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Influence of porosity on ultrasonic wave velocity, attenuation and interlaminar interface echoes in composite laminates: Finite element simulations and measurements

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ABSTRACT

The influence of porosity on the ultrasonic wave propagation in unidirectional carbon-fiber-reinforced composite laminates is investigated based on the two-dimensional finite element analysis and measurements. Random distributions of pores with different contents and size are considered in the analysis, together with the effects of viscoelastic plies and interlaminar resin-rich regions. The transient reflection waveforms are calculated from the frequency-domain finite-element solutions by the inverse Fourier transform. As the measures for porosity characterization, the ultrasonic wave velocity, attenuation coefficient, and interlaminar interface echo characteristics are examined for 24-ply unidirectional composite laminates. As a result, the wave velocity decreases with the porosity content in a manner insensitive to the pore size. On the other hand, the attenuation coefficient increases both with the porosity content and with the pore size. The time–frequency analysis of the reflection waveforms shows that the temporal decay rate of interlaminar interface echoes at the stop-band frequency is a good indicator of the porosity content. The measured porosity-content dependence of the wave velocity is better reproduced by the numerical simulations when the interlayer interfacial stiffnesses are adjusted according to the porosity content, indicating that not only the porosity features but also the interlaminar interfacial properties vary with curing conditions.

1. Introduction

Wide applications of carbon-fiber-reinforced plastics (CFRP) in aerospace, automotive, civil, and marine industries have considerably increased the importance of nondestructive evaluation for their diagnosis. It is recognized that one of the detrimental defects in CFRP laminates is the porosity [1], i.e., distribution of minute pores within the laminate. Porosity levels of more than 2 % by volume fraction [2] can significantly degrade the mechanical properties of the composite laminates such as interlaminar shear strength [3–7], flexural strength [3,8], tensile strength [4,7], compression strength [9], etc. For this reason, the nondestructive evaluation of the porosity content is essential and has been the subject of extensive investigation.

Conventional techniques to evaluate the porosity content have been based on the ultrasonic wave velocity [10–15] and attenuation [15–27] in the stacking direction of composite laminates. In practice, the attenuation is used more frequently than the wave velocity because of its higher sensitivity to the porosity content [2]. In particular, the slope of the attenuation coefficient with respect to the frequency has been shown to be useful for the estimation of porosity content [5,18]. More recently, the interlaminar interface echoes, also called structural [28] or backscattered signals [29,30], have been studied as an alternative parameter to evaluate the porosity content.

In order to corroborate the experimental findings for nondestructive porosity characterization, the numerical simulation of ultrasonic wave propagation is particularly effective as it can model the content, size, and arrangement of pores in the composite in a controlled manner. Finite difference [26–28] as well as finite element methods [31] have been adopted to simulate the ultrasonic wave propagation in porosity-containing composite materials. In these previous works, the composites are modeled as elastic solids with distributed pores. In polymer-based composite

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materials, however, the viscoelastic nature of plies has a significant effect on the wave attenuation. Furthermore, the interlaminar resin-rich zones can also affect the wave propagation behavior. These features should be accounted for in an appropriate manner when the effect of porosity on the wave propagation characteristics in composite laminates is to be evaluated by computational modeling.

In this paper, the two-dimensional finite element simulations of ultrasonic wave propagation in porosity-containing unidirectional CFRP laminates are presented. In contrast to the aforementioned works [26–28,31], the present analysis is carried out in the frequency domain. This is of particular advantage when incorporating the viscoelastic properties of CFRP exhibiting nearly linear frequency dependence of the attenuation coefficients [32–34]. Thin interlaminar resin-rich regions are modeled as spring-type interlayer interfaces with equivalent normal and shear stiffnesses [35–41]. The transient reflection waveform from the CFRP laminate immersed in water is obtained by the inverse Fourier transform of the frequency-domain solution. The influence of the content as well as the size of pores on the ultrasonic wave velocity, attenuation coefficient, and interlaminar interface echoes is examined based on the numerical simulations and the corresponding experimental results.

This paper is structured as follows. In Section 2, the procedure for the measurement of reflected waves from porosity-containing unidirectional CFRP laminates immersed in water is presented. In Section 3, the computational model and the frequency-domain finite element analysis are described. In Section 4, the numerical and experimental results of the wave velocity, attenuation coefficient, and interlaminar interface echoes for different contents and size of pores are discussed. The conclusion of this study is summarized in Section 5.

2. Experimental procedure

The specimens used in the measurement were unidirectional 24-ply carbon-epoxy composite laminates fabricated using the Toho Tenax UTS50/135 UD prepregs. Besides a porosity-free specimen manufactured under the standard conditions, six other specimens with different levels of porosity were prepared by modifying the compaction scheme and assigning improper curing conditions. The optical micrographs of the cross-section perpendicular to the fibers are shown in Fig. 1 for the representative specimens. The porosity content of each specimen was measured as the area fraction of pores in its micrograph using an image analysis technique, as summarized in Table 1 together with the measured laminate thickness and density. The other dimensions of the specimens were all 100 mm × 120 mm.

