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Composite Material Characterization using Acoustic Wave Speed Measurements

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

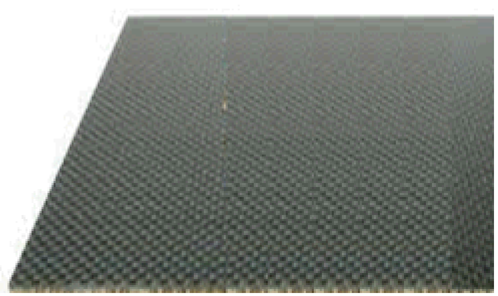
- Objectives
- Background
- Composite Material Specifications
- Experimental Setup
- Results
- Conclusions

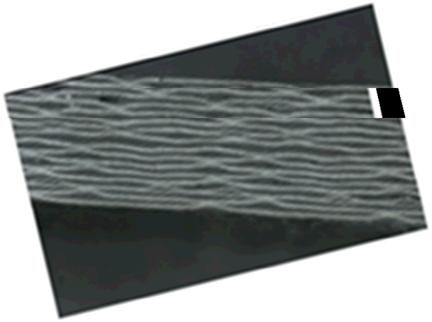
Objectives

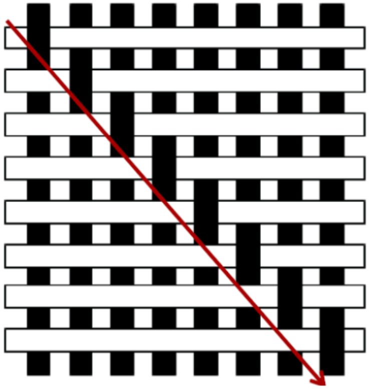
- Investigate the effect of different thicknesses (number of plies) when keeping the frequency constant

- Investigate the effect of different frequencies on one particular thickness

- Purpose- to characterize this particular composite







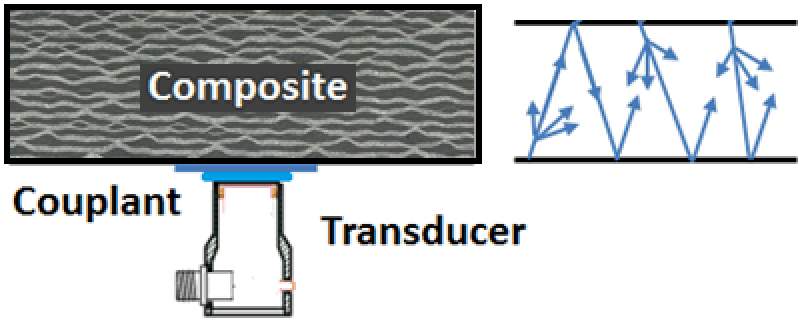
Background

- Applications [1]
  - High Strength
  - High stiffness
  - Good strength to weight ratio
  - Good flexibility to wrap around small and large radii

Background Continued

Previous Work [2-5]

- Materials that demonstrate frequency dependent velocity variation are known as dispersive materials.
- Propagation of ultrasound waves in anisotropic materials are different and more complex than isotropic materials because of the dispersive properties
  - Phase velocity does not necessarily travel in the same direction as group velocity
  - Phase velocity (v_p) = a continuous sinusoidal wave (one frequency) in a material
  - Group velocity (V_g) = a rate at which the point of maximum amplitude in the ultrasonic pulse (many frequencies) propagates through the material.



$$v_g = v_p + f\,\frac{\delta v_p}{\delta f}$$

Background Continued

Generalized Hooke's Law – 2nd Order Elastic Constants

$$
\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\
 & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\
 & & C_{33} & C_{34} & C_{35} & C_{36} \\
 & & & C_{44} & C_{45} & C_{46} \\
 & & & & C_{55} & C_{56} \\
 & & & & & C_{66}
\end{bmatrix}
\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix}
$$

Crystal Type	No. of Constants
triclinic	21
monoclinic	13
orthorhombic	9
trigonal	7
tetragonal	6
hexagonal	5
cubic	3
isotropic	2

Slide courtesy of Christian Boller and Eckhardt Schneider, Saarland University

Background Continued

- Constitutive Relationships between Sound and Elastic Constants
  - Usual Assumption:
    - Polycrystalline Material
    - Cubic symmetry structure
    - Isotropic and homogeneous state
  - Propagation velocity of elastic waves:
    - v =path length (s) / time-of-flight (t)
  - Propagation velocity of Longitudinal wave (v_L):
    - $\rho v^2_L = \lambda + 2\mu$
  - Propagation velocity of shear wave (v_T):
    - $\rho v^2_T = \mu = G$

