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Interfacial Evaluation of Adhesively Bonded CFRP Joints Based on Ultrasonic Reflection Spectrum

- Stiffness Estimation of Two Interfaces –

超音波反射スペクトルに基づく CFRP 接着界面評価

―2 界面の剛性推定―

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1. Introduction

Carbon fiber reinforced plastics (CFRP) are widely used in aircraft structures due to its advantages regarding weight and strength. CFRP components are often joined by adhesive bonding. Compared to other joining techniques, adhesive bonding reduces stress concentration in the joints and contributes to weight reduction.

Ultrasonic testing plays an important role in the nondestructive evaluation (NDE) of adhesive joints. Gross defects such as voids and cracks can be detected by ultrasonic testing. However, the detection technique for weak bonding areas is not fully established.[1-2] In our previous study, an interfacial stiffness evaluation method of adhesively bonded CFRP joints was proposed based on local minima frequencies of the ultrasonic reflection spectrum.[3] This study suggested that the proposed method can be applied to the evaluation of the effect of adherend contamination on the interface stiffness. However, one of the two adhesive interfaces was assumed to be a properly bonding interface in the evaluation procedure.

The aim of this study is to estimate the two interfacial stiffnesses simultaneously. Reflection spectra are measured for a bonded specimen which has an intentionally contaminated adhesive interface, and the interfacial stiffnesses are estimated.

2. Specimen

The schematic of a CFRP adhesively bonded specimen used in this research is shown in Fig. 1. Unidirectional laminates of carbon fiber reinforced epoxy composite (T800S/3900-2B, Toray Industries; 10 plies, nominal thickness h_0 = 2.0 [mm]) were bonded by an epoxy film adhesive (FM309-1M, Cytec; nominal thickness h_A = 0.25 [mm]). The length and width of an adherend are 250 mm and 100 mm, respectively.

In this study, a weakly bonded specimen, called L2, was formed by applying a release agent onto one surface of the adherend within a width of 50 mm, wiping it gently, and bonding the adherends.

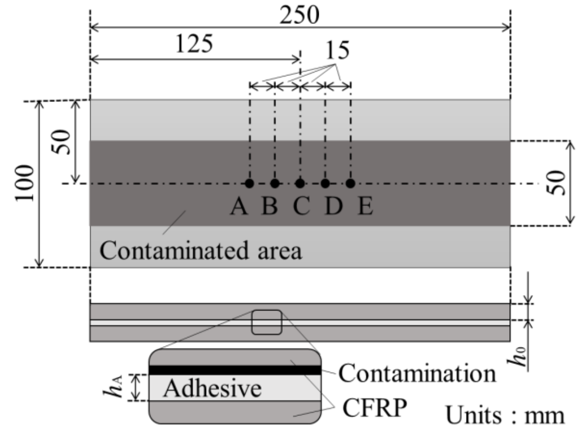

Fig. 1. Schematic of a CFRP adhesively bonded specimen with contamination.

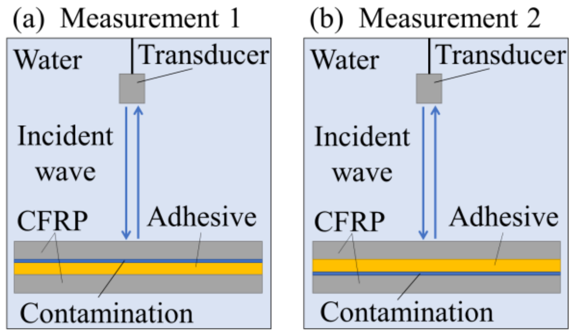

Fig. 2. Schematics of (a) the measurement 1 and (b) the measurement 2.

The amount of the dropped release agent was 100 mg/m^2.

3. Experimental method

Ultrasonic pulse-echo measurement was performed on the CFRP bonded joint immersed in a water tank. A pulser-receiver (DPR300, JSR Ultrasonics) and a water immersion probe (V311-SU, Olympus) with nominal frequency of 10 MHz were used for the measurement. At five points A-E, which were shown in Fig. 1, ultrasonic waves were incident normally and reflected waveforms were measured. Point C was set at the center of the specimen, and the other points were set at 15 mm intervals. In this study, two types of the measurements were performed. In the measurement 1, the incident wave was transmitted to the adhesive layer from the weakly bonded interface, as shown in Fig. 2(a). In the measurement 2, the specimen was the same as the one in measurement 1 but the ultrasonic wave was incident on the adhesive layer from the properly bonded interface, as shown in Fig. 2(b). To obtain the reference waveform, measurement was also carried out for a stainless-steel reflector. The amplitude spectra of the reflection and reference waveforms were calculated by fast Fourier transform (FFT), and the amplitude reflection coefficient $|R|$ was obtained as their ratio.

