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Curing monitoring and influence on the adhesive property by ultrasonic vibration treatment of adhesive layer

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1. Introduction

Adhesive bonding gains attention as a method of joining that has a potential to reduce the weight of structures and stress concentrations in joints. In order to apply adhesive bonding to structures, it is necessary to increase bonding strength and reliability.

The interaction of ultrasonic waves with adhesives in the curing process was investigated in previous studies. Fraisse et al.[1] proposed a monitoring method for the elastic moduli of adhesives by ultrasonic reflection coefficient. Yang et al.[2] reported that ultrasonic vibration treatment in the curing process can enhance bonding strength. In these previous papers, the adhesive layer was thinner than the ultrasonic wavelength.

In this paper, ultrasonic resonance of the adhesive layer was excited by high-frequency ultrasonic wave incidence. First, curing monitoring by measuring the change in the resonance frequencies of the adhesive layer is proposed. Second, an experiment is conducted to examine the effect of ultrasonic wave incidence during the curing process on the bonding strength.

2. Curing monitoring of adhesive

Fig. 1 shows the schematic of the experimental setup. Aluminum alloy plates with a thickness of 2 mm were bonded by an epoxy-based adhesive with a final curing time of 24 hours. Two 2.2 mm thick shims were used to make the bond thickness 0.2 mm.

First, shims and substrates were arranged and fixed with weights without applying an adhesive as shown in **Fig. 1**. An ultrasonic pulse wave was incident from a transducer placed on the overlap of the joint, and the reflected wave was measured and used as a reference waveform.

Next, an adhesive was applied between the substrates. The reflected wave from the adhesive layer was measured in a similar way to the reference waveform. This measurement was repeated at a regular time interval until the final curing time.

The measured waveforms were analyzed by fast Fourier transform (FFT). The reflection coefficient was calculated as the ratio of the amplitude spectra of the reflected and reference waveforms. The frequencies at which the reflection coefficient has local minima correspond to the resonance frequencies of the adhesive layer.

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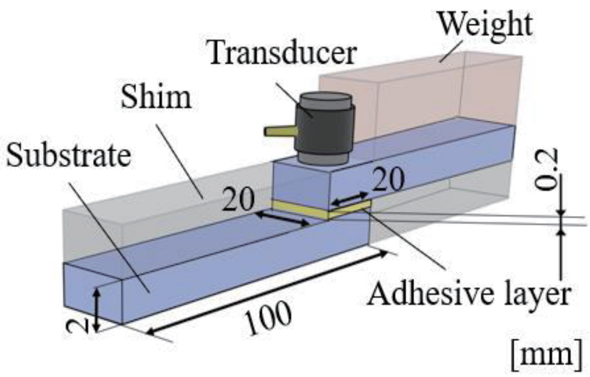

Fig. 1 The schematic diagram

When the adhesive layer is modeled as a purely elastic body, the resonance frequency of the layer is given by[3]

$$f_n = \frac{nc}{2h} \, (n = 1, 2, \cdots) \qquad (1)$$

where c, h, and n, respectively, are the longitudinal wave velocity in the adhesive, the nominal thickness of the adhesive layer, and the resonance number.

Fig. 2 shows the measured time variation of the first- and second-order resonance frequencies of the adhesive layer. **Fig. 3** shows the time variation of the longitudinal (L) wave velocity of the adhesive layer calculated by Eq. (1). Both the resonance frequency and the L-wave velocity changed significantly in the initial stage of curing and showed a monotonically increasing trend with a decreasing rate of change. If the formula of the resonance frequency, i.e. Eq. (1), is modified for a viscoelastic layer, it could be possible to monitor the time variation of the viscoelastic properties of the curing adhesive.

3. Influence on the adhesive property

This section, the influence of ultrasonic resonance on the bonding strength was investigated.