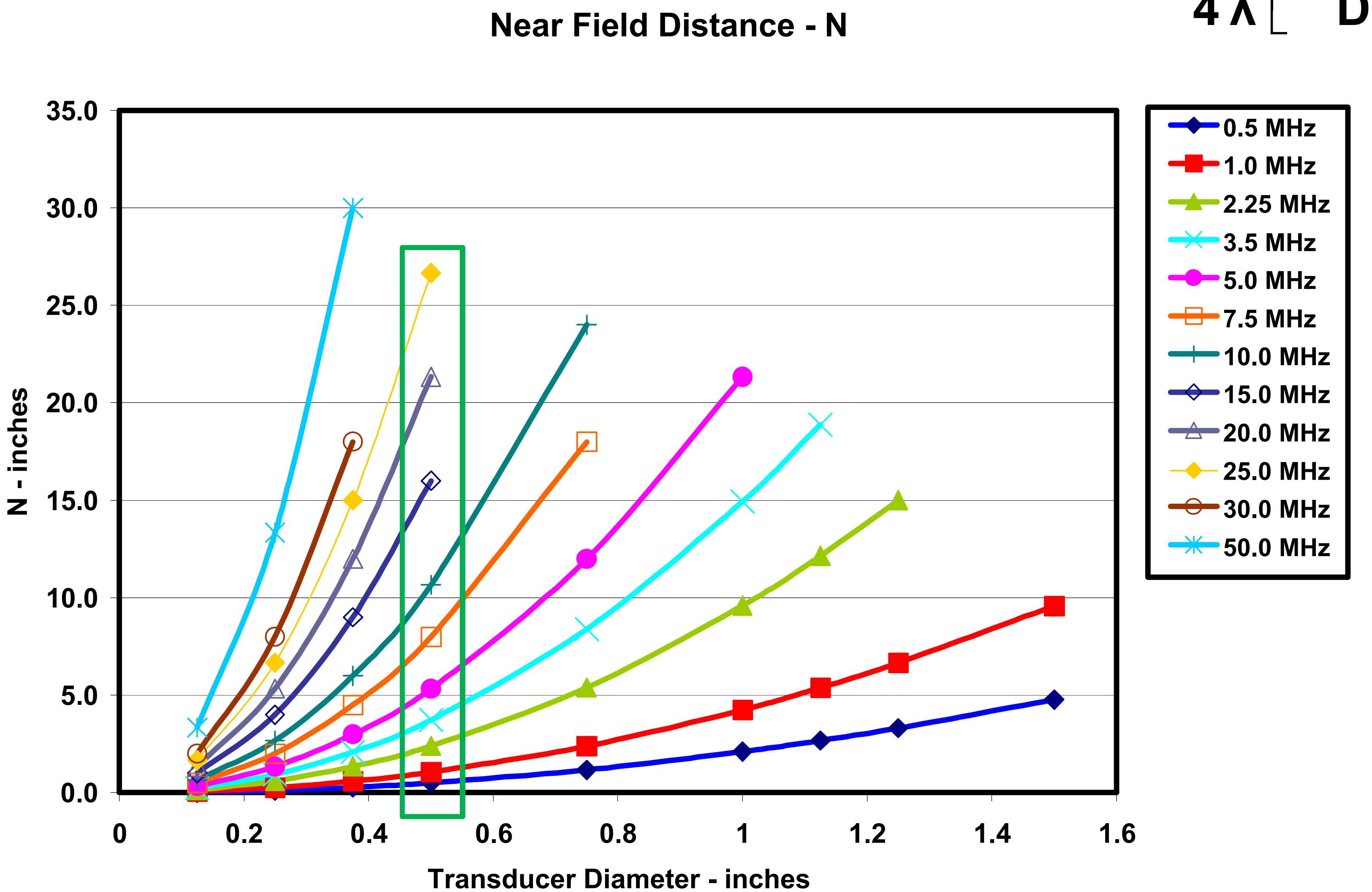
- Density= ρ
- Young's Modulus (E) :
  $E = \mu (3\lambda + 2\mu) / (\lambda + \mu)$
- Shear Modulus (G):
  $G = \mu$
- Poisson's Ratio (ν):
  $\nu = \lambda/2 (\lambda + \mu)$

Slide courtesy of Christian Boller and Eckhardt Schneider, Saarland University

Background Continued

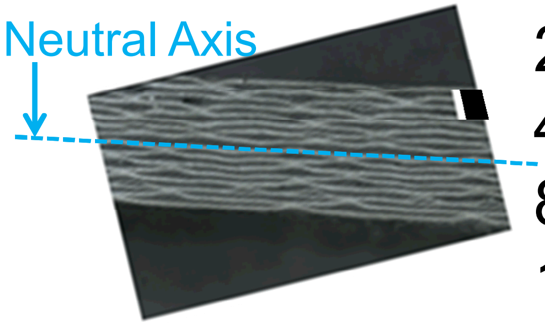
- Transducer Diameter - Near field effects

$$N = \frac{D^2}{4\lambda}\left[1-\frac{\lambda}{D}\right] \approx \frac{D^2 f}{4v}$$

