Ultrasonic Amplitude Fitting of Fibre Orientation in Fibre-Reinforced Polymers

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1. Introduction

Fiber-Reinforced Polymer (FRP) is a modern material used in a wide variety of industries. FRP is composed of multiple layers of thin glass fiber set in epoxy resin or a similar hardened polymer. As the material has greatest strength in tension along the length of the glass fibers, the fibers are often woven together at different angles to provide strength in more than a single direction. To evaluate both initial quality and service life of FRP, it is important to be able to determine the properties of the FRP both prior to and in service, such as the relative volume of glass and the orientation of the glass fibers within the material. However, conventional FRP testing is destructive in nature, and typically cannot be done without removing or damaging the material itself. [ASTM D 3171, ASTM D 3039] Thus, it is desired to develop non-destructive testing techniques for FRP that can be performed in situ and without material damage.

2. Basis for Ultrasonic FRP Testing

Ultrasonic attenuation measurements have recently become popular for nondestructive characterization of anisotropic materials such as composites [1]. The peak amplitude of both the reference ultrasonic wave at the transducer surface and the reflected echo after passing through the material are compared, allowing an estimate of the attenuation of the material for the given test geometry.

2.1 Ultrasonic Attenuation due to Scattering

In composite materials, a dominant source of ultrasonic attenuation is wave scattering by the embedded fibers [1]. These fibers are considered to be transversely isotropic, so the scattering effect should be symmetric along the length of the fibers. The transmitted ultrasonic energy in the material varies dependent on the angle of ultrasonic wave propagation relative to the fiber direction, as the fibers cause dispersion at all angles other than 0° and 90° [2]. In addition, a longitudinal wave crossing a fiber bundle will experience mode conversion to a transverse wave normal to the fiber direction [2] with associated loss of energy in the longitudinal direction. Hence, longitudinal waves will propagate best in the direction of the fibers. This is verified by measurement of polar backscattering in FRP, which forms a Gaussian distribution centered on the normal to fiber direction [3]. However, only fiber orientations less than 20° different from the normal to the plane of wave propagation can be considered using backscattering due to the negligible amount of backscatter at larger angles.

2.2 Prototype Functions for Ultrasonic Attenuation

It is desirable to determine the general relationship between the reference wave amplitude and the reflected wave amplitude as the fiber angle is varied. Incident angle with respect to fiber rotation is a sinusoidal relationship [2], and the fraction of energy transmitted is expected to vary as the square of the wave amplitude. Hence, a general sine-squared function is suggested as an estimate of the relative transmitted energy through the FRP with changing fiber angle:

$$f(k,a,n,\theta) = a\left[1 - k\sin^2(n\theta)\right] \qquad (1)$$

Here, $n = 180/\alpha$ and α is the angle between fiber layers. The parameter a provides freedom of general amplitude and overall reflective loss at the interfaces, while the parameter k provides freedom of amount of variation with fiber, proportional to the relative fiber content [2]. If only a single fiber direction is present, then $n = 1$. If two sets of fibers are woven together at right angles, then $n = 2$. Assuming a and k are constant for a given material and amplitude, the two cases are respectively:

$$f_{180°}(\theta) = a\left[1 - k\sin^2(\theta)\right] \qquad (2)$$

$$f_{90°}(\theta) = a\left[1 - k\sin^2(2\theta)\right] \qquad (3)$$

3. Ultrasonic Experiments on FRP

To validate the use of these functions for characterizing ultrasonic amplitude with varying angle, two FRP samples were used, a section of flat FRP with a 90° fiber weave (cross-ply) and a section of rounded FRP with an inner 60° fiber weave and outer 180° (unidirectional) wrap. An Olympus Epoch 4 ultrasonic flaw detector was used to insonify the FRP samples at a frequency of 500kHz. Two transducers with angled rubber matching layers, a receiver and a transmitter, were placed in contact with the FRP samples in a pitch-catch arrangement at an incident angle of 10°. Panametrics-NDT Ultragel couplant was used to ensure good contact. Measurements were taken for every 15° of specimen rotation, and the amplitude ratio of reflected wave to reference wave was calculated. Two test points per sample were used for repeatability. Fig. 1 shows a top view of the transducers on the FRP samples, and the arc of rotation they traverse in testing.

