ULTRASONIC MONITORING OF MATERIAL DEGRADATION IN FRP COMPOSITES

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ABSTRACT: This research uses laser ultrasonic techniques to monitor a (directly measurable) ultrasonic property—frequency-dependent Rayleigh wave velocity (material dispersion)—and then relates changes in this acoustic property to changes in the material's properties (such as stiffness) that characterize damage. The subject material system is a thick, glass-reinforced, vinylester (thermosetting) fiber-reinforced polymer (FRP) composite. Laser ultrasonics is an ideal methodology to monitor changes in the Rayleigh phase (or group) velocity of this material because of its high fidelity, broad bandwidth, point source/receiver, and noncontact nature. The experimental procedure consists of measuring a series of transient elastic waveforms in a thick FRP specimen and then operating on these waveforms with the 2D fast Fourier transform to develop the dispersion relationship for that specimen. Material degradation (damage) is introduced into these specimens with environmental aging, and the dispersion curves are used to quantitatively track changes in material properties as a function of degradation.

INTRODUCTION

The use of thick fiber-reinforced polymeric (FRP) composites in civil engineering applications has introduced the need for methodologies that can monitor the deterioration of an FRP component's material properties due to service loads and environmental conditions. Currently, there is no nondestructive methodology that can quantitatively track changes in material properties (within a control volume) as a function of accumulated damage. This deficiency is one impediment to the development of a quantitative understanding of deterioration in thick FRP components.

Ultrasonics is a candidate technique that has proven to be effective in similar applications. Consider ultrasonic phase velocity, a directly measurable acoustic property, which is related to a material's elastic constants and density; these phase velocities can provide a nondestructive measure of changes in a material's elastic properties as a function of deterioration. Note that the individual stiffness components, as well as density, are all coupled in these acoustic measurements [see Littles et al. (1998b) for the exact relationship between the material stiffness components, density, and ultrasonic phase velocity]. Unfortunately, the random and heterogeneous nature of pultruded FRP composites results in complicated ultrasonic signals that are difficult to interpret. One manifestation of this material complexity is that phase (or group) velocity can be frequency dependent; this effect is called material dispersion. Because different frequencies travel with different phase velocities, the shape of an ultrasonic wave will change as it propagates through a specimen. This change in shape makes it difficult to identify the precise arrival time of a specific wavefront (such as a Rayleigh surface wave), resulting in (potentially) inaccurate phase velocity calculations.

This research integrates laser ultrasonic techniques with the 2D fast Fourier transformation (2D-FFT) to accurately measure small changes in the frequency-dependent Rayleigh phase velocity, as a function of accumulated damage. The 2D-FFT is free from synthetic signal processing artifacts—there is no need for the arbitrary identification of the arrival of a specific wavefront within a complicated waveform. Laser ultrasonics is an ideal methodology to monitor small changes in a material's acoustic properties because of its high fidelity, broad bandwidth, point source/receiver and noncontact nature. By using this optical technique, it is possible to experimentally measure ultrasonic waves in an FRP specimen without any of the frequency biases present in, for example, piezoelectric transducers. In addition, laser ultrasonics allows for measurements with a point source and a point receiver, thus enabling spatial sampling techniques such as the 2D-FFT. Finally, the noncontact measurement procedure does not interfere with the surface phenomena being observed, thus providing an exceptionally clean detection process.

The proposed experimental procedure consists of measuring a series of transient elastic waves in a thick FRP specimen and then operating on these waveforms with the 2D-FFT to develop the dispersion relationship for a Rayleigh surface wave in that specimen. Degradation can potentially cause changes in the microstructure and stiffness of an FRP specimen, which in turn will cause changes in the phase velocity of a Rayleigh wave propagating in a degraded specimen. As a result, the experimentally measured dispersion curves are used to quantitatively track changes in an FRP specimen as a function of degradation.

