A NOVEL NON-DESTRUCTIVE METHODOLOGY FOR DETERMINING COMPOSITE LAMINATE STACKING SEQUENCE

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Keywords: Lamb Waves, Composites, Non-Destructive Characterization

ABSTRACT

The increased use of composites in industry and the expense in time and materials for the manufacture of composite components demands the development of Non-Destructive Testing (NDT) techniques for adequately assessing manufacturing quality and strength of completed parts. While many non-destructive techniques, commonly used for components manufactured from isotropic materials, are not capable of detecting defects and assessing strength of Orthotropic materials, acoustic/acousto-ultrasonic techniques have shown to be effective at providing information on CFRP laminates.

In this research, propagation studies are conducted to assess the stacking sequence effects on acoustic wave propagation through a fiber reinforced composite structure. Propagation velocities and the high frequency components of the recorded signals show directionally dependant variability with lay-up type.

1 INTRODUCTION AND MOTIVATION

Assessment of composite structures in industry is inherently more complex than for isotropic structures, due to the wide variabilities in their manufacture. Differences in weave, stacking sequence, fiber type and resin type are all significant factors which may affect the overall strength of a laminate. Often, this information may not be available for given structures to designers attempting to modify a composite structure. These individuals are required to be very conservative in their estimates of strength and elastic properties and validation of any calculations is difficult without some form of excess material procurement and destructive testing.

This research is conducted to assess a novel Non-Destructive Testing (NDT) methodology for identifying the stacking sequence of composite panels with unknown properties.

To determine the stacking sequence of a completed laminate, standard practice in industry after a composite structure is laid up is to cut off a small bit of waste section to observe under microscope for confirmation of ply orientation.

NDT for fiber orientation characterization has been investigated for various techniques, to include X-Ray radiography, optical diffraction of micrographs, microscopy techniques and pitch-catch ultrasonic scanning[1], [2].

An attractive quality of composite laminates is the ability to tailor the directional dependence of the stiffness and strength of a composite laminate, for a specific industry application, by variations in stacking sequence. The resulting directional stiffness variations are a key factor in the proposed methodology, which considers the effects of stiffness on lamb wave propagation studies. Lamb Waves, being a complex type of elastic “plate” wave that is guided by the boundaries of the solid, plate media, consist of different wave modes which result from a longitudinal or shear wave hitting and reflecting off a surface and splitting into both longitudinal and shear waves. The repetition of this process every time a longitudinal wave or shear wave hits a surface and the interference of the increasing number of waves with each other causes types of resonant waves to occur (Fig.1).

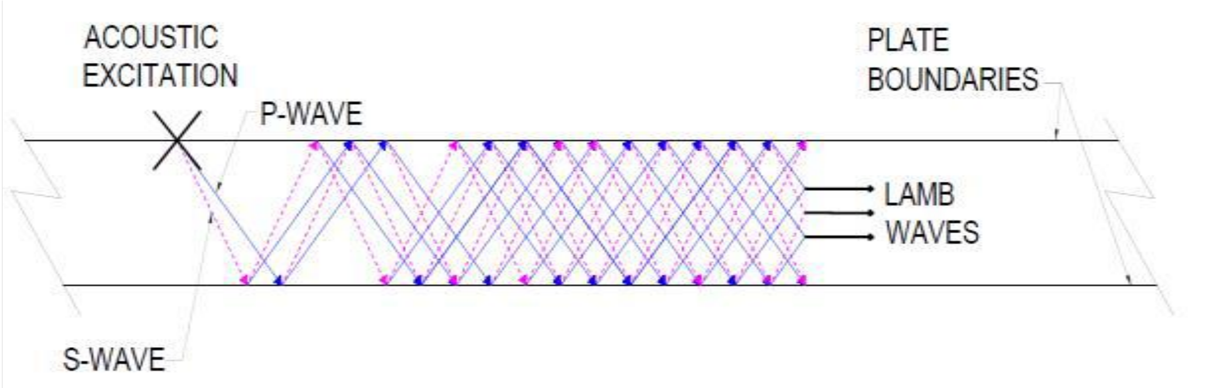

Figure 1: Lamb Wave Development.

