3P2-2

Interfacial Stiffness Evaluation of Adhesively Bonded CFRP Joints Based on the Out-Of-Plane Resonance for the Ultrasonic Wave Incidence

超音波入射時の面外共振に基づく CFRP 接着接合部の界面剛性評価

Shohei Ito[1‡], Kyota Nakagawa[1], Naoki Mori[2], Naoki Matsuda[3], Yasuaki Furuta[4], Takayuki Kusaka[2], Masaki Hojo[3]
([1] Grad. School Sci. Eng., Ritsumeikan Univ.; [2] Ritsumeikan Univ.; [3] Kyoto Univ.; [4] Grad. School Eng., Kyoto Univ.)
伊藤 匠平 [1‡], 中川 恭太 [1], 森 直樹 [2], 松田 直樹 [3], 古田 康晃 [4], 日下 貴之 [2], 北條 正樹 [3]
([1] 立命館大院 理工, [2] 立命館大 理工, [3] 京大 工, [4] 京大院 工)

1. Introduction

Carbon fiber reinforced plastics (CFRP) are increasingly used in aircraft and automobiles due to its light weight and high strength. Adhesive bonding is a popular method for joining CFRP components. Compared to other methods, adhesive bonding improves the stress distribution in the joints and allows a lighter structure.

Ultrasonic testing is widely used in the nondestructive evaluation (NDE) of adhesive joints because it is capable of detecting gross defects such as voids and cracks.[1)] However, the detection technique for weak bonding areas, which result from improper pretreatment of adherends, for example, is not yet established and is a subject of research interest.[2-3)]

In this study, a one-dimensional theoretical analysis using a spring-type interface model is performed to clarify the ultrasonic reflection characteristics for the normal wave incidence to an adhesive joint. Based on the theoretical results of the out-of-plane resonance induced by wave interference, the estimation method for the interfacial stiffness, adhesive thickness, and wave velocity of the adherend is proposed and applied to a bonded CFRP joint.

2. Theoretical model

As shown in Fig. 1, a wave propagating in the x direction is normally incident to a bonded CFRP joint immersed in water. Each adherend consists of 10 viscoelastic plies with interlaminar stiffnesses K_L.[5)] The wave velocity and thickness of the adherends are denoted as c_0 and h_0, respectively. The adhesive layer is modeled as viscoelastic material of wave velocity c_A and thickness h_A. Two interfaces between the adherend and adhesive, $x = x_1 = h_0$ and $x = x_2 = h_0 + h_A$, are modeled as spring-type interfaces,[4)] expressed as

$$\sigma_{x1} = K_{N1}[u_x]_1, \qquad \sigma_{x2} = K_{N2}[u_x]_2, \qquad (1)$$

where σ_{xj}, K_{Nj}, and $[u_x]_j$ ($j = 1, 2$) are the normal stress, interfacial stiffness, and normal displacement gap at the interface $x = x_j$, respectively.

For the incidence of a monochromatic wave, the amplitude reflection coefficient $|R|$ is calculated by the transfer matrix method.[5)] In this study, the wave velocity of the adhesive is set as c_A = 2.54 [km/s] based on the measured result of the epoxy adhesive. The viscoelastic property of the adhesive is assumed according to Ref. 6. The thickness, damping coefficient, and interlaminar stiffness of the CFRP plates are set as h = 2 [mm], η = 10 [Pa·s], and K_L = 0.8 [GPa/μm], respectively.

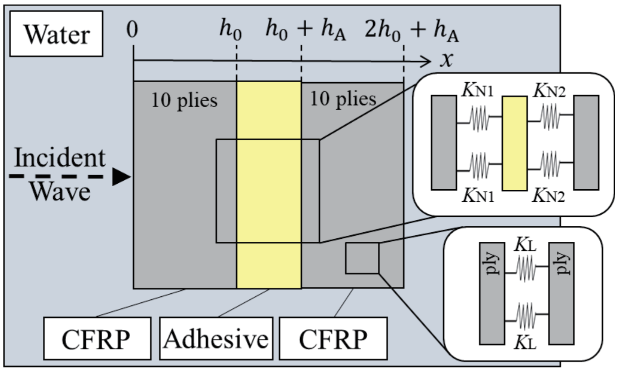

Fig. 1 Theoretical model of an adhesively bonded CFRP joint.

3. Theoretical results

In this paper, the theoretical results are shown for the case of identical interfacial stiffnesses, i.e. $K_{N1} = K_{N2} = K_N$. The frequency dependence of the reflection coefficient $|R|$ is shown for different interfacial stiffnesses K_N in Fig. 2. The reflection coefficient exhibits local maxima and minima at multiple frequencies. The local minima points indicate that resonance occurs due to wave interference in the multilayered structure.[4)] Some notch frequencies are found to vary sensitively when the interfacial stiffness decreases. Specifically, the notch frequencies in the range of 4.5-5.0 MHz become degenerated at K_N = 0.1 [GPa/μm]. Similar phenomena can be seen in the frequency ranges of 5.3-5.8 MHz and 6.0-6.5 MHz.

