A COMPARISON OF ACOUSTIC WAVE PROPAGATION THROUGH FRPS WITH VARYING RESIN SATURATION

I. McBrayer[1*], B. Stanford[2], D. Nagle[3]

[1] Delta Engineering Corp., New Castle, DE, U.S.A, [2] Delta Engineering Corp., New Castle, DE, U.S.A, [3] Delta Engineering Corp., New Castle, DE, U.S.A,
* Corresponding author (bstanford@delta-engineering.com)

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ABSTRACT

This research investigates the effect of resin saturation levels on the propagation of acousto-ultrasonic waves through fiber reinforced composite structures. Resulting potential impacts for materials characterization and NDE techniques are discussed.

Propagation studies were conducted on large Carbon Fiber reinforced epoxy resin panels, manufactured using a wet lay-up technique. Three categories of test specimens were included in the study, to include low, normal and high resin saturations. Results were assessed for wave velocity variations and further interrogated in the time-frequency domain. Data was collected for wave propagation along the 0°, 45° and 90° orientations. Variations of acoustic wave properties with resin saturation were observed in the results for both fiber-axis and off-fiber-axis wave propagation. A decrease in wave velocity was present along the 45° axis for both resin starved and resin rich panels.

1 INTRODUCTION AND MOTIVATION

Ultrasonic and Acoustic wave propagation are widely used in industry for the evaluation of Fiber Reinforced Polymer (FRP) structures. The use of ultrasonic evaluation is particularly prevalent in the location and identification of structural flaws.

Acoustic emission techniques are often employed for ascertaining source location of a structural flaw and require knowledge of wave velocity within the structure [1][2]. Thus, test methods to allow calculation of wave velocity through different media are often employed as a precursor for Non-Destructive Evaluations (NDE).

Techniques are well established for calculating wave velocity from tests conducted on unknown structure [3]. However, these velocities are highly dependent on the elastic properties of the laminate and results may be affected by directional variations caused by stacking sequence or fabric type, for example. The velocity of an elastic wave through a solid material is influenced by a solid material's resistance to the pressure that these waves induce and is thus dependent on the elastic constants and the density. The different mechanical properties between resins and reinforcing fibers mean that changing ratios of resin to fiber will affect the overall composite properties. Consequently, the wave velocity value will vary between composites with different Fiber Volume Fractions (FVFs).

Standard practice for determining acoustic wave velocity through a new media is to arrange two acoustic sensors at a known distance apart and then perform a pencil lead break (PLB) at a known distance behind one of the sensors.

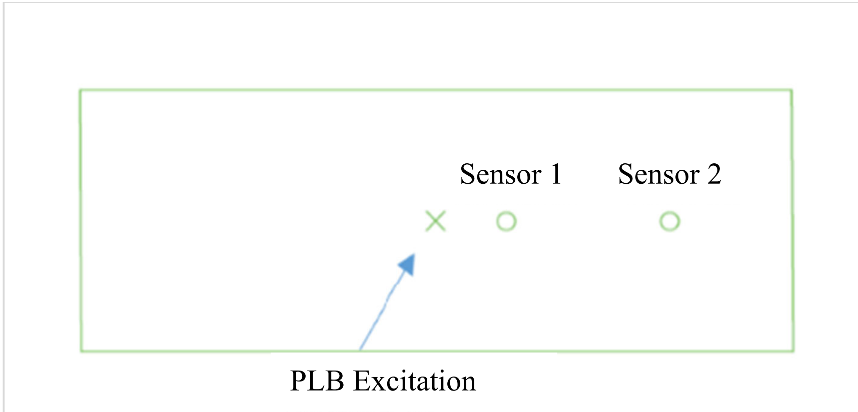

Figure 1: Sensor arrangement for wavespeed determination.

The velocity of the resulting wave may then be calculated from Eqn. 1.

$$V_W=\left(\frac{T_A-T_B}{D}\right). \tag{1}$$

V_W = Wave Velocity

T_A, T_B = Arrival Time Sensor A, Sensor B

D = Distance between sensors

In a thin plate, acoustic waves will interact with the boundaries in such a way that they will reflect and split into both longitudinal and shear waves and form wave packets known as lamb waves. The two primary lamb wave modes are symmetric and anti-symmetric. This describes the motion of the particles on the lower surface, relative to those on the upper surface of the plate, as the wave propagates along the length of the structure. Anti-symmetric lamb wave modes are characterised by low frequencies and high amplitudes, whereas the Symmetric modes are characterized by low amplitudes and high frequencies. The behaviour of these lamb wave modes is highly dispersive and has been found to be influenced by the microstructural details of the medium through which they are travelling.

This research was conducted to assess the variations in wave velocity with resin saturation for fiber-axis and off-fiber-axis wave propagation.