The velocities of these waves are influenced by the velocity of propagation of the initial longitudinal (V_L) and shear waves (V_S), as described in terms of the material elastic properties by equations 1 and 2.

$$V_L = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}}. \quad (1)$$

$$V_S = \sqrt{\frac{E}{2\rho(1+\mu)}}\ . \quad (2)$$

Where E, μ, and ρ are the stiffness modulus, Poisson's ratio and density, respectively.

The two most common types of resonant wave modes are **Symmetric** (S or extensional) and **Antisymmetric** (A or flexural) waves. The particle motion for these wave types and resulting mode shapes for these wave modes are presented in Fig.2. The mode names describe the motion relative to the mid-plane of the plate.

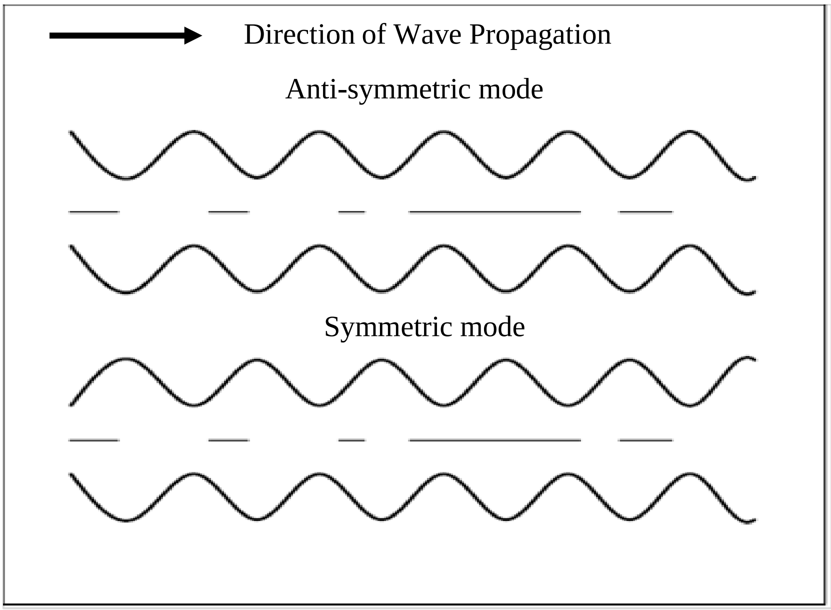

Figure 2: The two primary Lamb Wave Modes.

Experimentally, this dependence of Lamb wave mode propagation velocities on stacking sequence of a laminate has been shown by Ramadas [3], who found out of plane transmission factor to be dependent on stacking sequence and thickness ratio, In-plane variation being more prevalent in cross-ply laminates. Ramadas explained this by the dependance of the first symmetric mode (S0) on in-plane stiffness. An increase in the number of zero-degree plies results in a higher in-plane stiffness, consequently increasing phase velocity.

Similarly, Shevtstov et al [4], through experimental investigation of guided lamb waves in thin Carbon Fiber Reinforced Polymer (CFRP) panels of varying lay-ups, found the first antisymmetric mode (A0) wave propagation to primarily occur in the direction of greatest structural stiffness and minimal attenuation.

The current research is focused on the study of the effects of variations in stacking sequence on the propagation of lamb waves through CFRP laminates.

2 RESEARCH DESCRIPTION

2.1 Test Specimens

Experimental investigation was conducted on CFRP panels, in four configurations, as outlined in Table 1. Laminates were manufactured using the wet lay-up technique. The materials used for manufacture were a standard modulus Carbon Fiber woven fabric and a low viscosity epoxy resin system.

The standard size for the test panels was evaluated experimentally with consideration to the effect of edge reflections. Panels were sized to mitigate signal interference by edge reflections, while ensuring the presence of lamb wave modes.