The effects of the adhesive thickness h_A and the wave velocity in the adherends c_0 on the reflection coefficient are shown in Figs. 3 and 4, respectively. The increase in the adhesive thickness tends to shift the entire set of notch frequencies to the left. Similarly, the decrease in the wave velocity of the adherends results in a shift in the notch frequencies to the left. The theoretical results obtained above suggest that the interfacial stiffness, adhesive thickness, and wave velocity can be estimated by measuring the notch frequencies of the reflection coefficient.

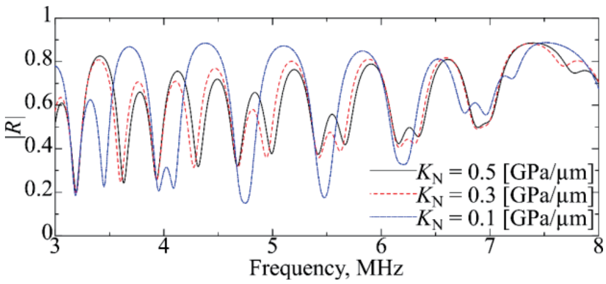

Fig. 2 Effect of the interfacial stiffness K_N on the reflection coefficient $|R|$.

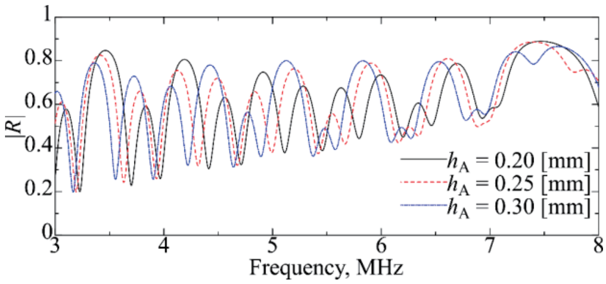

Fig. 3 Effect of the adhesive thickness h_A on the reflection coefficient $|R|$.

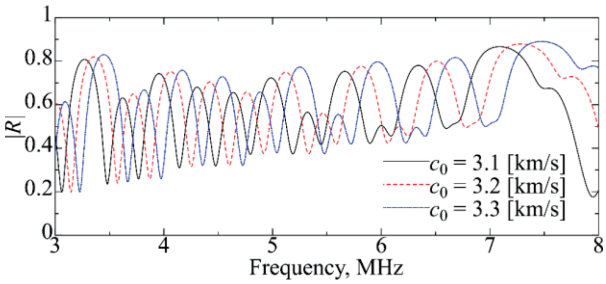

Fig. 4 Effect of the wave velocity c_0 of the adherends on the reflection coefficient $|R|$.

4. Estimation of the adhesive interfacial stiffness

Ultrasonic pulse-echo measurement was performed on a CFRP bonded joint immersed in a water tank. Unidirectional laminates of carbon fiber reinforced epoxy composite (T800S/3900-2B, Toray Industries; 10 plies, nominal thickness 2 mm) were bonded by an epoxy film adhesive (FM309-1M, Cytec; nominal thickness 0.25 mm). Measurement was also carried out on a stainless-steel reflector to obtain the reference waveform. 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.

The measured reflection coefficient $|R|$ is shown as a function of the frequency in Fig. 5. The reflection coefficient exhibits multiple notches similarly to the theoretical results. The notch frequencies are extracted from the measured reflection coefficient, and the interfacial stiffness of the bonded specimen is estimated by comparing the experimental and theoretical results of the notch frequencies. As a result, the notch frequencies show optimal agreement at K_N = 0.41 [GPa/μm], h_A = 0.24 [mm], and c_0 = 3.28 [km/s]. The theoretical reflection coefficient under these conditions is also shown in Fig. 5. The theoretical result is found to well reproduce the measured notch frequencies.

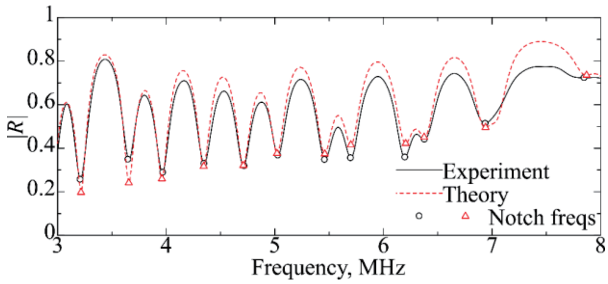

Fig. 5 Measured reflection coefficient and theoretical result obtained by the estimated parameters.

Acknowledgment

This study has been supported as a part of a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO) of Japan. The authors would like to thank Mitsubishi Heavy Industries, Ltd. for providing the test specimens used in the study.

References

1. X. Han, L. D. Favro, Z. Ouyang and R. L. Thomas: J. Adhes. **76** (2001), 151.
2. R. L. Vijaya Kumar, M. R. Bhat and C. R. L. Murthy: Ultrasonics **53** (2013), 1150.
3. D. N. Markatos, K. I. Tserpes, E. Rau, S. Markus, B. Ehrhart and S. Pantelakis: Compos. Part B Eng. **45**, (2013), 556.
4. A. I. Lavrentyev and S. I. Rokhlin: J. Acoust. Soc. Am. **103** (1998), 657.
5. Y. Ishii and S. Biwa: J. Appl. Phys. **111** (2012), 084907.
6. S. Biwa, Y. Watanabe and N. Ohno: Compos. Sci. Tech. **63** (2003), 237.