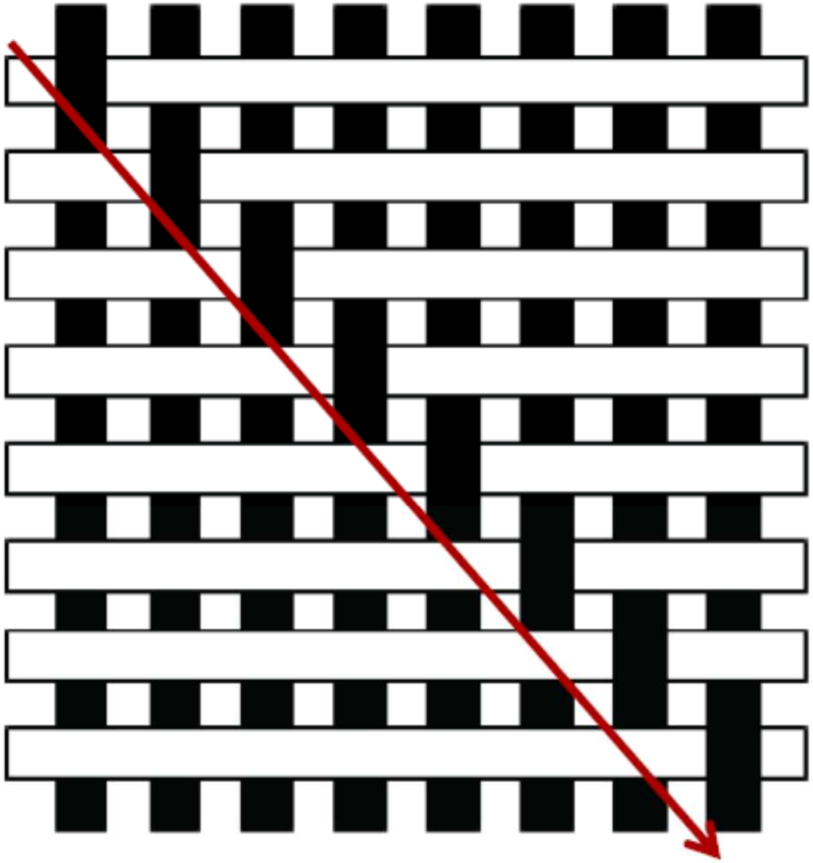


Composite Material

- Solid woven carbon fiber reinforced plastic (CFRP) composite consists of a polymeric binder and a carbon fiber weave.
- Carbon weave (8-harness satin weave) acts as reinforcement in the polymeric binder (UF3352 TCR™ Resin)



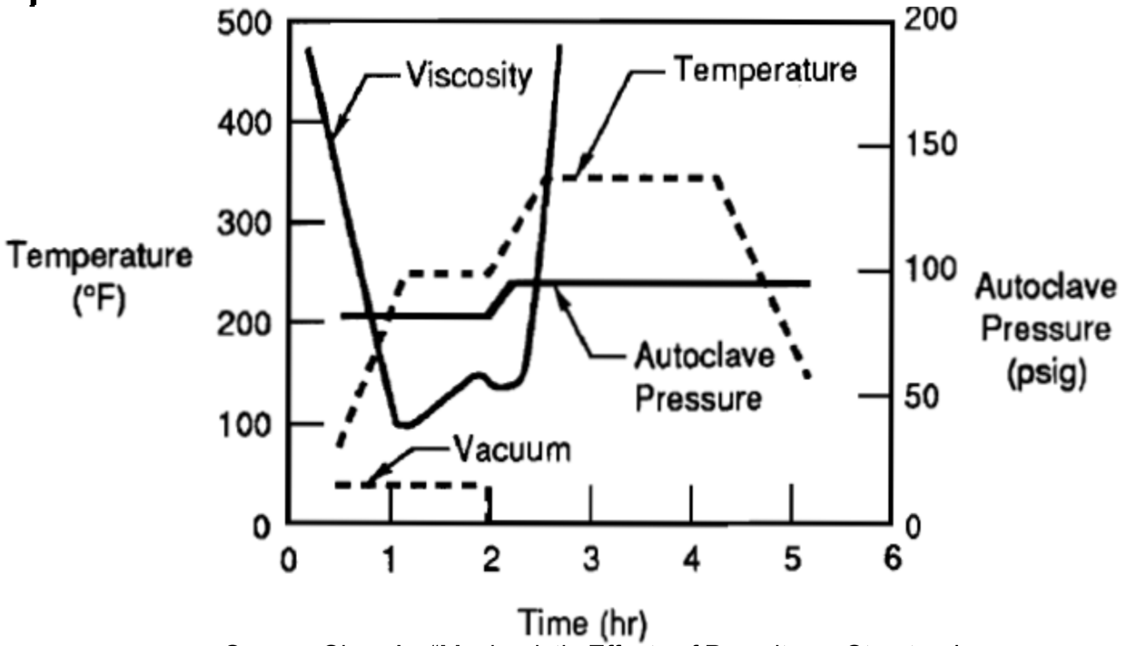
2ply $[0/90]]_s$
4 ply $[0/90]_2]_s$
8 ply $[0/90]_4]_s$
16 ply $[0/90]_8]_s$



This weave is resistant to wrinkles and allows for tight radius layups.

