Characterization of Fiber Orientation in FRP using Pitch–Catch Ultrasonic Technique

M. Post[1], Z.H. Zhu[1*], G. Clarkson[2]

[1] Department of Earth and Space Science and Engineering, York University
4700 Keele Street, Toronto, Ontario, Canada M3J 1P3

[2] Physical Plant Improvements Inc.
310 Christopher Dr., Cambridge, Ontario, Canada N1P 1B4

Abstract

This paper presents a non-destructive ultrasonic testing method to examine the fiber orientation of Fiber-Reinforced Polymer (FRP) composite laminates prior to and/or in service. A one-sided pitch-catch setup was used in the detection and evaluation of ultrasonic wave behavior and fiber orientation in the FRP composite laminates. Two ultrasonic transducers were joined side-by-side with an oblique angle between and used in the pitch–catch mode on the surface of the composites. The pitch–catch signal was found sensitive to the fiber orientation in the composites. Based on models of wave propagation in fibrous materials, a simple empirical relationship between the angle of ultrasonic wave propagation with respect to the fibers and the amplitude ratio of the reflected and incident ultrasonic wave is proposed. The experimental data show that this relationship fits the experimental results very well.

1. Introduction

Fiber-Reinforced Polymer (FRP) composite laminates are composed of multiple layers of thin

[*] Corresponding author. Tel.: +1 416 736 2100 ext 77729, Fax: +1 416 736 5817. E-mail address: gzhu@yorku.ca.

glass fiber set in epoxy resin or a similar hardened polymer. Since the strength and stiffness of FRP composites depend on the fiber orientations [1], the fibers are often woven together at different angles to provide the desired strength and stiffness in more than a single direction. Figure 1 shows the FRP composites with the fibers in (a) a unidirectional direction and (b) a 90 degree cross-ply woven configuration. To ensure the FRP composites are made to the required specifications, it is important to be able to determine the properties of these FRPs both prior to and/or in service [2], such as the relative volume of glass and the orientation of the glass fibers within the material, without material damage. However, the existing FRP tests are destructive in nature, and typically cannot be done without removing or damaging the material itself [3]. Thus, it is necessary to develop non-destructive testing techniques for FRPs, which can be performed in situ non-destructively.