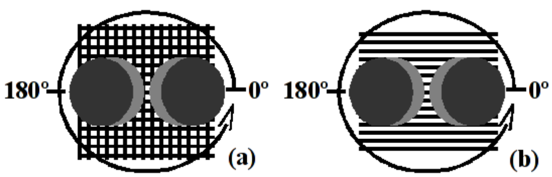

Fig. 1: Transducer positions and rotation on sample of (a) 90° cross ply FRP and (b) 180° fiber wrap FRP

4. Results of Ultrasonic Experiments

Since the flat FRP sample has a visible cross-ply weave, it is fitted to Eq. (3) as shown in Fig. 2. There is evident symmetry about both 90° and 45° angles showing equal fiber content in both axes, and lower amplitude shows more scattering at 45° angles.

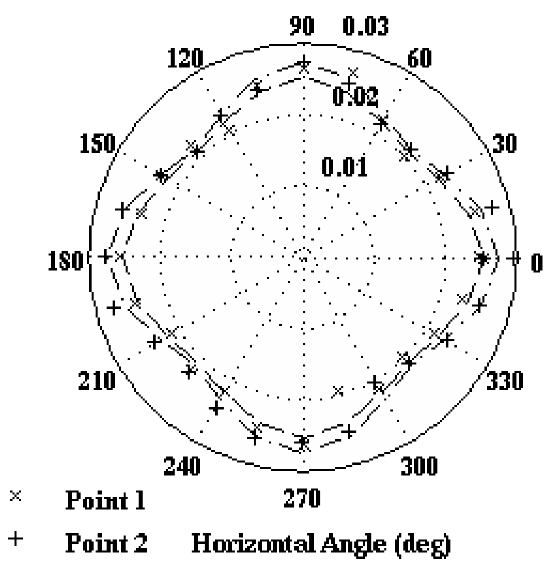

Fig. 2: Amplitude ratio change with angle in right-angle woven FRP.

For the rounded FRP sample, it is expected that the thicker fiber in the unidirectional wrap will dominate the signal. This indeed proves to be the case, as the amplitude ratio profile is symmetric only about 90° angles, is similar to that obtained in [2], and fits Eq. (2) quite well, as shown in Fig. 3. Table 1 shows the results of fitting the amplitude ratio change to the suggested functions.

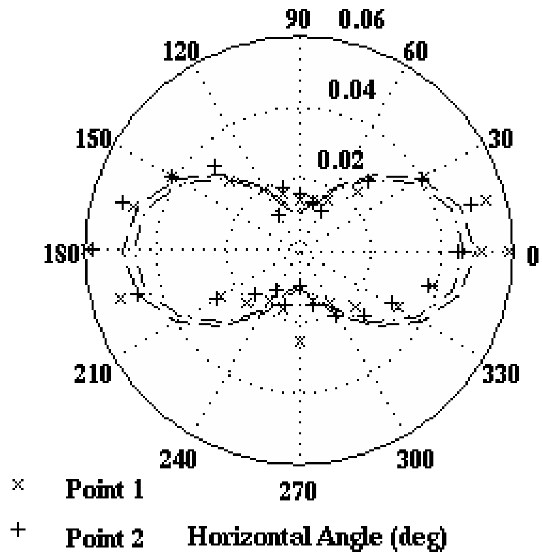

Fig. 3: Amplitude ratio change with angle in circumferentially-wrapped FRP.

Table 1: Fitted parameters of .amplitude ratio

Fibre Angle	Fit Equation	Param-eter 'k'	Param-eter 'a'	RMS error
90º	(3)	0.1797	0.0254	0.0014
90º	(3)	0.2125	0.0273	0.0012
180º	(2)	0.7815	0.0493	0.0070
180º	(2)	0.7885	0.0466	0.0060

5. Conclusions

The prototype functions suggested fit very well with the experimental results. Further work would allow more precise relations between the properties of the FRP sample and the fitting parameters a and k, as well as characterization of more types of FRP.

References

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