STRESS DEPENDENCE OF ULTRASONIC VELOCITY IN UNIDIRECTIONAL GRAPHITE/EPOXY COMPOSITES FOR LONGITUDINAL WAVES PROPAGATING ALONG THE DIRECTION OF STRESS

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INTRODUCTION

One effect of nonlinear elasticity on elastic wave propagation is that the velocity of the elastic wave is a function of the applied stress on the material. This effect has been used to characterize the nonlinear elastic properties of numerous materials and is also important in attempts to nondestructively characterize residual and applied stress in materials. In addition, investigations have established a possible correlation between the nonlinear elastic properties and ultimate strength in conventional materials such as aluminum [1] and carbon steel [2].

Measurements of elastic nonlinearity have also been made in graphite/epoxy (gr/ep) composite materials. Prosser [3] was able to calculate seven of the nine third order elastic coefficients (TOEC's) for a unidirectional gr/ep composite from measurements of the dependence of ultrasonic velocity on uniaxial compressive and hydrostatic stress. In other work Prosser [4] measured the dependence of the ultrasonic velocity on tensile stress while Mase et al. [5] measured acoustoelastic effects in unidirectional gr/ep and in several angle-ply Kevlar/epoxy composite laminates.

However, in all of these previous measurements of stress dependence of velocity under uniaxial stress, the direction of propagation of the ultrasonic waves was perpendicular to the direction of applied stress. In the present research, the stress dependence of velocity was measured for waves propagating along the direction of uniaxial compressive stress in a uniaxial gr/ep composite. The measurements were made with the stress and propagation along the fiber direction (x_3) as well as perpendicular to the fibers along the lamina stacking direction (x_1). These measurements allow a check of the previously determined TOEC's and it was hoped that they would allow calculation of the remaining undetermined TOEC's. Additionally, it was possible to determine the ratio of nonlinear to linear elastic properties which was then compared with a similar calculation for numerous other materials by Cantrell and Chern [6].

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THEORY

Measurements of the velocity changes in this work were made with reference to the unstressed or natural state. That is, changes in the "natural" velocity (W) as defined by Thurston and Brugger [7] were measured. W is given by

$$W = \frac{L_0}{t} \tag{1}$$

where L_0 is the specimen length in the unstressed state and t is the time of flight of the ultrasonic wave. Since L_0 is a constant, the normalized change in "natural" velocity is given by

$$\frac{\Delta W}{W} = - \frac{\Delta t}{t} \ . \tag{2}$$

Measurements of the normalized change in "natural" velocity with respect to stress were made using a pulsed phase locked loop (P2L2) ultrasonic interferometer developed by Heyman [8]. This instrument maintains a constant phase ultrasonic wave by varying the frequency of the wave. Since the phase (θ) given by

$$\theta = 2\pi ft \ , \tag{3}$$

where f is the frequency, is constant, it can be shown that

$$\frac{\Delta f}{f} = - \frac{\Delta t}{t} = \frac{\Delta W}{W} \ . \tag{4}$$

Thus, the normalized change in "natural" velocity is obtained by monitoring the normalized change of frequency of the ultrasonic wave as a function of stress.

However, in this research there was an additional complication. Since the direction of propagation was along the direction of compressive stress, a delay line had to be used to allow propagation into the specimen without loading the transducer. Therefore, it was necessary to correct the measured change in velocity through the delay line and specimen to obtain only the change in velocity through the specimen. Assuming effects of variations of the bond between the specimen and delay line to be negligible, an equation to make this correction was derived and is given by

$$\frac{\Delta f_s/f_s}{\Delta p} = \frac{1}{t_s}\left[(t_s + t_{dl})\frac{\Delta f/f}{\Delta p} - t_{dl}\frac{\Delta f_{dl}/f_{dl}}{\Delta p}\right] \tag{5}$$

where p is the applied load, t_i is the round trip time of flight in an unstressed condition. The subscript s refers to the specimen only, dl refers to the delay line only, and no subscript refers to propagation through the specimen and delay line. Therefore, from previous measurements of the time of flight in the specimen and in the delay line, and measurements of the normalized change in "natural" velocity for waves propagating through the delay line only and through the delay line and specimen, it is possible to determine the normalized change in "natural" velocity for the specimen alone. Since the delay line and the specimen were not of the same cross sectional area, the measurements were made as a function of the applied load and the resulting corrected quantity was normalized by the cross sectional area of the specimen to yield the normalized change in velocity as a function of stress.