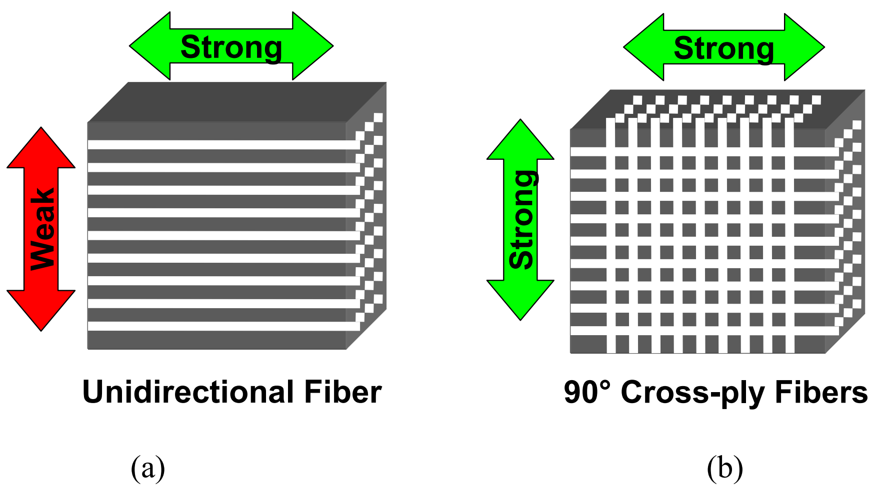


Fig. 1: Configuration of (a) 180° unidirectional fiber FRP (b) 90° cross-ply FRP

There are many non-destructive evaluation technologies in the literature [4] applicable for the current problem. For instance, ultrasonic, radiographic, thermographic, electromagnetic, and optic methods are employed to characterize the properties of FRPs. Among them, the ultrasonic technology is one of the most commonly used in industry because of its accuracy, portability, safety and low cost compared with other non-destructive testing methods [5]. The detection of fiber glass orientation using ultrasonic technology is based on the ultrasonic wave attenuation measurements [6-7, 8]. In this method, the amplitudes of both the incident ultrasonic wave at the top material surface and the echo wave after passing through and reflected at the bottom surface of the material are compared, leading to an estimate of the attenuation of composite laminates for a given fiber configuration. A dominant source of ultrasonic attenuation in composite materials is the wave scattering at the interface of the embedded fibers and matrix [6]. 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 dependents on the angle of ultrasonic wave propagation relative to the fiber direction, as the fibers cause wave dispersion at all angles other than 0° (parallel) and 90° (perpendicular) [7]. In addition, a longitudinal wave crossing a fiber bundle will experience mode conversion to a transverse wave normal to the fiber direction [7] with associated loss of energy in the longitudinal direction. Hence, the ultrasonic wave attenuation due to the energy loss of longitudinal wave passing through the fiber glass will depend on the angle between the longitudinal wave and the orientation of fiber glass [9]. The current experimental work will try to establish a relationship between the wave attenuation and the propagation direction of longitudinal wave with respect to the fiber orientation.

2. Ultrasonic Experimental Setup

The ultrasonic wave attenuation measurements are carried out by a pitch-catch ultrasonic technique as shown in Fig. 2. Two FRP samples were used, a section of FRP with a 90° fiber weave (cross-ply) and a section of FRP with unidirectional firers. 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°, see Fig. 2(c). Panametrics-NDT Ultragel couplant was used to ensure a good ultrasonic wave transmission into and out of the FRP samples. The pair of transducers is rotated in anticlockwise direction to measure the variations of ultrasonic wave attenuation with respective to the orientation of fibers embedded in the samples, see Fig. 2(a,b). Measurements were taken at every 15° increments starting from a reference direction of 0° parallel to the principal fiber direction. Then, the amplitude ratio of reflected wave to incident wave was calculated. Two test points per sample were used for repeatability.

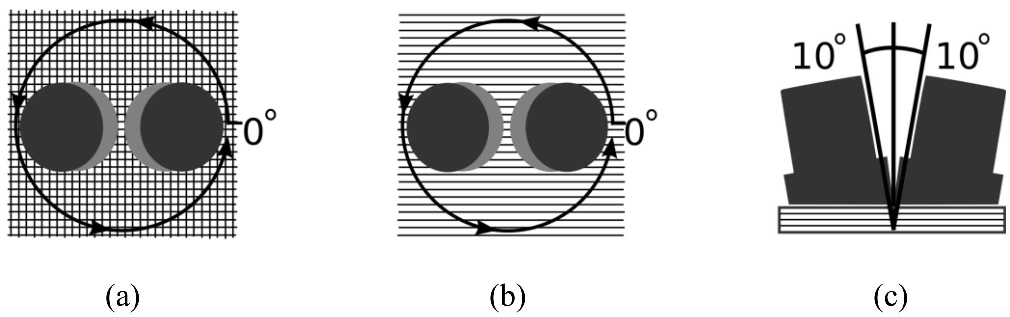
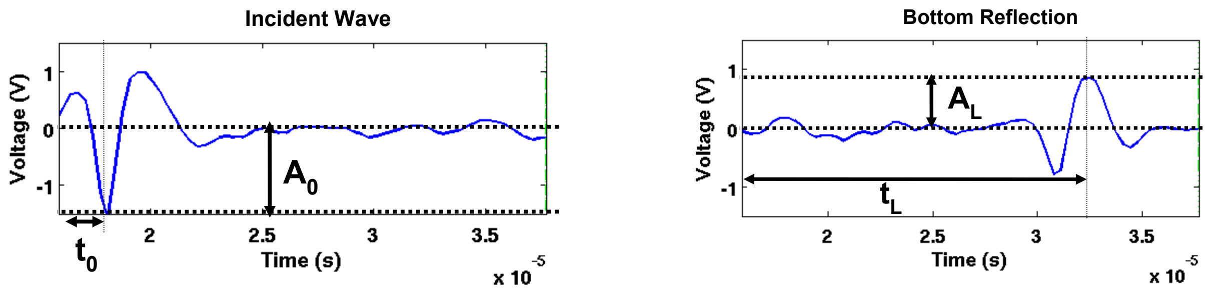


Fig. 2: Transducer position and rotation: (a) 90° cross ply and (b) 180° unidirectional fibers; (c) oblique incident angles.