Previous research into the propagation of ultrasonic waves in these thick FRP composites includes that of Littles et al. (1998a,b), who showed that it is possible to nondestructively measure each of the five elastic stiffness components. They had success using a two-point method to measure Rayleigh phase velocity (i.e., they measured arrival times at two different locations) but did not consider the effect of material degradation on the measured values. Immersion ultrasonic techniques have been developed to measure the engineering constants of a variety of composite materials [e.g., Stijnman (1995)], but these immersion techniques possess a number of inherent limitations, most importantly that the specimen must be placed in a tank of water. Methods that use surface acoustic wave speeds have been explored to a lesser degree [e.g., Rose et al. (1990)]. Balasubramaniam and Rose (1991) considered wave propagation in degraded anisotropic plates, including the effect of porosity, whereas Seale and Madaras (1999) used Lamb waves to quantify stiffness changes as a function of damage in thin composite plates. Stanullo et al. (1998) used ultrasonic methods, including changes in phase velocity, to track damage development in polymer composites. Note that

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an important advantage of the proposed technique (over previous research) is that it allows for the monitoring of changes in exactly the same control volume of an in-service FRP component.

DESCRIPTION OF MATERIAL SYSTEM

The material investigated in this research is a thick, pultruded FRP composite intended for civil structural applications. These structural members are manufactured by the pultrusion process in which fiber rovings and other preforms, such as a continuous strand mat, are impregnated with resin and pulled through a heated die (with a specific cross-sectional shape) where the composite system is cured. The roving and continuous strand mat fibers used in this composite system are E-glass, and the resin is a vinylester thermoset. The overall material system can be considered as an orthotropic, homogeneous medium.

Fig. 1 shows a magnified digital image of a typical cross section of the FRP microstructure; this image clearly shows the high level of variability and randomness (including the distribution of fiber bundles and the existence of voids) in this material. In addition to being much thicker than traditional aerospace composite materials, this material exhibits a level of variation in its material properties not normally associated with high performance composite materials. This lack of consistency and quality (as well as the strong, inherent inhomogeneity) in the FRP material will manifest itself in significant variations in material properties [e.g., Wang and Zureick (1994)]. Material property variations within the same specimen (or from specimen to specimen) can be even greater than the changes in these same properties caused by material degradation; this variability plays a critical role in defining reliable monitoring techniques. The proposed methodology tracks changes in a component's acoustic properties in *exactly the same material volume* (i.e., the control volume), thus removing any inaccuracies associated with material variability.

The specimens in this study are cut from plates with a nominal thickness of 0.5 in 12.7 mm (0.5 in.); the specimens' length and width are on the order of 200 mm but, because of the local nature of the proposed technique, have no bearing on the results.

DEVELOPMENT OF DISPERSION CURVES WITH 2D-FFT

The proposed experimental procedure measures a series of transient waveforms (each with a different propagation distance) to develop a quantitative measure of the frequency-dependent phase velocity of Rayleigh waves that propagate in an FRP component. This relationship is best interpreted in terms of a dispersion curve, which presents the relationship between frequency and wave number (or phase velocity). These dispersion curves are developed by operating on these transient waveforms with the 2D-FFT (Alleyne and Cawley 1991; Kley et al. 1999). The 2D-FFT requires multiple waveforms (generated with the same source), each having a different propagation distance and separated by an equally spaced increment. In this study, these multiple, equally spaced waveforms are generated with a repeatable optical source—the pulse of an Nd:YAG laser. Note that the 2D-FFT is most effective with a large number of broadband, transient signals, measured with a small spatial sampling distance.

One advantage of the proposed procedure is that it is independent of the relatively arbitrary choice of an arrival time; it is extremely difficult to identify the exact arrival of a specific feature, such as the Rayleigh wave, in the complicated waveforms that propagate in FRP components. In addition, this procedure can monitor changes in exactly the same control volume, thus avoiding the problems associated with material variability that can swamp and dominate any small changes in material properties caused by degradation. It is important to note that this study considers material, and not geometric, dispersion. Geometric dispersion, which is present when a plate specimen acts as a waveguide, is not evident in these thick plate specimens with the small (relative to plate thickness) propagation distances used here.

