The wave propagation was visualized by shifting the reception point (a transducer or a laser-probe) within a given area following generation at a fixed point ⁽¹⁶⁾. However, this method was not practical for specimens with curved surfaces or steps because maintaining the transducer in constant contact with the specimen was difficult when scanning, and because a laser probe required perpendicular incidence to the surface with appropriate focusing. Takatsubo et al. ⁽¹⁷⁾ developed a new technique to visualize wave propagation that scans the specimen by a pulsed laser for generation. This technique has the following advantages over the conventional reception-scan methods. (1) Non-contact shifting of the generation point enables us to test complex-shaped objects. (2) The measurement system is simple to operate since a pulsed laser requires no control of the beam incidence angle or focusing. (3) The signal-to-noise ratio of the received signal is high due to the use of a fixed receiving transducer, which leads to a clear snapshot. This technique can also use any receiver with sufficient sensitivity. (4) Remote inspection for a large area is possible. These advantages are well suited to inspections of real structures.

This study investigates damage detection for holed CFRP laminates by the visualization technique and discusses the possibilities of the technique in inspections of composite structures. This paper is organized as follows. Section 2 provides an outline of the technique to visualize ultrasound propagation. Section 3 describes the experiment setup for damage observation of holed composite laminates. Section 4 presents the inspection results of visualized wave propagation and demonstrates the usefulness of the present technique.

2. Procedure for Visualizing Propagation of Ultrasonic Waves

Figure 1 schematically illustrates the measurement system. Similarly to the conventional visualization technique ⁽¹⁶⁾, signals are collected at grid points within a given scan area, e.g. 100×100 signals for a $100 \text{ mm} \times 100 \text{ mm}$ square region. The specimen is illuminated with a pulsed laser, which is placed on a mechanical stage, to generate elastic waves. The laser illumination point is then shifted within the scan area under computer control. The laser requires no adjustment for the incident angle or focusing; only the coordinate of the illumination point should be precisely controlled. A piezoelectric transducer is attached on the specimen and receives the ultrasonic waves generated by each illumination of the laser. The received signals are stored in the computer by way of an

Fig. 1 Schematic diagram of the measurement system for visualizing propagation of ultrasonic waves.

amplifier and a digital oscilloscope. Here, the initial time ($t = 0$) of a signal is defined for each scan point by the trigger output from the pulsed laser. The signals need not be averaged since the signal-to-noise ratio is sufficiently high due to the use of the transducer. The current system requires ten minutes to collect 100×100 signals, but the scan speed could be improved considerably by using a high-speed scanning unit.

We obtain a snapshot of wave propagation by reconstructing the collected signals under the reciprocity assumption for wave propagation; i.e., the signal received at point B (Fig. 1) after generation at point A is identical to the signal received at point A after generation at point B, if the same two transducers are used for generation and reception. Similarly, the signal received by the transducer at point B after laser illumination at point A will be the same as the signal received at point A following illumination at point B. This assumption is verified in the appendix. Based on this assumption, we can consider the collected signals in the present technique to be the same as the signals measured by the conventional reception-scan method. The amplitude of the collected signals at time t is then plotted on a contour map, which becomes the snapshot of the wave propagation at the time. Finally, the maps are continually displayed in a time series and appear to be a moving diagram of wave propagation from fixed transducer point B.

Applying the conventional reception-scan method⁽¹⁶⁾ to CFRP laminates was difficult because of the poor sensitivity of the laser probe, in addition to the requirement for handling. Switching the generation and the reception points overcomes these difficulties and enables us to visualize the wave propagation on CFRP laminates.

3. Experiment Setup

The material used was CFRP (T800H/3631, Toray Industries Inc.) with a stacking configuration of $[0/90_2]_S$. A flat $300 \text{ mm} \times 300 \text{ mm}$ plate was fabricated by an autoclave. Coupon specimens were cut out from the flat plate by a diamond saw and were holed at the center by a drill. The specimens were 250 mm long and 25 mm wide with a hole diameter of 5 mm . GFRP tabs were glued to the ends of the specimen.