2 EXPERIMENTAL

2.1 Test Specimens

The materials used in this experimental investigation were a standard modulus Carbon Fiber woven fabric and a low viscosity epoxy resin system. Laminates were manufactured using the wet lay-up technique to produce a 0° stacking sequence configuration. Panels were sized to avoid edge reflection effects on acoustic data through previously conducted in-house testing. Manufacturing techniques and materials were altered to ensure variations in resin saturation. Destructive testing by resin digestion was then conducted to confirm FVFs, per ASTM D3171[1]. The specimen details are outlined in Table 1.

Panel Number	P-Film	Saturation
1	None	Low
2	Perforated	Standard
3	Solid	High

Table 1: Panel Descriptions.

2.2 Hsu-Nielsen Acousto-Ultrasonic Testing

A series of 30 pencil lead breaks were conducted at angles of 0°, 45° and 90° with respect to the laminate 0° on all three panels. Data was collected using Mistras Data Acquisition system and software. The wave velocities were then calculated from the resulting arrival times at each sensor.

3 RESULTS AND DISCUSSION

3.1 Wave Velocities

Calculated wave velocities, listed in Table 2, show that, in the 0° and 90° propagation directions, decreasing resin saturation caused an increase in wave velocity. Deviations from standard saturation, however, caused a decrease in wave velocity in the 45° propagation direction.

Panel Number	Wavespeed (m/s)		
	0°	45°	90°
1	6393	1440	6667
2	5852	4246	5827
3	5797	1189	5870

Table 2: Wave Velocities.

Wave propagation in all three panels was observed to be slower along the 45° when compared with the propagation along the fiber axes. With reference to the weave and stacking sequence of the panels (Fig.1), the 45° wave propagation would result in the acoustic waves travelling at 45° to the fibers, instead of along the fibers. As the elastic wave travels along the 45° angle, it encounters gaps between tows, more so than along the 90° and 0° angles. This would cause the waves to pass between fiber and resin more frequently. Sound travels through both resin and air at a slower rate than through Carbon Fiber, thus retarding the overall wave propagation.

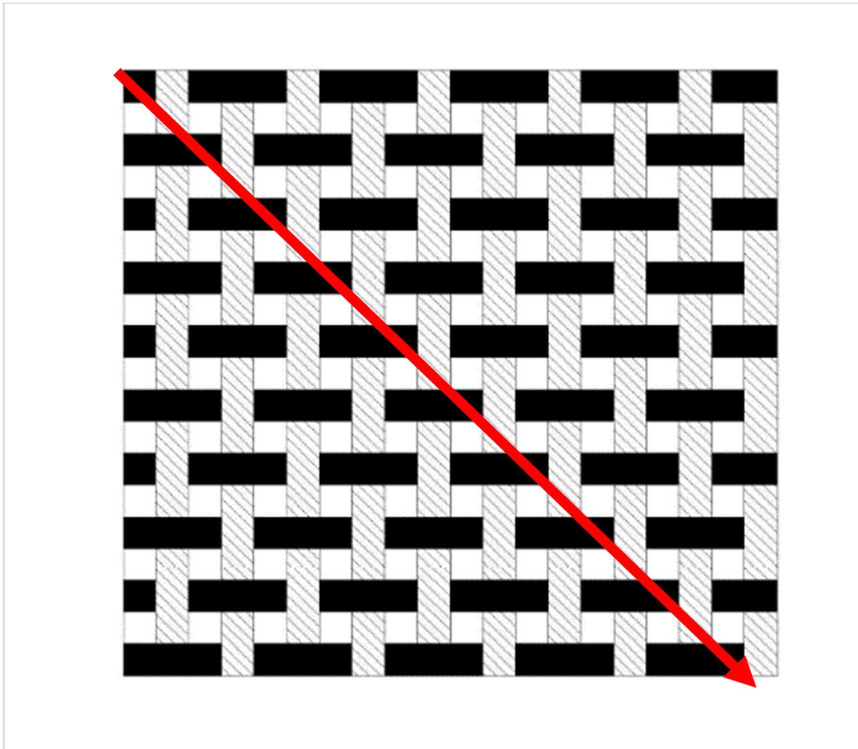

Figure 2: 45° wave propagation in a plain weave laminate.

The ratio of 45° wave velocity with respect to the 0° and 90° propagation directions was greater than 1:4 for both non-standard saturations.

With reference to Fig.2 and Fig.3, when the laminate is resin rich, the elastic wave propagation through the laminate must travel through a greater amount of resin before returning to the fibers, further slowing the wave. Resin starvation, on the other hand, will often result in microscopic pockets of air or vacuum (voids) throughout the laminate. This results in the elastic wave being forced to propagate between resin to air interfaces as well as through carbon fiber to resin interfaces. Since the speed of sound is slower through air than resin, this again causes a significant retardation of the wave.