The measurement of reflected ultrasonic waves from porosity-containing CFRP laminates was performed with the pulse-echo technique at normal incidence in water. Two kinds of non-focusing piezoelectric transducers with nominal center frequencies of 2.25 MHz and 10 MHz were used, and the reflection waveforms were digitized with the sampling frequency of 100 MHz. The 2.25 MHz transducer was used for the measurement of the wave velocity and attenuation from the front and back wall echoes. After the Fourier transform was carried out for the recorded waveforms, the wave velocity $V(f)$ and attenuation coefficient $\alpha(f)$ in the thickness direction were obtained as functions of the frequency f using the following equations [42]:

$$V(f) = \frac{4\pi f d}{\theta_{\mathrm{Front}}(f) - \theta_{\mathrm{Back}}(f) + 2n\pi}, \tag{1}$$

$$\alpha(f) = \frac{1}{2d} \ln\left[\frac{1 - \{R(f)\}^2}{A_{\mathrm{Back}}(f)/A_{\mathrm{Front}}(f)}\right], \tag{2}$$

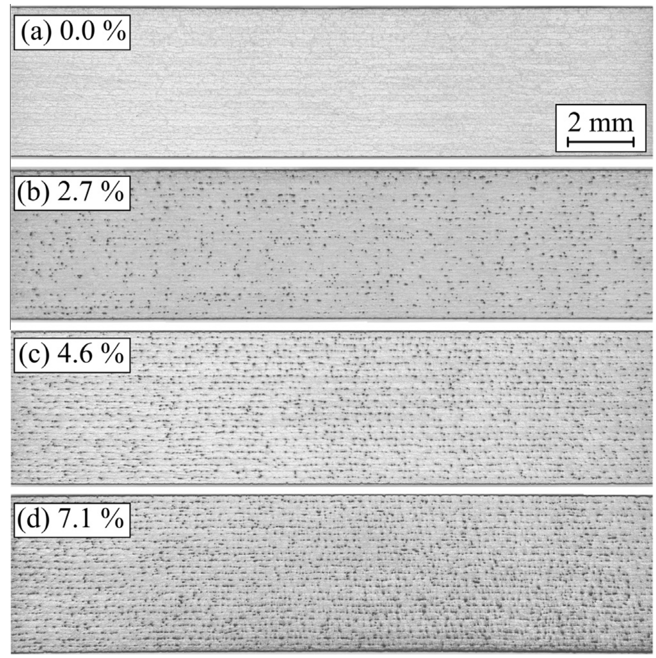

Fig. 1. Micrograph of cross-sections perpendicular to the fiber direction of 24-ply unidirectional CFRP laminate specimens with different porosity contents.

where $\theta_{\mathrm{Front}}(f)$ ($\theta_{\mathrm{Back}}(f)$) and $A_{\mathrm{Front}}(f)$ ($A_{\mathrm{Back}}(f)$) are the phase and amplitude spectra of the front (back) wall echo, n is an integer to be determined by phase unwrapping, and d is the thickness of the specimen. In Eq. (2), $R(f)$ is the amplitude reflection coefficient at the water-specimen interface given by

$$R(f) = \frac{\rho_{\mathrm{w}} V_{\mathrm{w}} - \rho_{\mathrm{s}} V(f)}{\rho_{\mathrm{w}} V_{\mathrm{w}} + \rho_{\mathrm{s}} V(f)}, \tag{3}$$

where ρ_{w} and V_{w} are the density and the wave speed of water, and ρ_{s} is the density of the specimen. On the other hand, the 10 MHz transducer was used for the characterization of the interlaminar interface echo signals. The time–frequency analysis was then performed by calculating the short-time Fourier transform (STFT) of the reflection waveforms in order to obtain the temporal evolution of the frequency components in the interlaminar interface echoes.

The experimental procedure outlined above was also applied to measure the wave reflection by a polished surface of an aluminum block immersed in water using the same transducers. The recorded reflection waveforms for the two transducers are shown in Fig. 2. These waveforms were regarded to be proportional to those of the incident waves from the transducers, and used as the displacement waveforms of the incident waves in the numerical simulations described below.

3. Two-dimensional frequency-domain finite element analysis

3.1. Computational model

The computational model for the two-dimensional plane-strain ultrasonic wave propagation in a composite laminate is shown in Fig. 3. It occupies the domain of $0 \leqslant x_1 \leqslant L$ and $0 \leqslant x_2 \leqslant 2H_{\mathrm{w}} + H$, and consists of an N-layered unidirectional CFRP laminate of total thickness H ($H_{\mathrm{w}} \leqslant x_2 \leqslant H_{\mathrm{w}} + H$) and water regions of height H_{w} ($0 \leqslant x_2 \leqslant H_{\mathrm{w}}$ and $H_{\mathrm{w}} + H \leqslant x_2 \leqslant 2H_{\mathrm{w}} + H$). In the present analysis, the length parameters are set as H_{w} = 1 mm, H = 4.56 mm, N = 24, and L = 10 mm. The computational model in Fig. 3 is discretized by square-shaped four-node isoparametric elements having the identical dimensions of 0.01 mm × 0.01 mm. This element size