Composite Processing

- Pre-impregnated “pre-preg” woven carbon plys stacked according to specification
- Cured in autoclave under specific temperature and pressure profile



Source: Siver A., “Mechanistic Effects of Porosity on Structural Composite Materials” Thesis, University of California Los Angles (UCLA) 2014

Experimental Setup

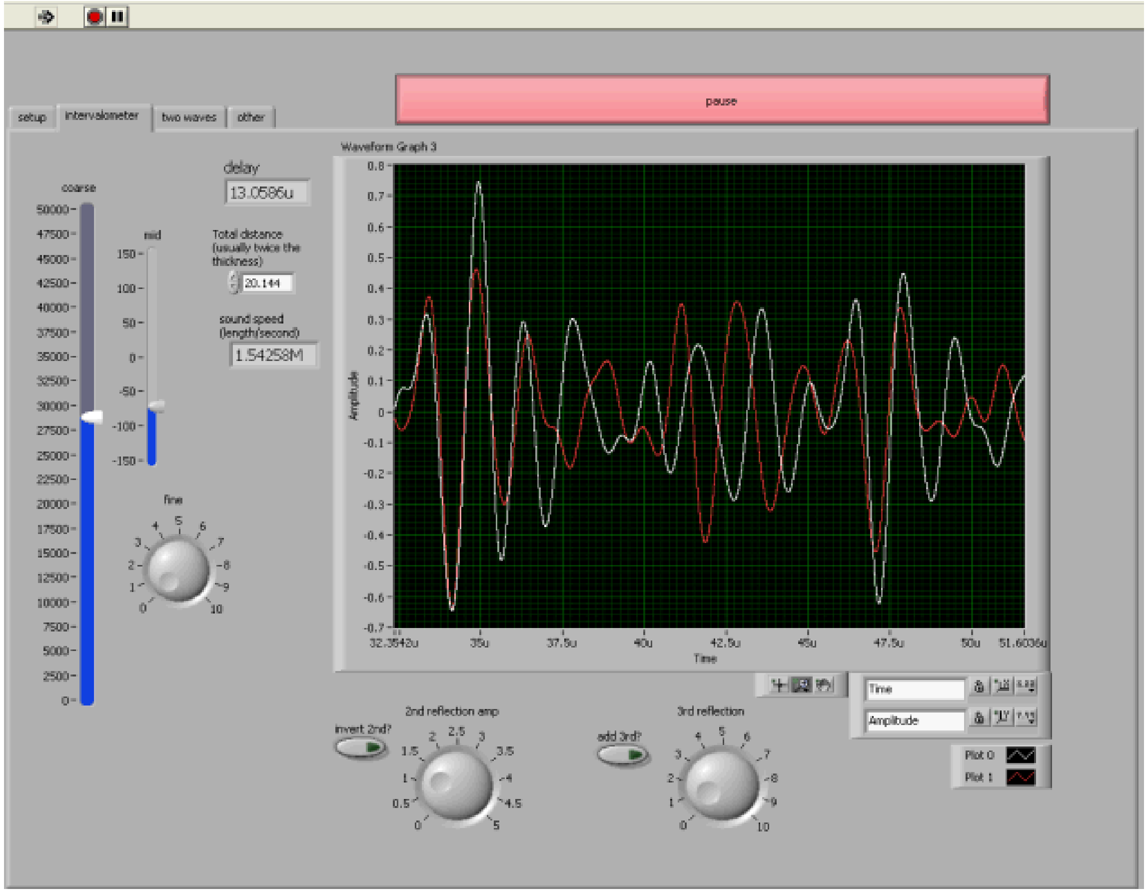
- Contact Ultrasonic Measurements
  - Pulser Voltage was kept constant at 300 for all frequencies and thicknesses for longitudinal velocity measurements
  - The other gains and pulser voltages were kept constant for all thicknesses at one frequency.

	1MHz	2.25MHz	5MHz	10MHz
Pulser Voltage (Longitudinal)	300	300	300	300
Gain (Longitudinal)	30	40	10	0
Pulser Voltage (Shear)	100	200	400	
Gain (Shear)	10	20	40	