Quasi-static tensile tests were conducted for the holed specimens at room temperature. The tensile strain was measured by a strain gage (gage length 20 mm) bonded 60 mm from the hole along the axial direction. Specimens with 0% , 0.5% , 0.7% and 0.9% strain loading were then inspected by visualizing the ultrasound propagation. Finally, the damage in these specimens was observed by soft X-ray radiography, and the inspection results were compared in detail.

Figure 2 illustrates the experiment setup for visualizing ultrasound propagation. In order to obtain clear snapshots, the laser beam was focused in this study. To this end, the pulsed laser was fixed, and the specimen on the mechanical stage was shifted slightly with

Fig. 2 Experiment setup to visualize ultrasound propagation on holed CFRP specimens.

every illumination of the laser to scan the region near the hole. This study used an Nd:YAG pulsed laser; the pulse duration was 10 ns with 5 mJ energy per pulse, and the diameter of the beam spot was 2 mm before focusing. A 30 mm $\times$ 25 mm region around the hole was scanned at a constant illumination spacing of 0.2 mm. The receiver was attached 20 mm from the hole on the rear surface of the laser illumination, as illustrated in Fig. 2(b). We used a rod-shaped transducer (45 mm long, 2.1 mm wide, and 2.6 mm thick) to visualize a plane wave.

4. Results and Discussion

Figure 3 presents the soft X-ray photographs of the holed CFRP cross-ply laminates. Short splits in the 0° ply and some transverse cracks in the 90° ply appeared at the hole edge in the specimen with 0.5% strain (Fig. 3(b)). The splits extended, and the number of transverse cracks increased with increased loading (Fig. 3(c)). Delamination at the 0°/90°

Fig. 3 Damage patterns in the holed cross-ply laminates observed by soft X-ray radiography.

ply interface was observed along the splits at 0.9% strain (Fig. 3(d)). In addition, all specimens exhibited delamination around the hole, which was introduced during manufacturing.

The wave propagation snapshots are presented in Fig. 4 for these four specimens. We can clearly observe two types of ultrasonic waves in the specimen without loading, i.e., a fast wave ($c_g = 5100$ m/s) with low amplitude and a slow wave ($c_g = 1400$ m/s) with high amplitude. These are the Lamb waves, one of guided waves that propagate in a thin plate while satisfying the traction-free boundary conditions on the surfaces⁽¹⁸⁾. The Lamb waves have multimode characteristics and are divided into two modes, symmetric (S) and anti-symmetric (A) modes, which are defined by the displacement field with respect to the mid-plane. A finite number of symmetric or anti-symmetric modes can exist for a given frequency-thickness product, and they are generally dispersive; i.e., their velocities depend on the frequency. Figure 5 plots the calculated dispersion curves for the laminate used in

Fig. 4 Lamb-wave propagation on the holed CFRP specimens.

Fig. 5 Calculated dispersion curves for the CFRP laminate with lay-ups of [0/90₂]_s.

Table 1 Material properties of the unidirectional CFRP (T800H/3631) laminate⁽¹⁹⁾.

Longitudinal Young's modulus, E_L (GPa)	144
Transverse Young's modulus, E_T (GPa)	9.16
In-plane shear modulus, G_{LT} (GPa)	3.83
Out-of-plane shear modulus, G_{TZ} (GPa)	3.40
Poisson's ratio, ν_{LT}	0.33
Density, ρ (kg/m ³)	1530
Thickness of a ply (mm)	0.125

Fig. 6 Received signal at point A in Fig. 4(a) for the specimen without loading.

this study; only the fundamental mode and the first mode are shown⁽¹⁹⁾. The material properties listed in Table 1 were used for the calculation. Figure 6 depicts the measured waveform at a point 5 mm from the hole edge along the width direction in the specimen without loading (point A in Fig. 4(a)). The Fourier transform of the waveform revealed that the signal contained mainly the 500 kHz frequency component. The dispersion curves in Fig. 5 demonstrated that only the S_0 mode and the A_0 mode can exist at 500 kHz and that the group velocities of these modes almost coincided with those observed in Fig. 4(a). These analyses identified the visualized waves as the two fundamental Lamb modes and demonstrated the validity of the present technique.