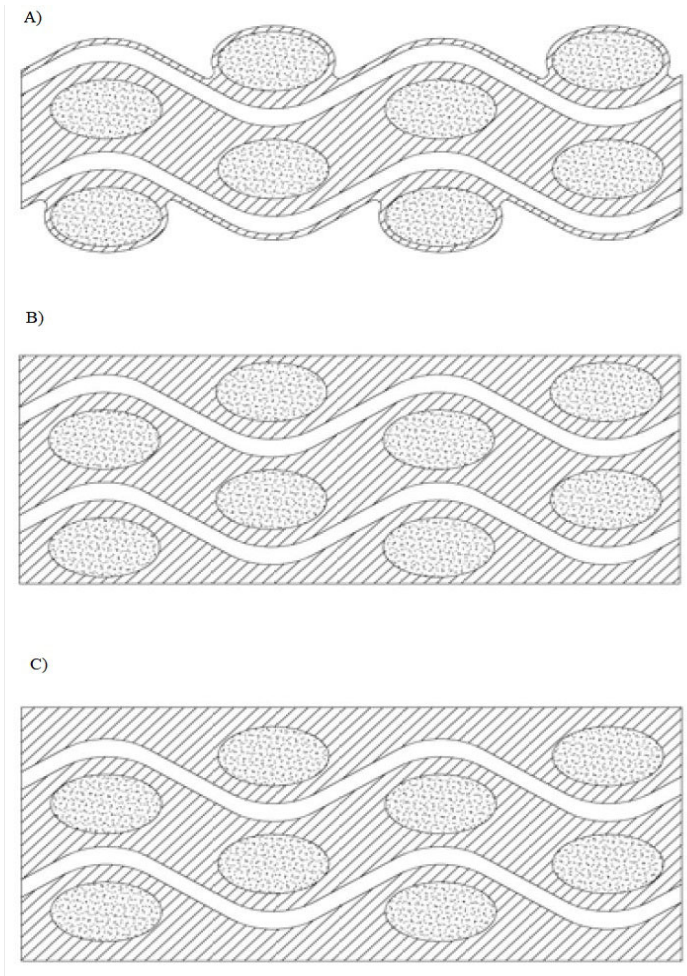

Figure 3: Cross-Sections of A) Resin Starved, B) Normal Saturation and C) Resin Rich Laminates.

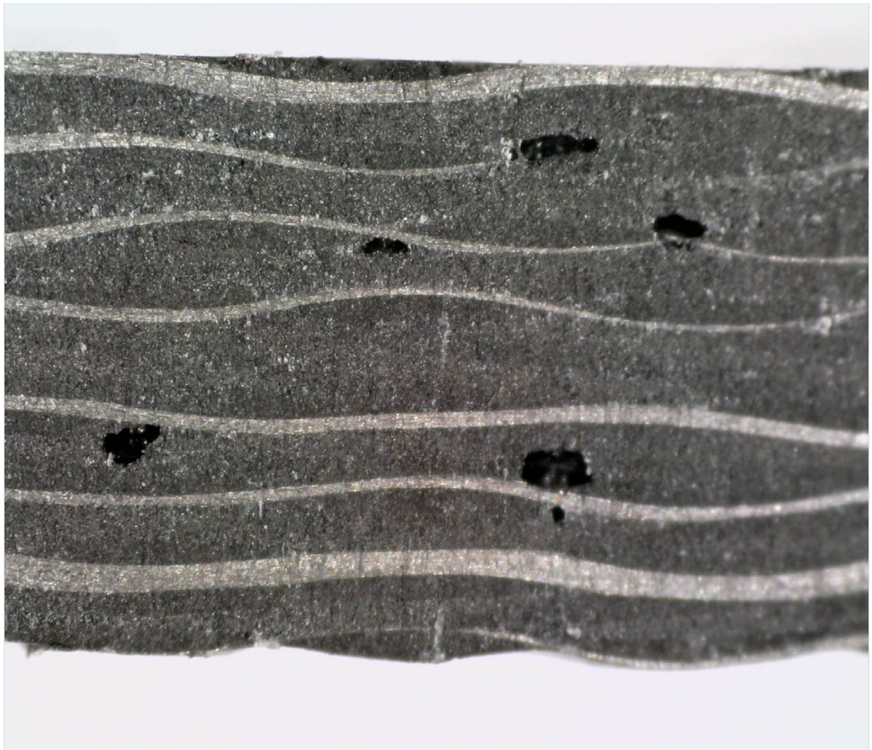

Figure 4: Microscope image of void defects within laminate.