EXPERIMENTAL PROCEDURE AND RESULTS

The beam from an Nd:YAG laser (450-mJ, 4–6-ns pulse) is attenuated and focused before striking the specimen. A focusing lens and alignment mirror are mounted on a (micrometer-driven) translation stage that allows for precise (horizontal) movement of the optical source (Fig. 2). This setup provides a laser source (i.e., a thermoelastic source in this

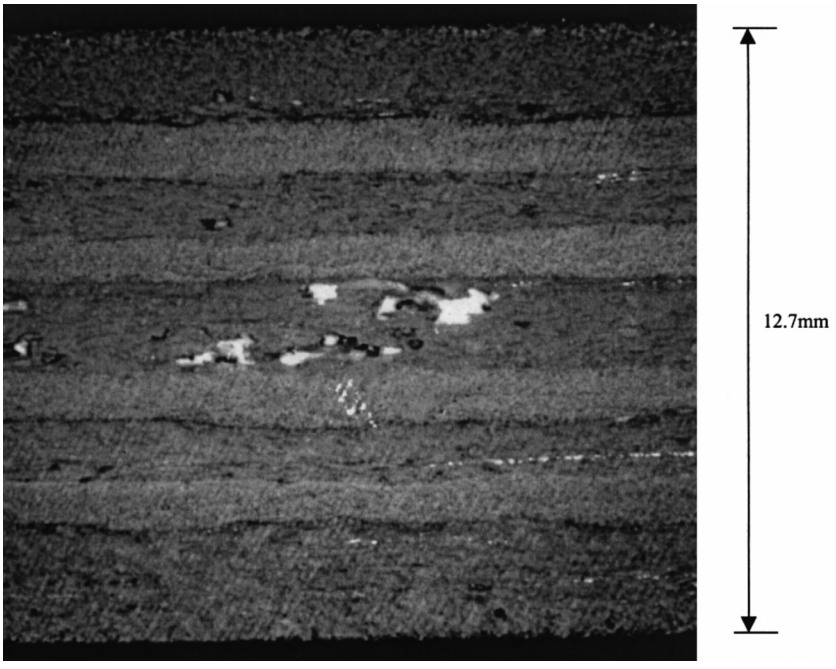

FIG. 1. Magnified Digital Image of Typical FRP Cross Section

study) that generates exactly the same ultrasonic signal, at multiple, equally spaced locations, throughout each test. Note that this setup does not guarantee that the laser source is exactly the same (spot size of approximately 1 mm) for all the specimens (or for a specimen that is removed and reinstalled) but only that the laser source remains constant as the source is translated to different spatial locations on the same specimen. Laser detection of these ultrasonic waveforms is accomplished with a heterodyne interferometer that is a modified version of the instrument described in detail by Bruttomesso et al. (1993). This optical device uses the Doppler shift to simultaneously measure out-of-plane surface velocity (particle velocity) at a point on the specimen's surface. This interferometer makes high fidelity, absolute measurements of surface velocity over a bandwidth of 200 kHz to 10 MHz.

While the receiver is kept in a fixed position, the source is placed at 71 equally spaced locations; an incremental (Δx) distance of 0.2 mm separates each source location for a total length of 14 mm. This results in the (generation and) detection of 71 waveforms, each with a different propagation distance and each generated with the same laser source. For example, Fig. 3 shows 22 (of 71) typical transient waveforms (every other wave is presented, so Δx = 0.4 mm). These waveforms are measured in a 12.7-mm-thick FRP specimen, with propagation distances ranging from 27.4 to 36.2 mm. Note that these measurements are made (along) in the same direction as the fiber bundles, and all waveforms are the result of signal averaging—typically 40 signals are averaged to improve signal-to-noise ratio. The dominant feature in each of these waveforms (i.e., the large amplitude portion with a pair of sharp