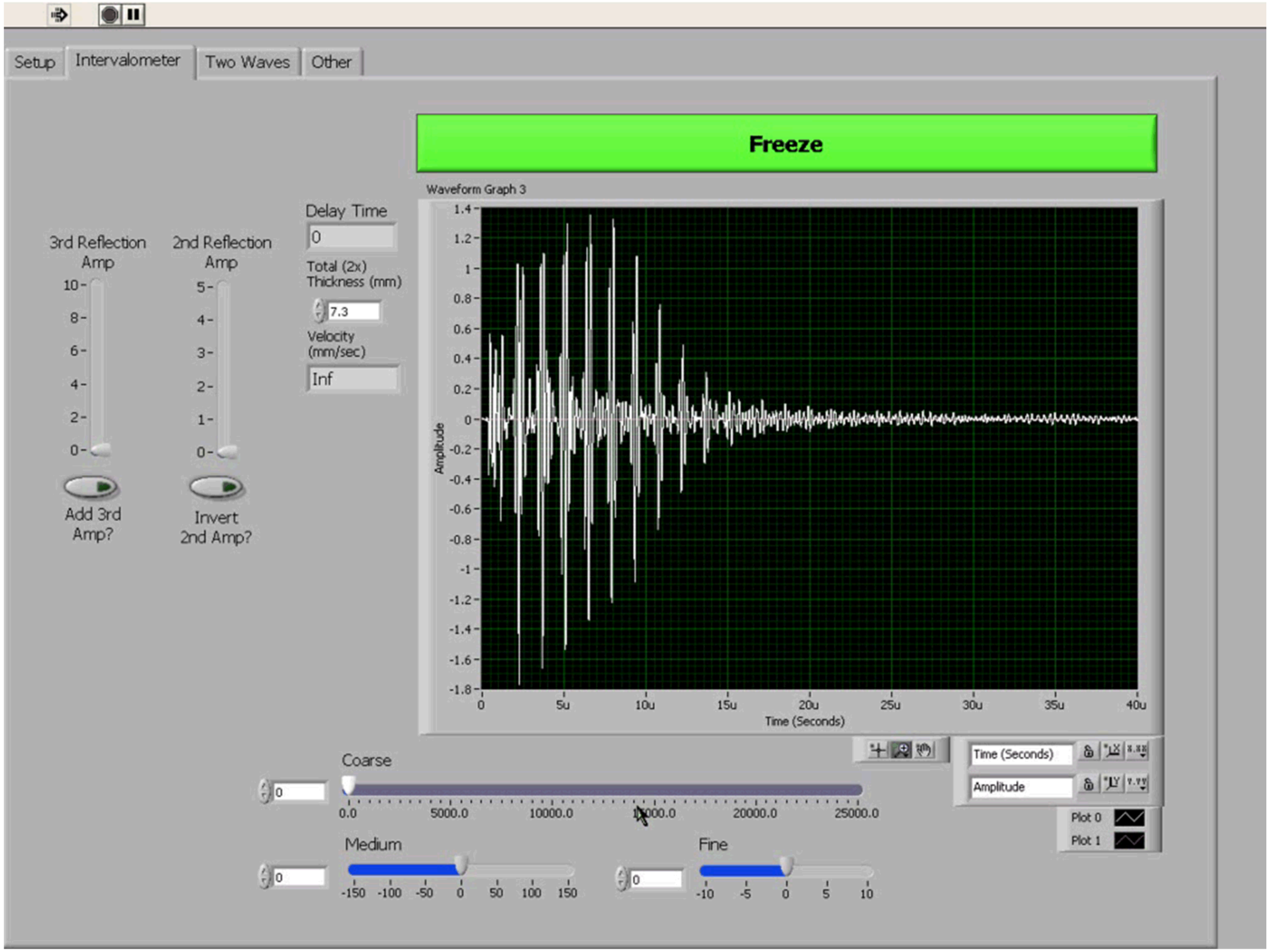
  - Used Sonotech® Soundsafe couplant for all longitudinal velocity measurements
  - Used Sonotech® Shear Gel Couplant for all shear velocity measurements