In the experiments, the amplitude of the incident wave was measured by physically coupling the transmitter to the receiver directly face to face, so that nearly no energy is lost other than that lost within the transducers and the measuring system themselves, shown in Fig. 3(a). Then, the amplitude of the reflected wave from the bottom surface of FRP sample were measured and compared with the incident wave. Figure 3(b) shows the reflected wave, which is inverted because the bottom surface of the FRP is a solid to air interface. The exact locations of the peaks of both waves were located by means of time-domain wavelet correlation. The amplitude ratio ζ of the reflected to the incident waves can then be calculated by $\zeta = A_L / A_0$, where A_L and A_0 are the peak amplitudes of the reflected and the incident waves, respectively. The wave velocity in the material is calculated by $V_L = \left(\frac{\tau}{h}\right)\cos(\theta)$, where τ is the difference in arrival times $\tau = t_L - t_0$ as shown in Fig. 3, h is the thickness of sample, and θ in this case is 10°, respectively.



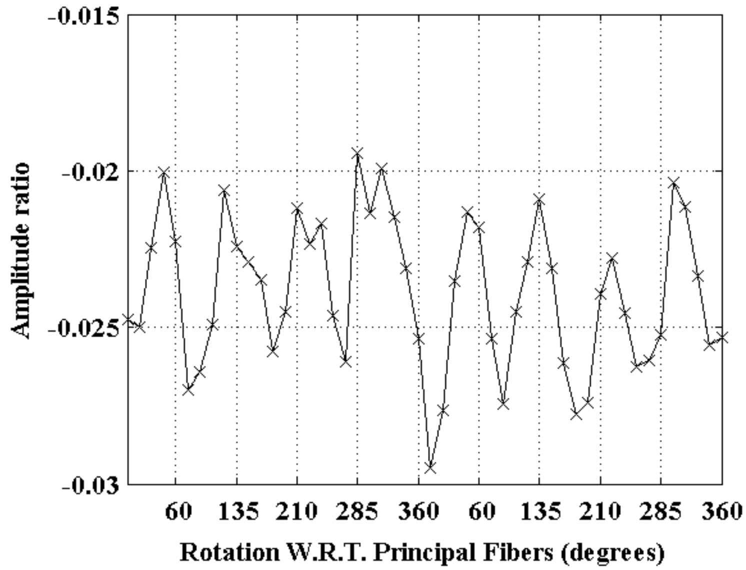
(*a*) (*b*)

Fig. 3: Peak amplitudes of (a) incident wave pulse and (b) the reflection wave pulse from the bottom of FRPs.

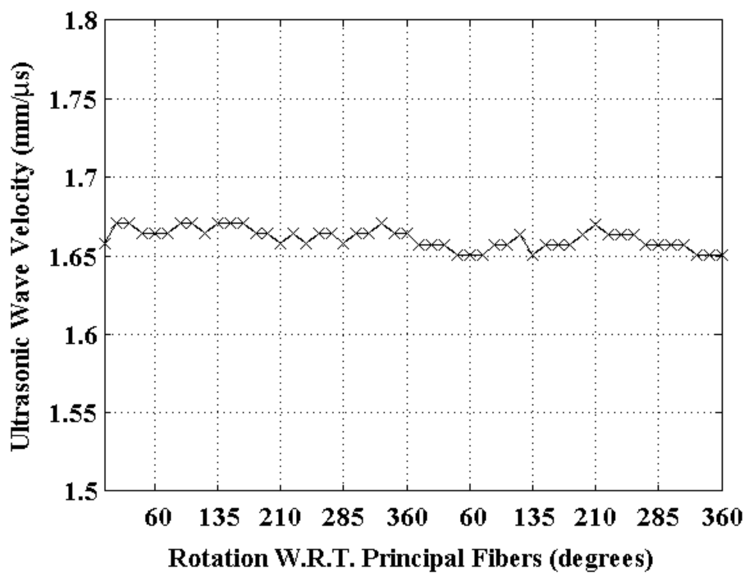
3. Results of Ultrasonic Experiments

3.1 Effects of FRP anisotropy duo to fiber orientation

To evaluate the effects of the anisotropy of FRPs due to the fiber orientation, both the ultrasonic amplitude ratio and ultrasonic wave velocity were evaluated in the cross-ply (90°) FRP sample. Fig. 4 shows the variation of (a) the amplitude ratio and (b) the wave velocity with a full rotation of the transducers in 15 degree increments.