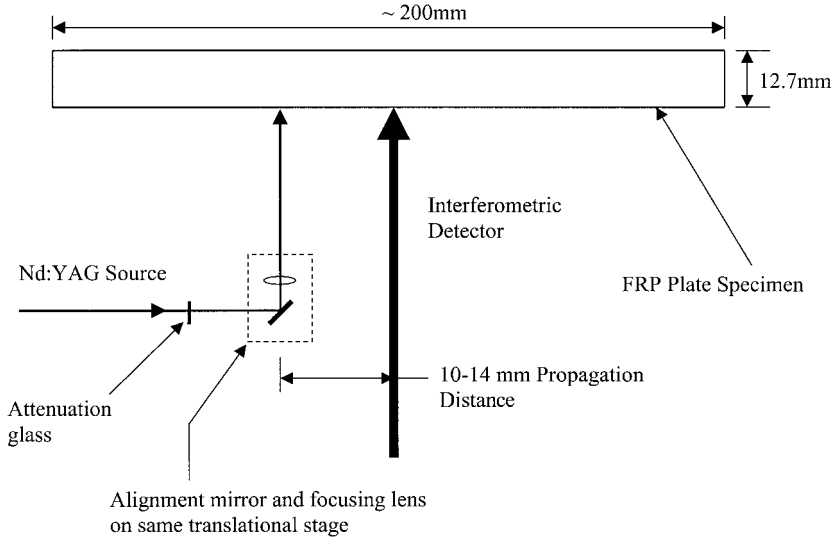

FIG. 2. Schematic of Experimental Setup

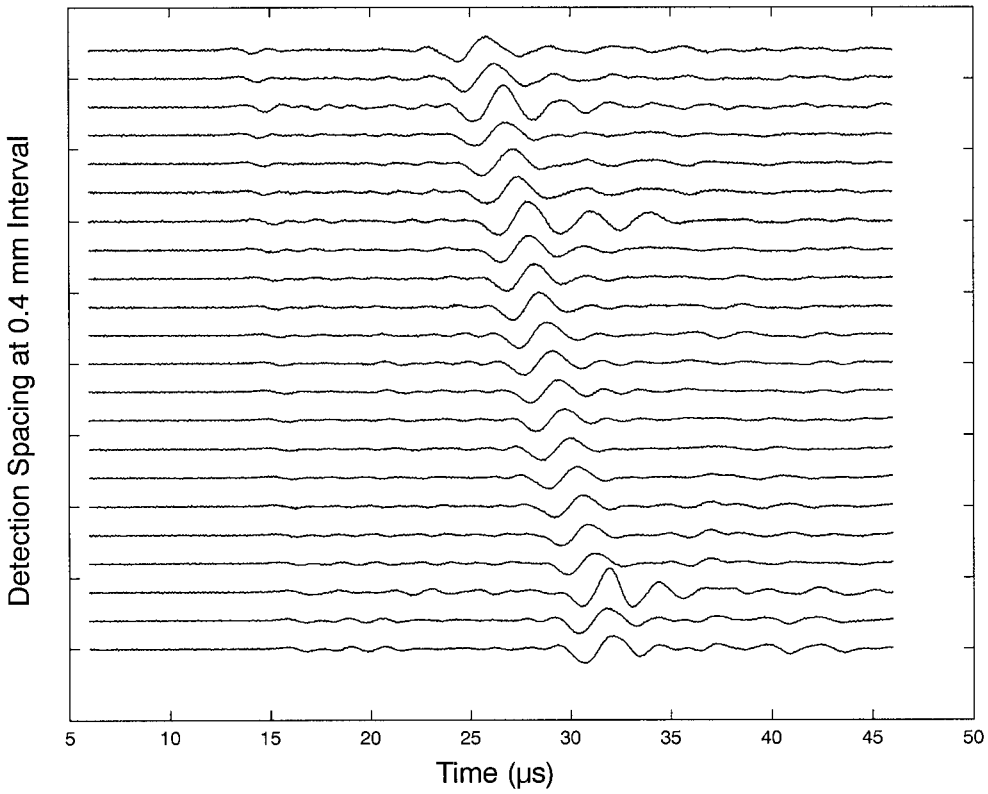

FIG. 3. Comparison of 22 Typical Waveforms with Propagation Distances Varying from 27.4 to 36.2 mm (with Δx = 0.4 mm)

peaks) coincides with the arrival of the Rayleigh surface wave. A comparison of these waveforms demonstrates the difficulty in accurately identifying the exact arrival time of the Rayleigh wave; this task is complicated by any shape changes due to dispersion. Although the overall trend is consistent (increases in arrival times and decreases in wave amplitudes due to attenuation/spreading), there are isolated discrepancies when determining the difference in arrival times between any two (arbitrary) waves. A clear benefit of the 2D-FFT is that it operates on all 71 of the transient waveforms to determine the ''average,'' frequency-dependent Rayleigh phase velocity of the line (largest source-to-receiver propagation distance) being interrogated.