4. Experimental results

The frequency dependence of the reflection coefficients obtained in the measurement 1 and 2 are shown in Fig. 3. In each case, the reflection coefficient takes local minima at multiple frequencies. Some of these notch frequencies, specifically in the ranges of 5.4-6.0 MHz, 6.2-6.4 MHz and 6.8-7.2 MHz, show different values in the measurements 1 and 2. Furthermore, in the range of 3.0-3.6 MHz and 4.0-4.3 MHz, the notch depths are found to be different in measurements 1 and 2. The experimental results obtained above imply non-negligible contrast of the two adhesive interfaces.

5. Estimation of interfacial stiffnesses

The estimation method in Ref. 3 is modified and two interfacial stiffnesses are estimated in this paper. Upper and lower adhesive Fig. 2 are characterized by interfacial stiffnesses K_{N1} and K_{N2}, respectively. Namely, the two interfaces are modeled as spring-type interfaces, expressed as

$$\sigma_1 = K_{N1}[u]_1, \qquad \sigma_2 = K_{N2}[u]_2 \qquad (1)$$

where σ_j, K_{Nj}, and $[u]_j$ (j = 1, 2) are normal stress, interfacial stiffness, and normal displacement gap at an interface, respectively.

Theoretical reflection coefficient $|R|$ is shown as a function of the frequency in Fig. 4. The reflection coefficient exhibits multiple notches similarly to the experimental results. The notch frequencies are extracted from the measured reflection coefficient, and the two interfacial stiffnesses of the bonded specimen are estimated by comparing the experimental and theoretical results of the notch frequencies.

The two interfacial stiffnesses estimated for the measurements 1 and 2 are summarized in Fig. 5. In each case, the interfacial stiffness of the weakly bonded interface is found to be lower than that of the properly bonded side.

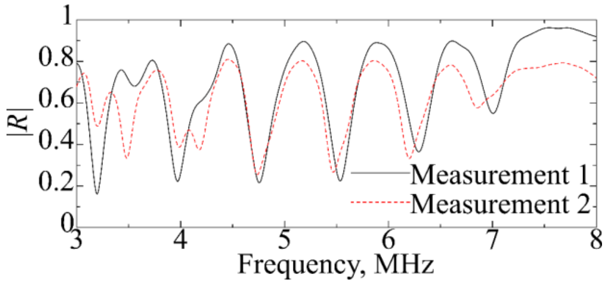

Fig. 3. Comparison of the frequency dependence of the reflection coefficient $|R|$ obtained in the measurement 1 and 2.

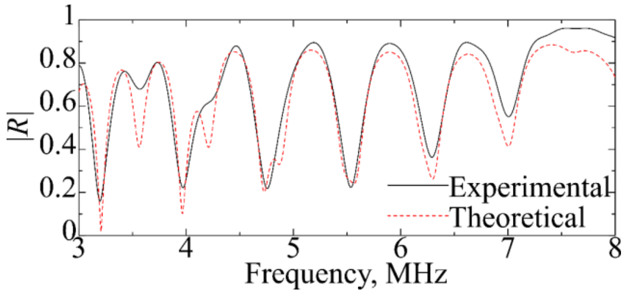

Fig. 4. Measured reflection coefficient and theoretical result obtained by the estimated parameters in the measurement 1.

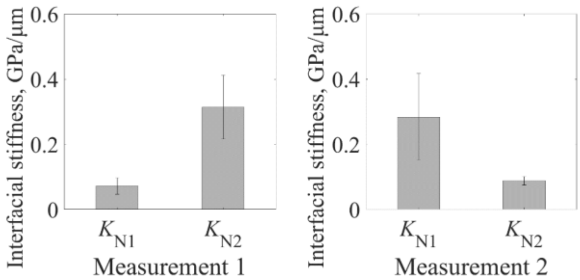

Fig. 5. Average values of the estimated interfacial stiffness and 95 % confidence intervals for measurement 1 and 2.

Acknowledgments

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References

1. R. L. Vijaya Kumar, M. R. Bhat, and C. R. L. Murthy: Ultrasonics **53** (2013), 1150.
2. D. N. Markatos, K. I. Tserpes, E. Rau, S. Markus, B. Ehrhart, and S. Pantelakis: Compos. Part B Eng. **45**, (2013), 556.
3. S. Ito, K. Nakagawa, N. Mori, N. Matsuda, Y. Furuta, T. Kusaka, and M. Hojo, Proc. Symp. Ultrason. Electron., **40**, 3P2-2 (2019).
4. Y. Ishii and S. Biwa: J. Appl. Phys. **111** (2012), 084907.