In the Lamb wave propagation on the specimen without loading (Fig. 4(a)), diffraction and scattering by the hole were clearly observed for the A_0 mode. Although there were splits in the 0° ply and transverse cracks in the 90° ply in the specimens with 0.5% and 0.7% strain, the wave propagation in these specimens (Fig. 4(b) and (c)) was almost the same as that in the specimen without loading; the present inspection missed these ply cracks. However, the sensitivity to damage may be improved by using waves with higher frequency.

Scattering of both the S_0 mode and the A_0 mode was observed in the region from the edge of the hole along the longitudinal direction in the specimen with 0.9% strain, as depicted in Fig. 4(d). We can identify the area of wave scattering as the delamination from the X-ray photograph presented in Fig. 3(d). Moreover, scattering of the A_0 mode around the hole was visible in all specimens, and its region was particularly large in the specimen with 0.9% strain. This region was identified as the delamination area introduced during the manufacturing process by the soft X-rays. Thus, visualizing and observing the scattered Lamb waves was very useful for detecting the delamination, even small delaminations.

We can also observe the large variation in the amplitude within the damaged region because of the interference between the forward proceeding waves and the scattered waves. The maximum amplitude in the waveform at each scan point was plotted on a contour map as depicted in Fig. 7. The maximum amplitude in the delamination was greater than that in the other region, and the shape of the damage was indicated. Figure 8 depicts the distribution of the maximum amplitude for the frequencies over 900 kHz, which can be

Fig. 7 Distribution of the maximum amplitude at each scan point.

Fig. 8 Distribution of the maximum amplitude for the frequencies over 900 kHz. Delamination was clearly indicated in the loaded specimen.

obtained by Fourier transformation. The Lamb waves with short wavelength were indicated in the moving diagram of wave propagation, although these frequencies were beyond the resonance frequency of the receiving transducer. These waves were scattered more sensitively, and the damage in the laminate was successfully represented on this map.

5. Conclusions

This study applied a new technique that visualizes ultrasound propagation to inspection of composite laminates. In this technique, the specimen was scanned by a pulsed laser for generation, and the signal for each illumination was received by an attached transducer with high sensitivity. Reconstruction of the collected signals provided a moving diagram of the wave propagation from the fixed receiver. Switching the generation and the reception points from the conventional reception-scan method overcame the difficulties of sensitivity and enabled us to observe wave propagation on CFRP laminates. We then investigated damage detection in the holed CFRP laminates by visualizing the Lamb waves. The conclusions are summarized below.

1. We identified the visualized wave propagation on the CFRP laminate as the two fundamental modes of Lamb waves, and demonstrated the validity of the present visualization technique.
2. We successfully visualized the Lamb waves scattered by the delamination and the damage generated in the manufacturing process. The delamination was also indicated in the contour map on the maximum amplitude of the received signals.
3. The region of wave scattering coincided with the observation by soft X-ray radiography. These inspection results demonstrated the usefulness of the present technique for damage detection in composite laminates.

Appendix

The visualization technique for wave propagation described in Section 2 was based on the reciprocity assumption; i.e., the two waveforms were identical when the generation and reception points were exchanged. This assumption was then verified experimentally. The

Fig. 9 Comparison of the waveforms from two propagation paths.

wave propagation between points A and B illustrated in Fig. 9(a) was investigated for a holed CFRP cross-ply laminate without loading. Figure 9(b) compares the waveform received by a fixed transducer at point B following the laser illumination at point A with the waveform when generation and reception points were exchanged. We can observe that the two signals approximately agreed; although a slight difference remained in amplitude. This difference may result from the bonding condition of the transducer and from the difference in the diameters of the beam spot (2 mm) and the transducer (4 mm). However, the phase was almost identical in these two signals.

The phase and the amplitude correspond to the position of the wave front and the contrast of the wave in the snapshots in Fig. 4. Although the exchange of the generation/reception points causes small errors in the contrast of the snapshot, the shape of the wave front never changes. Accordingly, slight differences in amplitude between the two signals will not cause trouble in the non-destructive inspection or identification of the scattered waves.

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