Implementation of the 2D-FFT is fairly straightforward—perform a temporal Fourier transform (from time to frequency domain) followed by a spatial Fourier transform (from spatial to wave-number domain). The temporal FFT operates on the entire Rayleigh portion of these waveforms (a 10-μs window, or 1,000 points at this sampling rate, centered on the dominant Rayleigh peaks) padded to its original length, and then each of these 71 frequency domain signals (in their entirety) are used in the spatial FFT. The resulting frequency f versus wave-number k spectrum indicates that certain k-f combinations have significant amplitudes (peaks), and these combinations are solutions to the dispersion relationship of the Rayleigh wave (Alleyne and Cawley 1991). The resulting contour plot (plus local maxima in the vicinity of the peaks) is shown in Fig. 4; these points are the Rayleigh wave spectrum (dispersion curve). Because this dispersion curve is nearly a straight line, there is limited (material) dispersion present in Rayleigh waves propagating in the undamaged specimen.

The slope of this dispersion curve is used to calculate the Rayleigh group velocity (group velocity is $d\omega/dk$, where $\omega = 2\pi f$), and because it is nearly a straight line, the group velocity is equal to the Rayleigh phase velocity ($c = \omega/k$) at all frequencies. Note that the Rayleigh phase velocity is equal to a coupled combination of the elastic stiffness components and material density [see Littles et al. (1998a) for the exact relationship]. As a result, the slope of the dispersion curve (the Rayleigh phase velocity) in Fig. 4 is a direct measure of the current, coupled relationship of stiffness to density in the control volume being examined. The penetration depth of a Rayleigh wave is related to its wavelength; in an isotropic material, a Rayleigh wave causes significant motion in a layer equal to about 1 or 1.5 times its wavelength (Achenbach 1973). Dokun (1999) shows that this penetration depth (1.5 times wavelength) is a good approximation for Rayleigh wave penetration in this composite material system. Because the wave number is inversely proportional to wavelength (wavelength = $2\pi/k$), Fig. 4 shows the depth at which the Rayleigh wave penetrates into the material. For example, a Rayleigh wave with a frequency of 200 kHz (the lower frequency limit of the interferometer) has a wavelength of about 8 mm, and so these Rayleigh waves should penetrate most of the way through the thickness of the specimen. However, the center of the energy in the Rayleigh waves generated by the pulse laser is around 0.8 MHz (see the contour plot in Fig. 4) meaning the maximum usable penetration is on the order of 3–4 mm. As a result, the control ''volume'' interrogated is best represented by the largest source-to-receiver distance of the 2D-FFT (a 36.2-mm line) times the penetration depth (3–4 mm).

Note that the repeatability of the proposed procedure is demonstrated by measuring the dispersion curve for a specific control volume, removing the specimen (but not degrading it), and then repeating the experimental procedure to recalculate the Rayleigh wave's dispersion curve. As shown in Fig. 5, the second dispersion curve is very close to the first [i.e., their phase velocities differ by 1% (1,403 m/s versus 1,390 m/s) at 0.8 MHz] demonstrating that this procedure is robust enough to track small acoustic changes caused by material degradation. Note that the curves in Fig. 5 represent the best fit of a quadratic function.

MATERIAL DEGRADATION DUE TO ENVIRONMENTAL LOADING

To demonstrate the effectiveness of the proposed methodology, hot-moist conditions are used to environmentally age an FRP specimen, and the Rayleigh dispersion curve (Fig. 4) is used to track how the Rayleigh phase velocity (and thus