EXPERIMENT

A specimen in the shape of a cube with nominal dimensions of 0.8 in. on a side of T300/5208 unidirectional gr/ep composite was used for these measurements. The original laminate from which this specimen was cut had been previously ultrasonically C-scanned for defects and none were found to be present. Fig. 1 shows the experimental apparatus used. The delay line was an aluminum cylinder three in. in diameter and 2.5 in. in length from the transducer to the specimen. A computer monitored the frequency of the P2L2 and the voltage output of a load cell to determine the load on the specimen.

As discussed in the previous section, it was necessary to measure several parameters to make the corrections for the delay line and determine the change in velocity of the specimen. First, the frequency shift for waves reflecting off of the specimen-delay line interface was measured as a function of load to determine the frequency shift for the delay line only. Then the load ramp was repeated as the frequency shift was measured for a wave propagating through the delay line and the specimen. These were used together with the previously measured round trip time of flight to make the necessary corrections. A commercial damped 2.25 MHz ultrasonic transducer was used in these measurements and the nominal frequency used was 2.25 MHz.

Originally, ultrasonic couplant was applied between the transducer and the delay line and between the delay line and the specimen. It was not applied between the specimen and the lower compression load fixture. However, as load was applied, the specimen began to couple ultrasonic energy into the lower fixture. This led to severe phase and amplitude deviations in the reflected wave which was being monitored. Above a certain load when coupling reached its maximum, the phase and amplitude of the reflected wave became constant allowing the measurement to be made. It was discovered that by using couplant between the rear surface of the specimen and the compression fixture that this effect could be reduced. Although there was still anomalous behavior at lower loads, the

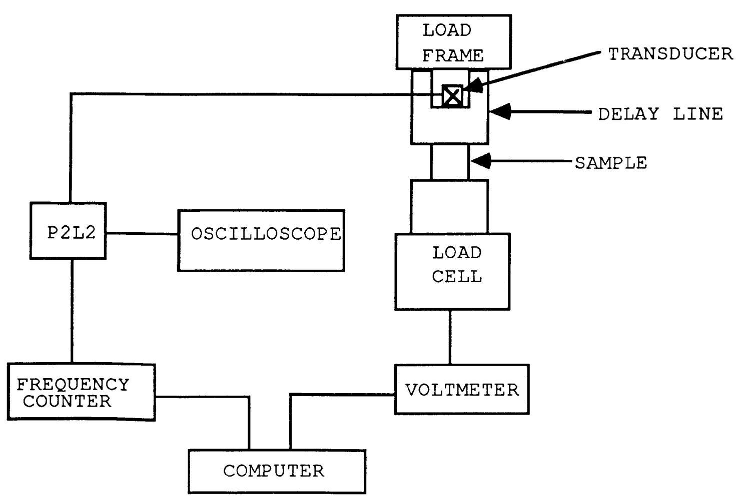

Fig. 1 Block diagram of experimental apparatus to measure "natural" velocity shifts as a function of load along the direction of load.

load at which the effect became negligible was much lower. Fig. 2 shows the normalized change in frequency for the delay line for propagation through the specimen along the fibers (x_3) and perpendicular to the fibers (x_1). Two separate measurements for each case are shown with the transducer and specimen having been rebonded between each measurement. These curves demonstrate the anomalous behavior at lower loads followed by linear behavior at higher loads where the slopes are approximately equal for both cases as expected. The difference in behavior at lower loads is due to the large difference in acoustic impedance in these two directions of propagation which have a great effect on the reflection and transmission coefficients.