Panel Number	Stacking Sequence
1	$[0°]_{16}$
2	$[0°/ 45°]_{8}$
3	$[0°/ 45°/ 90°/ -45°]_{4}$
4	$[0°/ 45°/ 90°/ -45°]_{2S}$

Table 1: Test Specimen Lay-up descriptions.

2.2 Test Set-Up and Apparatus

Investigation of variations in acoustic wave propagation characteristics resulting from differences in stacking sequence has been conducted by the simulation of an acoustic emission event. Simulating an event may be done by way of Pencil Lead Break (PLB) Methodology. This technique is well established for the calibration of Acoustic Emission sensors, due to its capability of producing a repeatable signal [5][6]. To ensure repeatability, care must be taken to perform the PLB at the same distance from the sensor, while keeping consistency in break angle each time. A small Teflon collar called a Hsu-Nielsen shoe is installed onto the mechanical pencil to control the angle of lead break each time.

Thirty PLBs were performed adjacent to two acoustic emission sensors. The wave velocities were then calculated from the resulting arrival times at each sensor. This was repeated for angles of 0°, 45° and 90° on each panel type, with respect to the layup. The 0° angle being with reference to the warp direction of the top ply weave while the 90° angle refers to the weft/fill direction. Data was collected using Mistras Data Acquisition system and software.

3 RESULTS AND DISCUSSION

3.1 Wavespeed

The calculated wavespeeds for the panels show a decrease in wavespeed along the 0°/90° for the panels with plies oriented at 45° (Fig. 3). Conversely, the wavespeeds increase for those same panels along the 45° axis.