(a)



(b)

Fig. 4: Variation of (a) amplitude ratio and (b) wave velocity versus rotation angles.

The ultrasonic amplitude ratio shows a very strong dependence on the angle of wave propagation with respect to the principle fiber direction that has a period of approximately 90°.

However, there is only very little variation (<1.8%) in the ultrasonic wave velocity as the angle of wave propagation with respect to the fibers is changed, with no clear indication of angular dependence. It is therefore justified to focus on the amplitude ratio changes with respect to the angle of wave propagation.

3.2 Experiments of FRP sample with cross-ply woven fibers

Firstly, the FRP sample with cross-ply (90°) woven fibers embedded in matrix was tested. Two sets of measurement at two distinct points were carried out. Figure 5 shows the polar plot of the amplitude ratio of reflected and incident waves with respect to the principal direction of the fibers. It has shown clearly that the amplitude ratio varies as the relative angle between the direction of wave propagation and the fiber orientation changes. There is evident symmetry about both 90° and 45° angles showing equal fiber content in both axes, and lower amplitude ratio shows more scattering at 45° angles. The amplitude ratio maximized when the direction of wave propagation was aligned with the direction of fibers (0° or 90°) and minimized when the direction of wave propagation was at the middle between the directions of fibers (45°). Since the wave attenuation is caused by the scattering of wave energy at the interface of fibers and matrix, which is proportional to the square of wave amplitude, we can propose an empirical formula to fit the data, such as,

$$f(k,a,\theta)=a\left[1-k\sin^2(2\theta)\right] \tag{1}$$

The parameters *k* and *a* in Eq. (1) are shown in Table 1 and the fitted curves are plotted in Fig. 5 in the dashed lines. Clearly, Eq. (1) fits the experimental data very well.

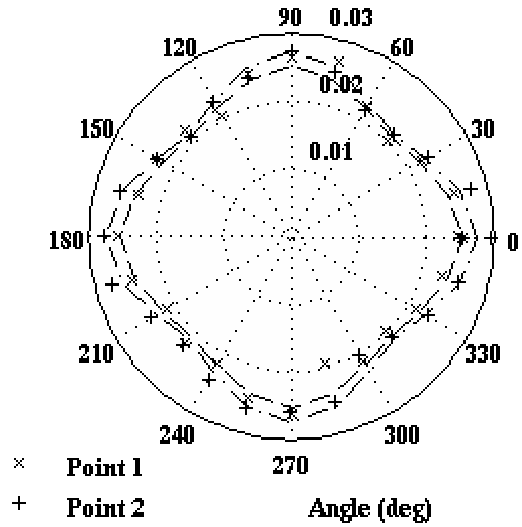


Fig. 5: Variation of amplitude ratio with respect to cross-ply woven FRP.

Table 1 Parameters of curve fit for cross-ply woven FRP sample.

Point No.	*k*	*a*	RMS error (%)
1	0.1797	0.0254	0.14
2	0.2125	0.0273	0.12

3.3 Experiments of FRP sample with unidirectional fibers

Secondly, a FRP sample with unidirectional fibers (180°) was tested. Similarly, two sets of measurement at two distinct points were carried out. Figure 6 shows the polar plot of the amplitude ratio of reflected and incident waves with respect to the principal direction of the fibers. Similar to the sample with cross-ply woven fibers, it has shown a strong dependence of the amplitude ratio on the relative angle between the direction of wave propagation and the fiber orientation. There is evident symmetry about both horizontal and vertical axes. The amplitude ratio maximized when the direction of wave propagation was aligned with the direction of fibers (0° or 180°) and minimized when the direction of wave propagation was perpendicular to the fibers (90° or 270°).

Since the wave attenuation is caused by the scattering of wave energy at the interface of fibers and matrix, which is proportional to the square of wave amplitude, we propose an empirical formula to fit the data, such as,

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

The parameters *k* and *a* in Eq. (2) are shown in Table 2 and the fitted curves are plotted in Fig. 6 in the dashed lines. Clearly, Eq. (2) fits the experimental data very well.