The next measurement was of the frequency shift for the wave propagation through the specimen perpendicular to the fibers and the delay line. Results of this are shown in Fig. 3. Three separate measurements are combined on this plot with the transducer, specimen, and delay line having been rebonded between each measurement. As can be seen from the small scatter in the data, the effects of rebonding are small. The data was fit to a linear curve and the slope was determined to be 1.717×10^{-6} lb.$^{-1}$. A fit of the linear portion of the delay line response for this direction of propagation yielded a slope of 1.454×10^{-7} lb.$^{-1}$. The time of flight of the specimen in this direction was 13.341 µs. while it was 19.94 µs. in the delay line. These factors along with the cross sectional area of the specimen were all used to determine the stress dependence of the normalized "natural" velocity which is also known as the stress acoustic constant (SAC) [1]. The value was calculated to be 3.77×10^{-10} Pa^{-1}. This compares favorably with the value of $4.5 \pm 0.8 \times 10^{-10}$ Pa^{-1} which was calculated from the previously determined TOEC's [3].

Another parameter of interest which can be calculated from this measurement is the ratio of nonlinear to linear elastic properties. This

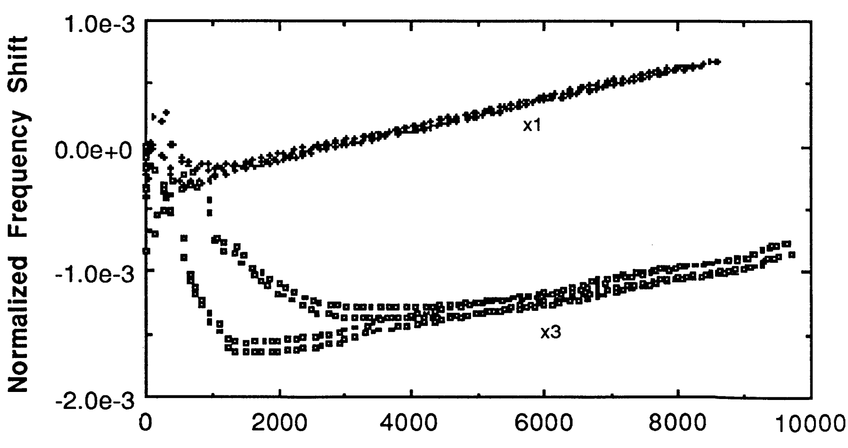

Fig. 2 Normalized frequency shift versus load for propagation through the delay line only with the sample oriented for propagation along the fibers (x_3) and perpendicular to the fibers (x_1).

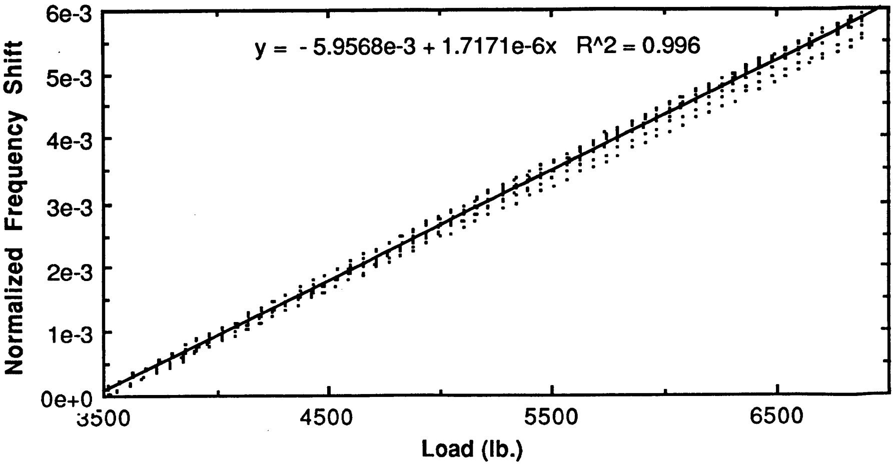

Fig. 3 Normalized frequency shift versus load for wave propagating through delay line and specimen perpendicular to fibers (x_1).

quantity was examined by Cantrell and Chern [6] where they defined R as

$$R = \frac{H}{d\epsilon/d\sigma} \quad (6)$$

where H is the stress acoustic constant under tensile loading, and σ and ε are the stress and strain respectively. They determined values of R for numerous materials including several types of steel, aluminum, copper, molybdenum, tungsten, bronze, and fused silica. Except for fused silica, this parameter was relatively insensitive to type of material and had values that ranged from -2.7 to -3.9 even though the elastic coefficients of these materials vary in range more than 700%. Using the measured value of the SAC for gr/ep and multiplying by negative one to account for the difference in compressive versus tensile loading and dividing by the appropriate previously measured elastic compliance, the value of R perpendicular to the fibers was determined to be -4.1. Interestingly, this value is near the range of values of the other materials even though again the difference in linear elastic properties for gr/ep perpendicular to the fibers to materials such as steel is quite large.

