

Identification of Delamination in Anisotropic Laminated Plate

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Abstract. The energy released from damages may give rise to small surface displacements and cause transient elastic waves in materials. Wave propagation of thin plates usually takes the form of lamb waves, and the modes of the lowest symmetric (S_0) and anti-symmetric (A_0) lamb waves are called the extensional and the flexural modes, respectively. In this study, a formulation, including the effect of shear deformation and rotary inertia, was derived to valuate the velocity of plate waves. The characteristics of plate wave propagation in thin laminated plates were investigated. Acoustic emission (AE) signals were generated by function generators and lead breaks, and propagated in laminated plates. These waves would be detected by broadband AE sensors because of their high sensitivity. With wavelet transform, AE waves were analyzed and the wave velocities of A_0 and S_0 modes were exactly calculated. Moreover, a simple method was presented to evaluate delamination in laminated plates. The length of delamination was predicted, and agreed well with the actual length.

Introduction

The energy released from vibration source may give rise to small surface displacements and cause transient elastic waves in materials. When the materials are plate-like, the waves propagating in them are usually called lamb waves, and the extensional and the flexural mode waves are the lowest symmetric (S_0) and anti-symmetric (A_0) Lamb waves, respectively [1]. In recent years, wavelet transform, as an efficient analysis method, have been adopted to analyze wave signals and many researches have been reported. The triangulation technique by several sensors was developed according to the difference in arrival times of A_0 mode wave from the vibration source [2]. With S_0 mode, Hu et al. identified the delamination position in cross-ply laminated composite beams [3].

In this study, the signals generated by pencil lead breaks (Hsu-Neilsen source [1]) were received by high sensitivity broadband AE sensors. And then the waveforms of S_0 and A_0 modes were analyzed with wavelet transform. It was found that the velocities of S_0 and A_0 modes could be distinguished by one sensor at the frequency of 165 kHz. A theoretical approach for the detection of delamination in thin laminated plate was presented by S_0 and A_0 mode waves. Moreover, according

to the differences in arrival times of S_0 and A_0 mode waves, the delamination of laminated plates was detected by only one sensor, and that the length of delamination could be measured.

Theory

Wavelet transform. The signals generated in this study were time series that contain nonstationary waveform at various frequencies. By wavelet transform, the waveform at a certain frequency could be extracted to derive the arrival times. For a time series $f(t)$, the wavelet transform $W_f(b, a)$ is defined as

$$W_f(b, a) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{a}} \overline{\psi\left(\frac{t-b}{a}\right)} f(t) dt \quad (1)$$

where parameter a and b are scale and shift coefficients, respectively. ψ is wavelet function, which must have zero mean, and be localized in both time and frequency space. The morlet wavelet [4] is adopted in this study, and given by

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \quad (2)$$

where η is the nondimensional time and ω_0 is the nondimensional frequency.

Theoretical approach on delamination. The velocities of S_0 and A_0 mode waves in 16-ply unidirectional laminated plate are defined as V_S and V_A , respectively. In the case of no delamination, the difference in arrival times between S_0 wave and A_0 wave from vibration source to sensor is given by

$$\Delta t(f) = t_A(f) - t_S(f) = \frac{L}{V_A(f)} - \frac{L}{V_S(f)} \quad (3)$$

where f is the frequency of the waves and L is the distance from vibration source to sensor. t_A and t_S are the arrival times of A_0 and S_0 mode waves, respectively. However, when the waves propagate in the 16-ply unidirectional laminated plates with delamination, it is considered that the waves propagate in two 8-ply parts split by the delaminated area. Assuming the velocities of S_0 and A_0 mode waves in 8-ply unidirectional laminated plate as V_{S-d} and V_{A-d} , respectively, then, the difference in arrival times of S_0 and A_0 mode waves for laminated plates with delamination can be given by

$$\Delta t_d(f) = t_{A-d}(f) - t_{S-d}(f) = \left[\frac{L-d}{V_A(f)} + \frac{d}{V_{A-d}(f)} \right] - \left[\frac{L-d}{V_S(f)} + \frac{d}{V_{S-d}(f)} \right] \quad (4)$$

where d is the length of delamination. t_{A-d} and t_{S-d} are the arrival times of A_0 and S_0 mode waves, respectively. Because the frequency depends hardly on the wave velocity of S_0 mode, V_{S-d} is considered to be equal to V_S . The change of the differences in arrival times between S_0 and A_0 mode waves due to the layer delamination is given by

$$\Delta(f) = \Delta t_d(f) - \Delta t(f) = \frac{d}{V_{A-d}(f)} - \frac{d}{V_A(f)} \quad (5)$$

Moreover, according to the Eq. (5), the length d can be obtained from

$$d = \frac{V_A(f) \times V_{A-d}(f)}{V_A(f) - V_{A-d}(f)} \times \Delta(f) \quad (6)$$

Experiments

In this study, carbon fiber reinforced plastics (CFRP) was used to fabricate the laminated plates. The thickness of prepreg was 110 μm . The 16-ply unidirectional laminated plates were prepared by hot pressing. In order to obtain a delamination, a teflon film sheet with the thickness of 50 μm was inserted between the 8th and 9th prepreg plies. The 16-ply unidirectional laminated plate, with middle delamination formed after removing teflon sheet, was fabricated.