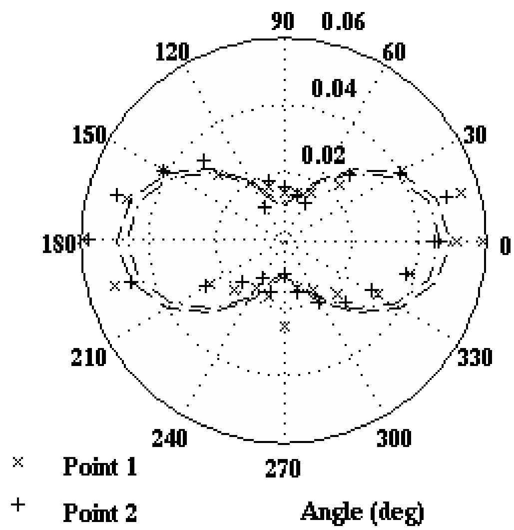


Fig. 6: Variation of amplitude ratio with respect to unidirectional fiber FRP.

Table 2 Parameters of curve fit for unidirectional fiber FRP sample.

Point No.	*k*	*a*	RMS error (%)
1	0.7815	0.0493	0.70
2	0.7885	0.0466	0.60

4. Conclusions

The experiments indicate there is a strong dependence of the amplitude ratio of reflected and incident wave on the relative angle between the direction of wave propagation and the fiber orientation. In addition, two empirical formulae, Eqs. (1-2), are proposed to predict the relationships between the amplitude ratio of reflected and incident wave and the relative angle of wave propagation with respective to the fiber orientations. The equations fit with the experimental data very well. Based on the experimental data, Eqs. (1-2) can be further generalized as:

$$f(k,a,\alpha,\theta)=a\left[1-k\sin^2\left(\frac{180}{\alpha}\theta\right)\right] \tag{3}$$

where α is the angle in degrees between principal fiber directions, and the parameters k and a are functions of properties of fibers and matrix as well as volume fraction of fibers. For instance, α = 180° for FRPs with unidirectional fiber and Eq. (3) will reduce to Eq. (2). If the FRPs are made by cross-ply (90°) woven fibers, then α = 90° and Eq. (3) will reduce to Eq. (1). Future work will be carried out to determine the dependence of parameters k and a on the properties of fibers and matrix as well as volume fraction of fibers.

References

[1] G. Li, D. Maricherla, K. Singh, S. Pang, M. John, "Effect of fiber orientation on the structural behavior of FRP wrapped concrete cylinders", *Composite Structures,* Vol. 74, No. 4, pp. 475-483, 2006.

[2] K. W. Neale, "FRPs for structural rehabilitation: a survey of recent progress", *Progress in Structural Engineering and Materials*, Vol. 2, No. 2, pp. 133 – 138, 2000.

[3] D. G. Taggart, R. B. Pipes, J. C. Mosko, "Test method evaluation for fiber-reinforced

molding materials", *Polymer Composites*, Vol. 1, No. 1, pp. 56 – 61, 2004.

[4] H. Kaiser, V.M. Karbhari, " Non-destructive testing techniques for FRP rehabilitated concrete. I: a critical review", *International Journal of Materials and Product Technology*, Vol. 21, No. 5 pp. 349-384, 2004.

[5] M. A. Hamstad, "A review: Acoustic emission, a tool for composite-materials studies", *Experimental Mechanics*, Vol. 26, No. 1, pp. 7-13, 1986.

[6] S. Biwa, Y. Watanabe, N. Ohno. "Analysis of wave attenuation in unidirectional viscoelastic composites by a differential scheme", *Composites Science and Technology*, Vol. 63, pp. 237-247, 2003.

[7] R. Prakash, C. N. Owston. "Ultrasonic determination of lay-up order in cross-plied cfrp", *Composites*, Vol. 8, No. 2, pp. 100-102. 1977.

[8] I. Yang, K. Im, D. K. Hsu, et al., "Feasibility on fiber orientation detection of unidirectional CFRP composite laminates using one-sided pitch–catch ultrasonic technique", *Composites Science and Technology*, doi:10.1016/j.compscitech.2009.01.007, 2009.

[9] G. Bechtold, K. M. Gaffney, J. Botsis, K. Freidrich, "Fibre orientation in an injection moulded specimen by ultrasonic backscattering", *Composites*, Vol. 29, No. 7, pp. 743-748. 1998.