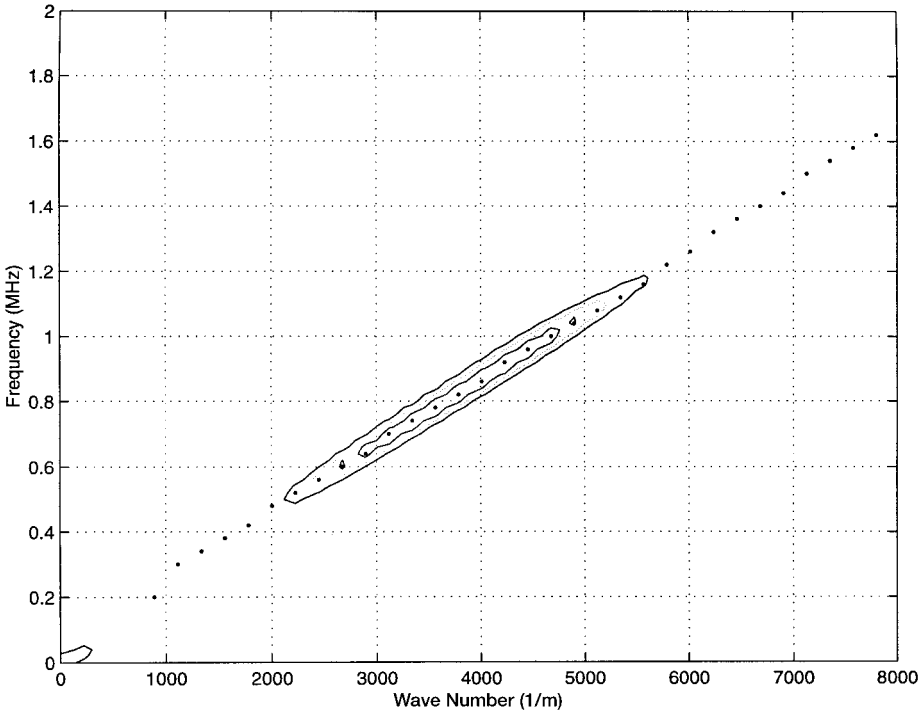

FIG. 4. Contour Plot of Frequency versus Wave-Number Spectrum plus Local Maxima

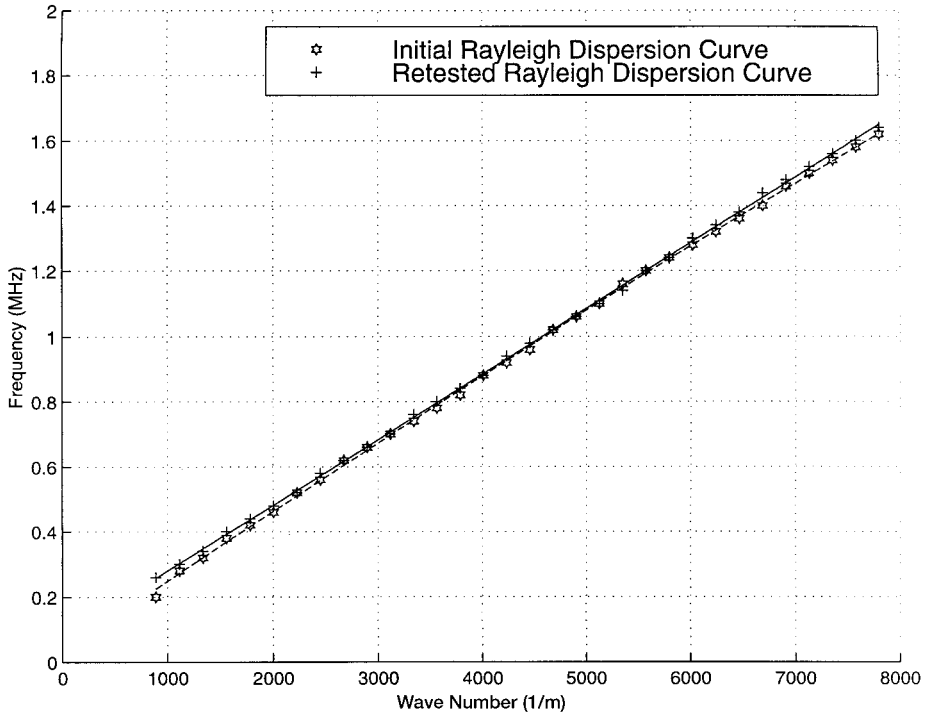

FIG. 5. Comparison of Rayleigh Dispersion Curves for Same Control Volume That Demonstrates Repeatability of Measurement Procedure