Figure 1 shows schematic diagram of the delamination experiment with one sensor. In this experiment, the distance L from vibration source to sensor was changed from 60 mm to 120 mm and the delamination length d was 45 mm. For each distance L , the same experiment was carried out in an intact plate with the same thickness. With wavelet transform, the differences in arrival times at a certain frequency were compared and the delamination was detected. Moreover, the length of the delamination was investigated.

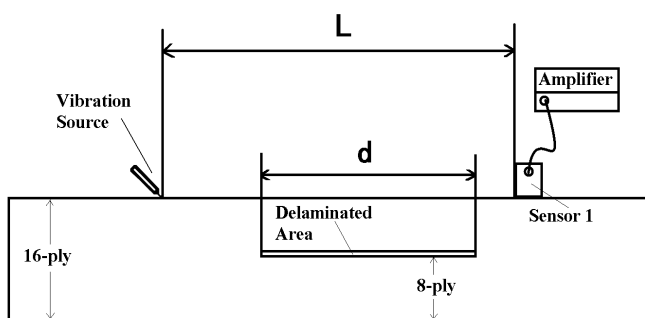


Figure 1 Schematic diagram of experiment.

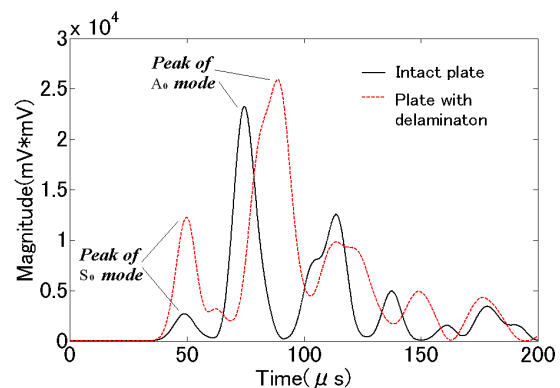


Figure 2 Arrival times of peaks at 165 kHz.

Results and discussion

In this study, the waveforms from 100 kHz to 600 kHz were investigated, and the frequency of 165 kHz was found to have the best response. Figure 2 shows the arrival times of S_0 and A_0 mode waves on intact plate and plate with delamination in the direction perpendicular to fibers. And the distance L from 60 mm to 120 mm, the differences in arrival times are shown in Fig. 3. It is clearly observed for the different vibration source that the differences in arrival times in plate with delamination are larger than those in intact plate. This implies that the plate delamination can be detected with one sensor.

From Eq. (6), it is known that the distance d is only related with the velocities of A_0 mode wave. From the theoretical prediction, V_A and V_{A-d} were 942 m/s and 732 m/s at frequency of 165 kHz, respectively. The measured delamination lengths are shown in Fig. 4. In this study, the actual length of delamination was 45 mm. When the distance L was 60 mm, the measured length is 44 mm that agreed well with the actual length. The measured lengths were about half of the actual length for the distance L from 80 mm to 120 mm. With increasing distance L , the attenuation of waves increases and the delamination will accelerate the attenuation. In particular, the arrival time of S_0 mode wave is easily influenced by the distance L because the wave is weak. For the plate with delamination, therefore, the difference in arrival times of S_0 and A_0 mode waves will decrease

rapidly when the distance L is too long. In this study, the accurate result was derived within the distance L of 60 mm. The experiment was repeated 5 times at each distance L , the errors of measured lengths were ± 0.8 mm.

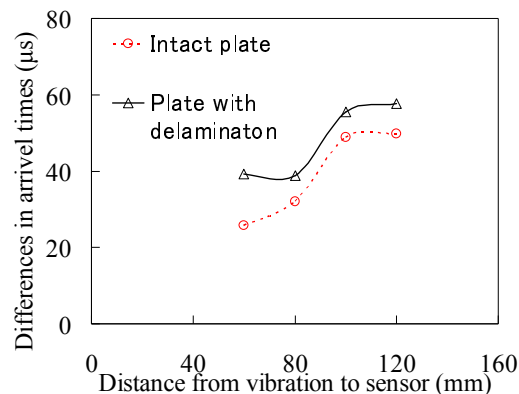


Figure 3 Differences in arrival times.

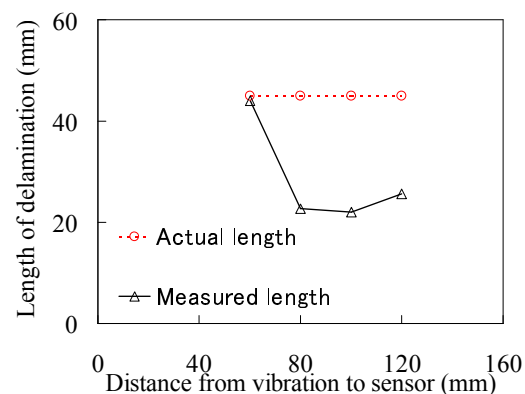


Figure 4 Length of delamination.

Conclusions

In this study, a theoretical approach on detection of delamination in thin laminated plate was presented. With wavelet transform, the waveforms received by AE sensors were extracted and investigated from 100 kHz to 600 kHz. The frequency of 165 kHz could be selected to determine the wave speed because of the best response. Moreover, a delamination of laminated plate could be detected by using only one AE sensor within the distance from 60 mm to 120 mm. The length of delamination was calculated by comparing the difference in arrival times of S_0 and A_0 mode waves in the plate with delamination with that in intact plate. It was clearly known that the measured length decreased with increasing distance L . That was because the arrival time of S_0 mode wave was easily influenced by distance and delamination. In this study, the accurate result was derived within the distance L of 60 mm.

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