Experimental Setup

- Equipment:
  - Olympus 5077PR Square Wave Pulser/Receiver
  - LabVIEW Software

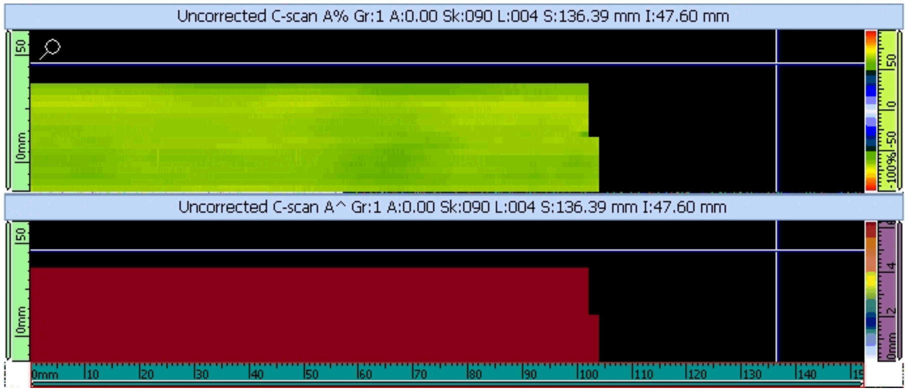


LabVIEW Ultrasonic Contact Testing

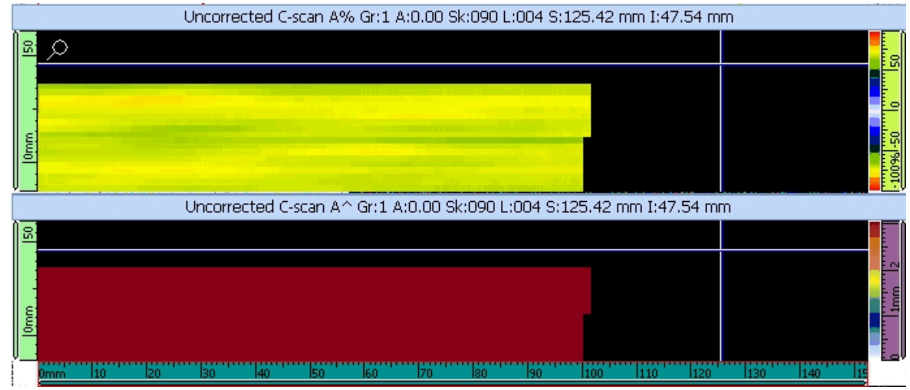


Check for Internal Defects

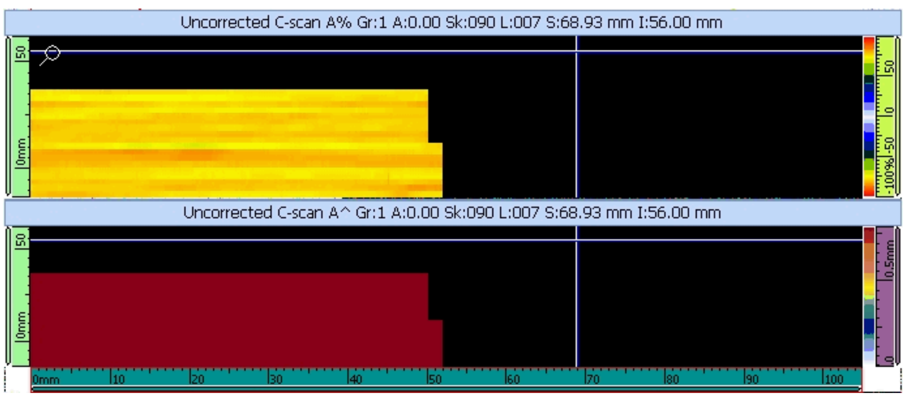