Measurements were also made with propagation and stress direction along the fiber direction. The SAC along this direction together with previous measurements would have enabled calculation of the remaining two TOEC's. The data for several measurements, again after rebonding transducer and specimen between each measurement, are shown in Fig. 4. Very unusual behavior is demonstrated in these curves. The curves are very nonlinear and actually reverse direction at higher loads. The magnitude of the changes are much smaller than in measurements in the perpendicular direction and there is much more scatter in the data. Thus, it seems that this measurement is much more sensitive to variations in the bond. From this experiment, it is impossible to determine whether the change in slope of the stress-velocity curves, which seems reproducible, is due to actual material response or is due to variations in bonding conditions as load is applied.

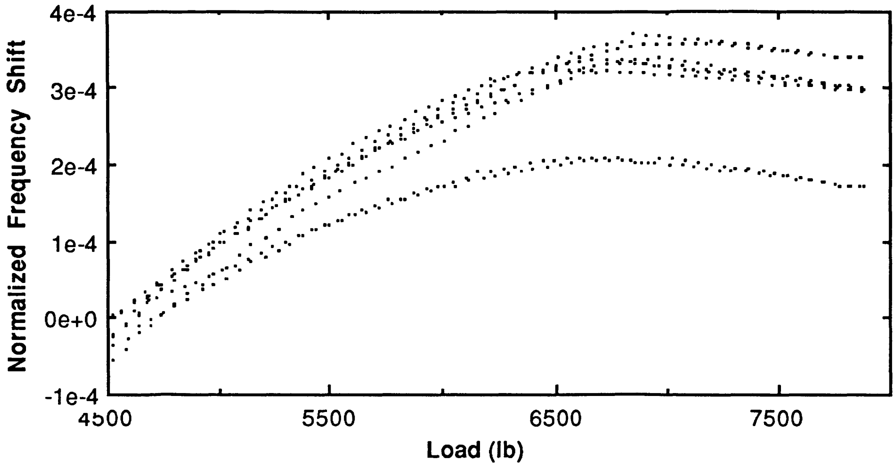

Fig. 4 Normalized frequency shift versus load for wave propagating through delay line and specimen along fibers (x_3).

Because of the large scatter in data and the unusual behavior of the measured curves, the data cannot be interpreted in the usual manner. That is, a SAC value cannot be determined as the slope of this curve is highly dependent on load for unknown reasons. Also, without the SAC, the value of R for propagation along the fibers cannot be calculated and the two remaining TOEC's cannot be determined.

SUMMARY

The first measurements of the stress induced velocity changes for propagation directions along the direction of applied stress in gr/ep composites have been presented. For propagation and stress direction perpendicular to the fiber direction, the data demonstrated a linear relation between normalized velocity shift and stress. After corrections for the delay line were made, the slope or SAC was determined and compared favorably with the expected value calculated from the previously determined nonlinear coefficients of this material. The ratio of the SAC to the elastic compliance for this direction of loading was evaluated and found to have a value similar to numerous other materials which have very different linear elastic properties.

Measurements with stress and propagation along the fibers yielded unusual behavior. The curves were very nonlinear and even shifted direction at higher loads. The large scatter in the data due to bond variations made separation of material effects from bond induced artifacts impossible. Thus the SAC, R, and the remaining two unknown TOEC's could not be determined for this direction of propagation.

These measurements further expand the basis of determining nonlinear elastic properties of composite materials. These properties may be useful in developing much needed NDE techniques to determine such important parameters as residual stress after cure and residual strength after impact damage. Additional study is needed to measure the nonlinear behavior in other composite materials including angle ply laminates.

Also, other techniques to measure elastic nonlinearity such as harmonic generation should be applied to composites to improve the understanding of these properties and their importance.

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