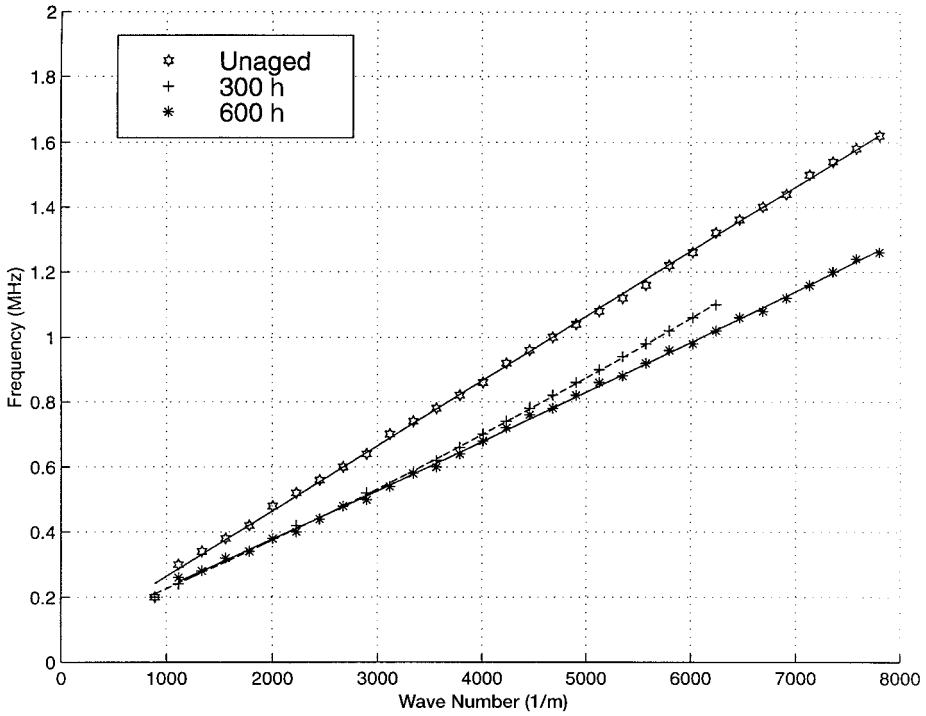

FIG. 6. Comparison of Rayleigh Dispersion Curves for Unaged, 300 h, and 600 h at 84°C Temperature

stiffness) changes with age. Previous research (Sridharan 1997) determined that significant material degradation occurs when these FRP components are aged in water at a temperature below the glass transition temperature (117°C for this material). For example, Sridharan (1997) showed that there is approximately a 10% decrease in longitudinal tensile modulus for a specimen aged for 600 h at 80°C. Note that this modulus value is measured destructively, and so multiple specimens are used to track changes in modulus as a function of age; this introduces problems associated with material variability (discussed previously). Sridharan (1997) showed that the drop in modulus is not due to changes in the matrix but is caused by a combination of the degradation of the glass fibers and failure of the fiber matrix interface.

Figure 6 shows the dispersion curves (local maxima plus best quadratic fit) for Rayleigh waves that propagate in exactly the same control volume at three states: unaged and aged in 84°C water for 300 and 600 h. The specimen is air dried (at 60°C for about 200 h) to remove all of the absorbed moisture (the ultrasonic measurements are not started until the specimen returns to its original dry weight). Fig. 6 shows that the Rayleigh phase velocity decreases with age, indicating a decrease