- Phased Array 1.5MHz Probe



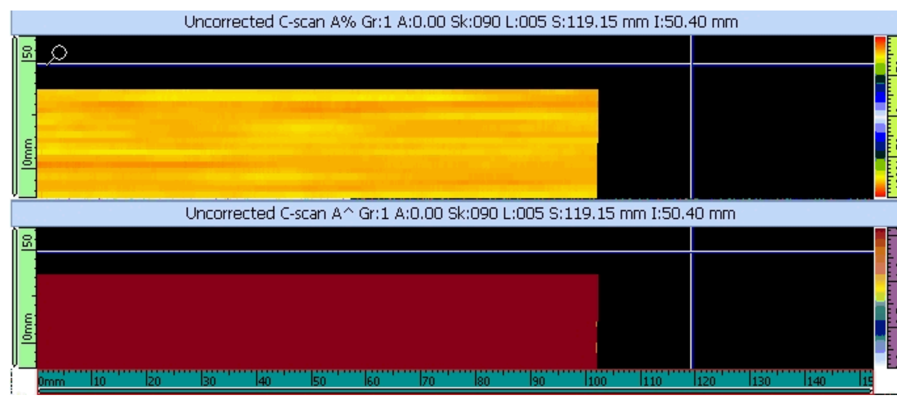
2 PLY



4 PLY



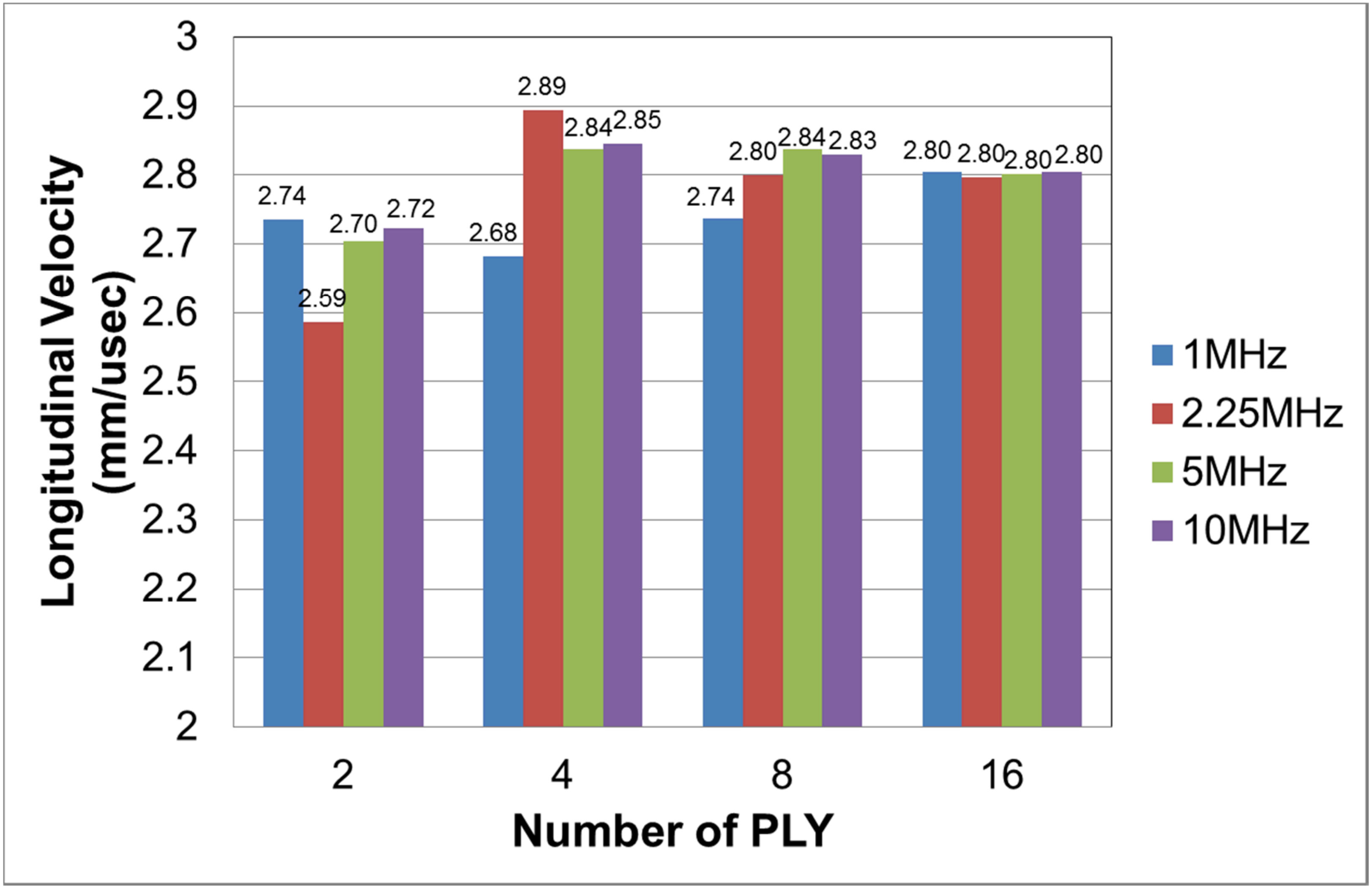
8 PLY



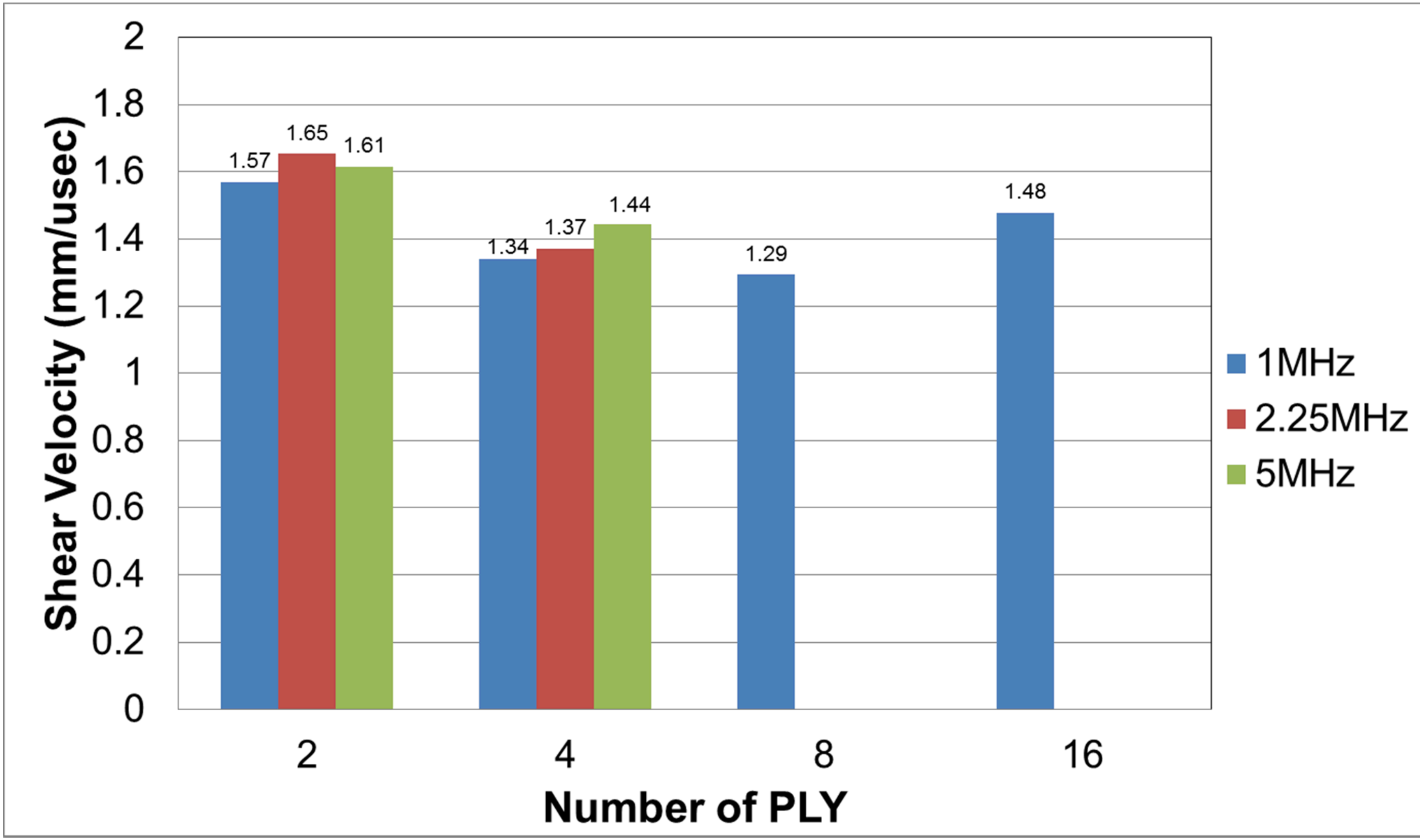
16 PLY

From these A-Scans we see that there are no defects present and that the thickness of the samples does increase