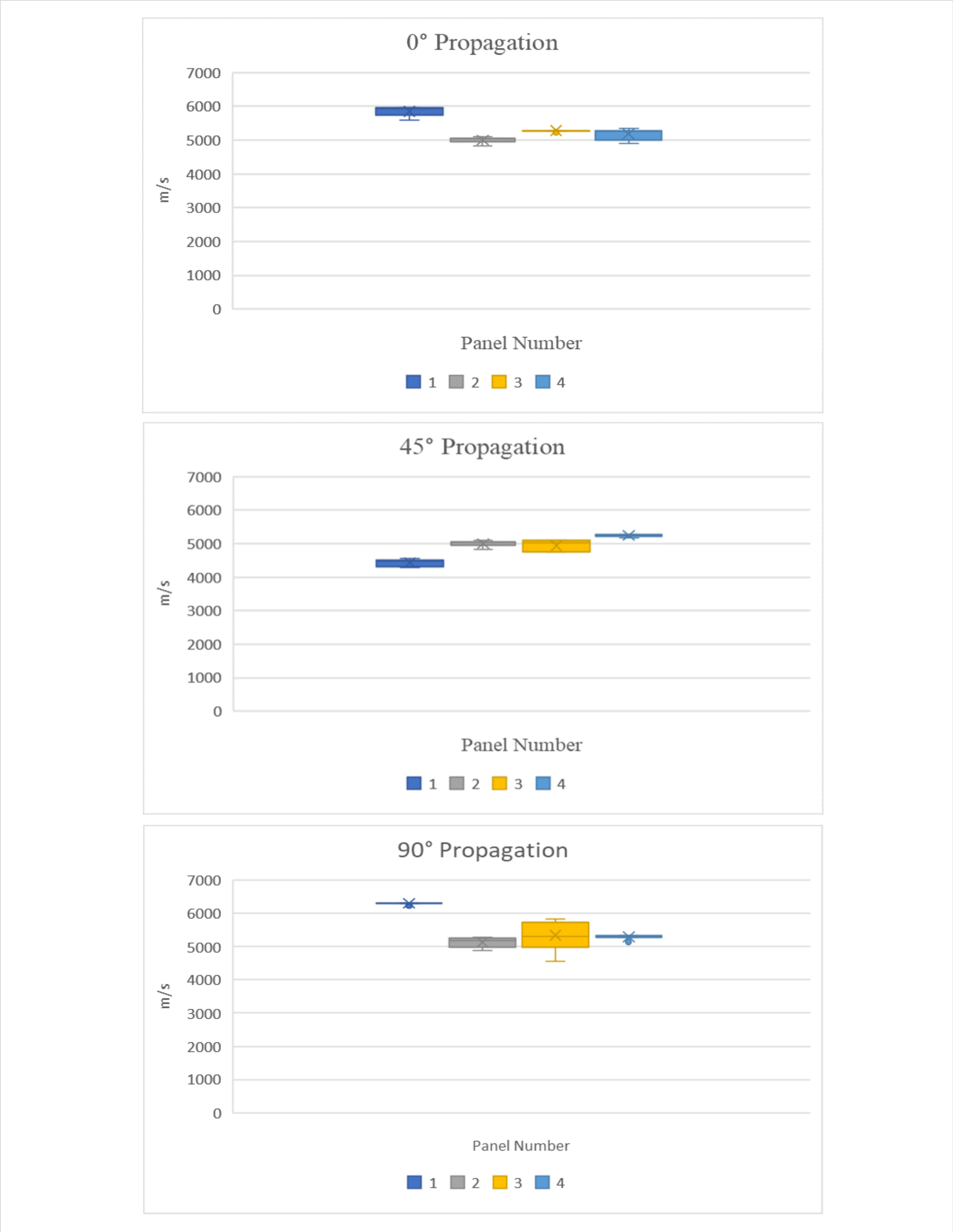

Figure 3: Wavespeeds for 0°, 45° and 90° Propagation

As sound velocity through carbon fiber is faster than through cured resin, slower wavespeeds suggest waves are travelling through a greater amount of resin. The ratio of velocities between the laminate 45° and 0°/90° in Panel 1, therefore, suggests a high tendency of fibers to lie in the 0°/90° directions. The 0°/45° wavespeed ratio for the other panels, however, were closer to unity (Table 3), suggesting an almost equivalent presence of fibers oriented at a 45° angle with respect to ply orientation.

Panel Number	0°/45° Ratio
1	1.38
2	1.00
3	1.04
4	1.01

Table 2: Wavespeed 0°/45° Ratio.

3.2 Time-Frequency Analysis

Wavelet scalograms, taken from the waveforms collected at the farther sensor, highlight a tendency for panel stacking sequence to influence the relationship between the A0 mode and S0 mode energies (Fig. 4). The disparity between the S0 mode and A0 mode coefficient values appears to be significantly lower for panels with 45° plies. Ratios of the maximum values of the coefficient moduli for the two fundamental Lamb wave modes are calculated below (Table 3). It is apparent that laminate symmetry is of significance, as the ratios for panels 3 and 4 show large discrepancies, despite having an equal number of plies oriented in the same direction.