Ultrasonic waves were incident into the overlap of a single lap joint during the adhesive curing using the experimental system shown in **Fig. 1**. Sinusoidal waves at fixed frequencies were input into the transducer. After the final curing, a tensile shear test was conducted to measure the bonding strength. In this paper, the nominal value of the first-order resonance frequency f_1 was used as the

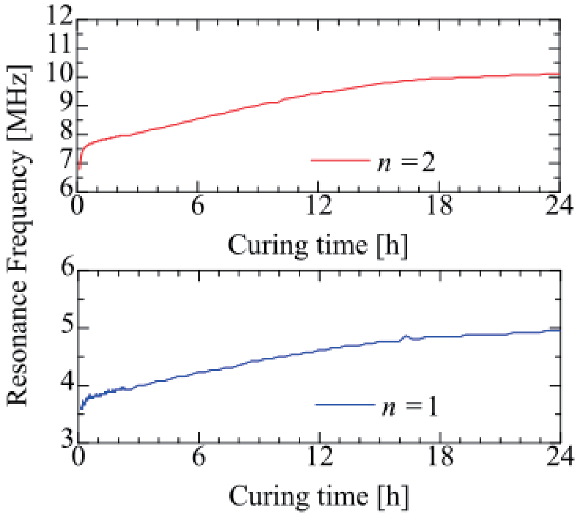

Fig. 2 Time variation of the resonance frequency of the adhesive layer

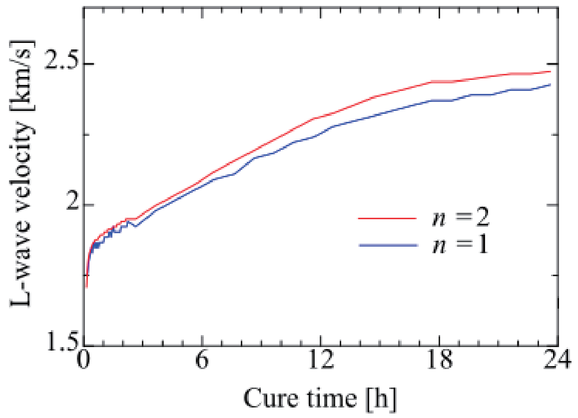

Fig. 3 Time variation of the estimated L-wave velocity of the adhesive layer

frequency of the input waveform. The nominal thickness of the adhesive layer h = 0.2 [mm] and the velocity of an uncured epoxy resin c = 1.93 [km/s][1] to Eq. (1). As a result, the resonance frequency of the adhesive layer was calculated to be 4.8 MHz.

Aluminum alloy plates with sanded surfaces were used as substrates. A sinusoidal wave with a frequency of 4.8 MHz and a voltage amplitude of 10 V_{pp} was applied to the transducer. Three different durations of the ultrasonic wave were examined, and at least four specimens were produced on each condition.

The measured tensile shear strengths are shown in **Table I**. The average strength value with a 95% confidence interval at each incidence time is shown in **Fig. 4**. Table I shows that the ultrasonic incidence did not bring an obvious increase/decrease in the tensile shear strength of the joints. This tendency can also be confirmed in Fig. 4. The mean tensile shear strength decreased by 1.9 % at 15 min and 30 min, which seems trivial. On the other hand, the width of the 95% confidence interval increased by 7.9 % at 15 min, which expanded to 24.7 % at 30 min.

These results indicate that no significant improvement in the average bonding strength is observed when ultrasonic waves are input at the resonance frequency determined from the nominal values of the L-wave velocity and thickness and the theoretical relation, i.e. Eq. (1).

Table I. Measured tensile shear strength [MPa]

Incidence time [min]	0	15	30
A	4.415	4.877	
B	3.706	3.678	3.531
C	4.355	3.978	4.405
D	4.741	4.426	4.971
E	5.895	5.876	5.389

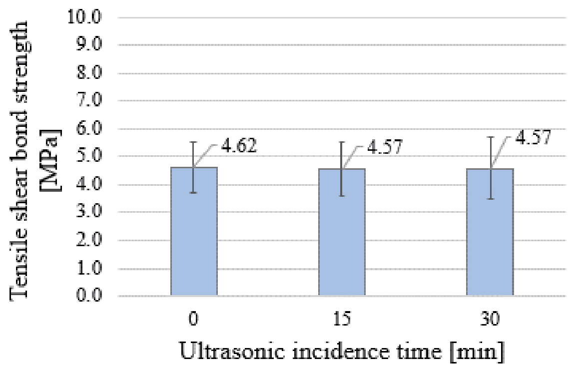

Fig. 4 Average values and 95% confidence intervals of tensile shear strength

4. Conclusion

The interaction of curing of the adhesive with ultrasonic waves has been examined in this paper. It was found that the curing of the adhesive can be monitored by measuring the change in the resonance frequency of the adhesive layer.

The incidence of the ultrasonic wave at the nominal resonance frequency of an adhesive layer did not clearly affect the averaged bonding strength.

References

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