2.2 Coefficient Ratios

Wavelet scalograms of the waveforms shown in Fig.4 highlight the effects of resin saturation on the transmission of the primary antisymmetric (A0) and symmetric (S0) modes. An inverse correlation of the ratio of maximum A0 mode to S0 mode wavelet coefficients to saturation level is present.

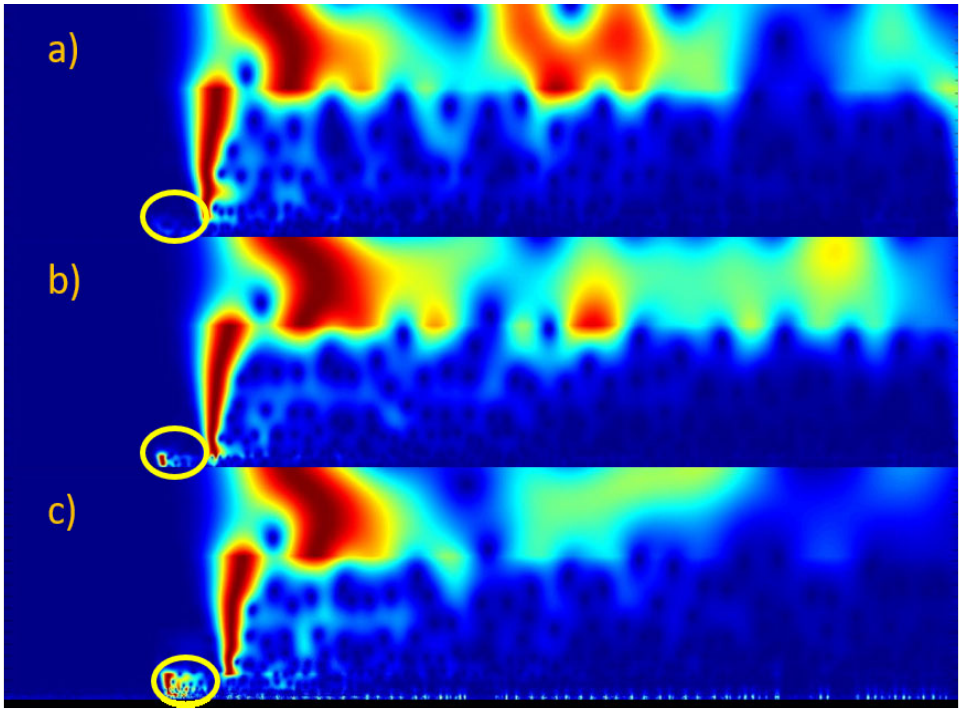

Figure 5: Scalograms for A) Resin Starved, B) Normal Saturation and C) Resin Rich Laminates.

It is apparent that an increase in resin with respect to the fiber content allows higher energy from the S0 mode high frequencies to be transmitted across a distance (Table 3). This can be attributed to parameter variations that were identified in both the previous discussion on wavespeeds for varying resin saturations and discussion on undulations present at each tow intersection. It is presumed that at every undulation a degree of scattering occurs due to reflections and refractions, it has been well researched that the presence of defects in a structure can result in mode conversion, scattering and reflection (energy loss mechanisms)[4][5]. In a similar manner, undulations may be seen as discontinuities, causing the same phenomena. Although the overall velocity changes as a wave crosses interfaces between two media, a resin rich laminate will likely contain fewer discontinuities within the resin itself as opposed to a laminate of typical saturation levels. A resin starved laminate, on the other hand, is likely to have a greater number of discontinuities. These discontinuities, in addition to the discontinuities caused by undulations, will cause high frequencies to reflect and scatter. Such discontinuities would exist in the form of voids within the laminate structure and would thus decrease the energy transferred by high frequency modes.

Panel Number	S0/A0 Coefficient Ratio								
	0°S0	45°S0	90°S0	0°A0	45°A0	90°A0	0°	45°	90°
1	0.07	0.009	0.069	34.2	15.4	34.2	414.6	1720.5	499.6
2	0.222	0.033	0.305	38.6	14.8	34.6	147.1	444.7	114.4
3	0.305	0.043	0.35	26.5	12.5	30.7	87	294.1	79.5

Table 3: Wavelet Coefficients.

4 CONCLUSIONS

Resin saturation tends to significantly affect wavespeeds along off-fiber axes, as the waves are encountering an increased number of discontinuities and media changes.

Since calculation of wavespeeds is a key step in the locating of internal flaws, this has the potential to cause inaccuracies in the results of these methods.

For certain applications it may be useful to be able to evaluate the resin content of a structure non-destructively. A combined wavespeed analysis along with further interrogation of wavelet coefficients for the waveform has been shown to be capable of providing further insight into the resin saturation of a structure.

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