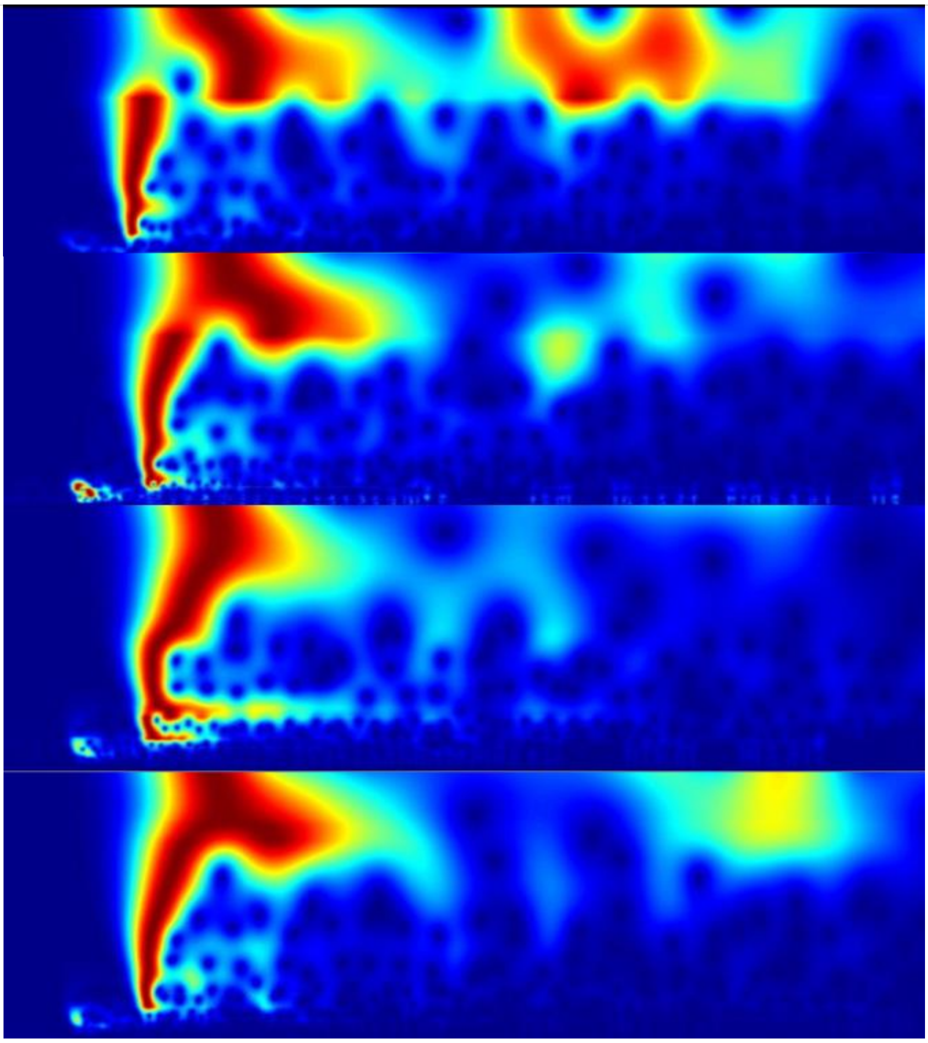

Figure 4: Wavelet Scalograms for 0° Propagation

Panel Number	Coefficient Ratios		
	0°	45°	90°
1	150	440	110
2	270	230	300
3	490	500	240
4	220	210	250

Table 3: Test Specimen Coefficient Ratios

3.3 Stiffness Relationship

Theoretical values for flexural stiffness were extracted from Femap models of the panels (Table 4). Input Fiber Volume Fraction values were found experimentally, by resin digestion destructive testing. Panels with a symmetric lay-up have a greater flexural stiffness greater than for panels with an unsymmetric lay-up, whereas the extensional stiffness values remain the same between symmetric and unsymmetric lay-ups. General vibration theory states that increasing stiffness increases the natural frequency of an object [7]. If all other properties are kept the same, this increase in stiffness would result in a lower amplitude of vibration. A higher flexural stiffness would then be expected to result in a lower energy of the flexural or antisymmetric mode of vibration. This theory may, therefore, suggest that the discrepancy between the flexural stiffness and tensile stiffness of the symmetric panel 4 may explain the coefficient differences between panels 3 and 4.

Panel Number	Modulus (MSI)			
	E_X	E_Y	E_{Xb}	E_{Yb}
1	9.3	9.3	9.3	9.3
2	6.5	6.5	6.5	6.5
3	6.6	6.6	6.6	6.6
4	6.7	6.7	7.3	7.3

Table 4: Test Specimen Theoretical Modulus Values.

4 CONCLUSIONS

Wavespeed may be manipulated to provide some information on stacking sequence, as the ratio between 0° and 45° speeds lies close to unity if an equal number of 45°/-45° to 0°/90° plies are present.

Stiffness coupling has been shown to be highly influential on the energy ratio. It should be noted that scattering of high frequency components due to undulations in the weave may also influence energy ratios. Taking into consideration the wavespeed combined with the Energy Ratio may ascertain if the discrepancies are stiffness or undulation influenced.

ACKNOWLEDGEMENTS

Thank you to Delta Engineering Corporation for funding and supplying materials and expertise to enable this continuing research.

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