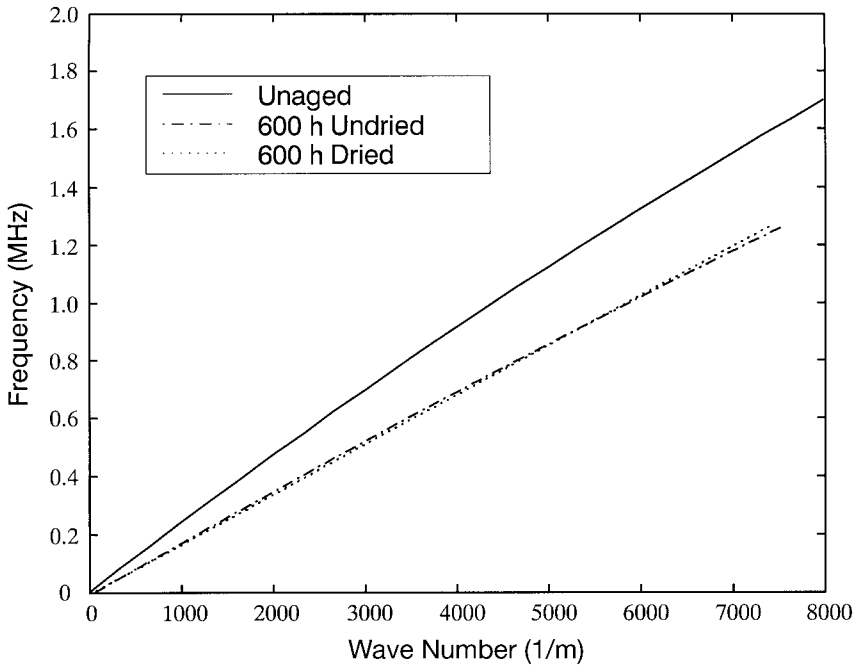

FIG. 7. Comparison of Rayleigh Dispersion Curves for Unaged, 600-h Undried, and 600-h Dried (Aging at 84°C)

in stiffness; this change is more severe in the first 300 h of aging compared to the second 300 h. For example, consider a frequency of 0.8 MHz. Here the Rayleigh phase velocity decreases 19.8% (from 1,368 to 1,097 m/s) in the first 300 h, and the same Rayleigh phase velocity decreases 23.5% (1,368 to 1,046 m/s) from unaged to 600 h.

The effect of moisture absorption and removal during the aging and drying process, which can potentially change the specimen's density, as well as cause additional damage, is determined by comparing the results from a dried and an undried specimen. This study is critical, since this acoustic metric (Rayleigh phase velocity) provides a coupled measure of stiffness and density. Fig. 7 shows the dispersion curves for Rayleigh waves that propagate in a new control volume at three states: (1) Unaged; (2) aged in 84°C water for 600 h, but not dried; and (3) aged in 84°C water for 600 h and then air dried at 60°C for 200 h. The dried and undried curves are nearly identical, indicating that there is no velocity change due to moisture absorption and drying damage. As a result, the decrease in Rayleigh phase velocity from the unaged to 600-h states, which is clearly evident in Figs. 6 and 7, is due to a decrease in material stiffness and not a change in density. Dokun (1999) shows that any swelling due to moisture absorption in the specimen from Fig. 7 causes volume changes that are <2%.

Of equal significance is that Fig. 6 shows that there is more material dispersion present in the Rayleigh waves that propagate in the aged states. For example, the dispersion curve for the 300- and 600-h states begins to curve upward at approximately 0.5 MHz, with the 300-h state showing more curvature. This frequency-dependent behavior, which cannot be ascertained when measuring Rayleigh phase velocity using arrival times only, provides a more quantitative measure of possible changes in the specimen's microstructure. A frequency measure can be translated to a length scale (wavelength = $2\pi/k$) that can be used to quantify a distribution of damage such as microcracks. In the case of hot-moist aging, the 3-mm wavelength (at 0.5 MHz) may correspond to a dominant void parameter (either size or distribution) present in the control volume.

CONCLUSIONS

This research demonstrates the effectiveness of combining laser ultrasonic techniques with the 2D-FFT to monitor changes in stiffness of an FRP specimen, as a function of degradation; it is possible to experimentally measure the dispersion curves of Rayleigh waves propagating in an FRP component and then to use this acoustic measure to track changes in material properties. These experimental measurements are only possible because of the high fidelity, (frequency) unbiased, broadband, point source/point receiver, and noncontact nature of laser ultrasonics.

The effectiveness of the proposed procedure is demonstrated by monitoring the same control volume of a specimen that is aged in hot-moist conditions and by observing that the Rayleigh phase velocity decreases with age, indicating a decrease in stiffness. In addition, more material dispersion is present in the Rayleigh waves that propagate in the aged states, indicating possible changes in the specimen's microstructure. As a result, the potential exists to use this procedure to develop a technique that tracks changes in exactly the same control volume of an in-service FRP component, thus providing a quantitative methodology for structural health monitoring.

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