Longitudinal Velocity



Shear Velocity



1 MHz Frequency, All Numbers of PLY

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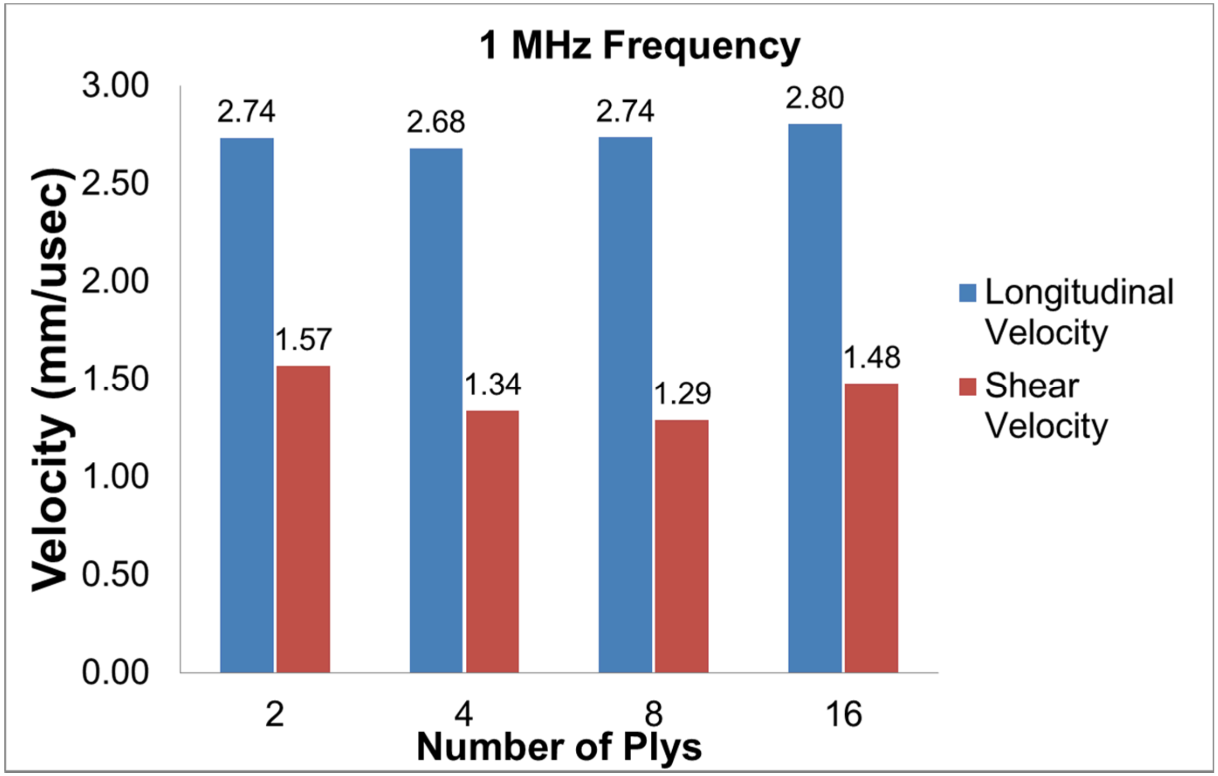
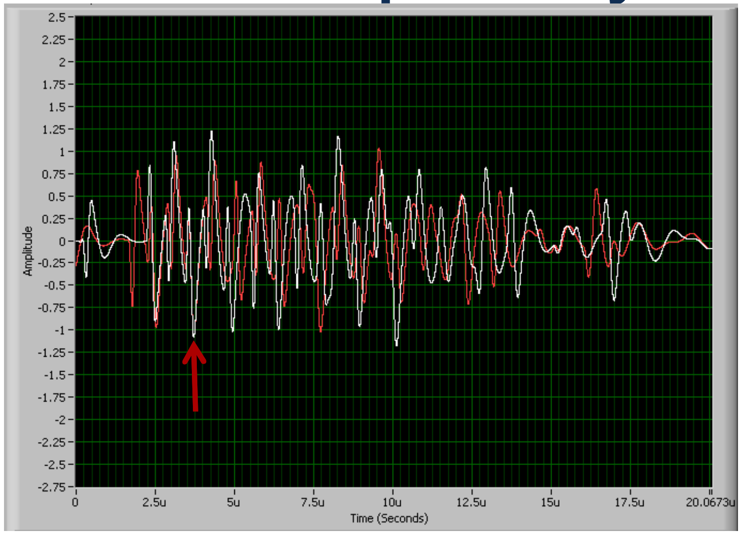
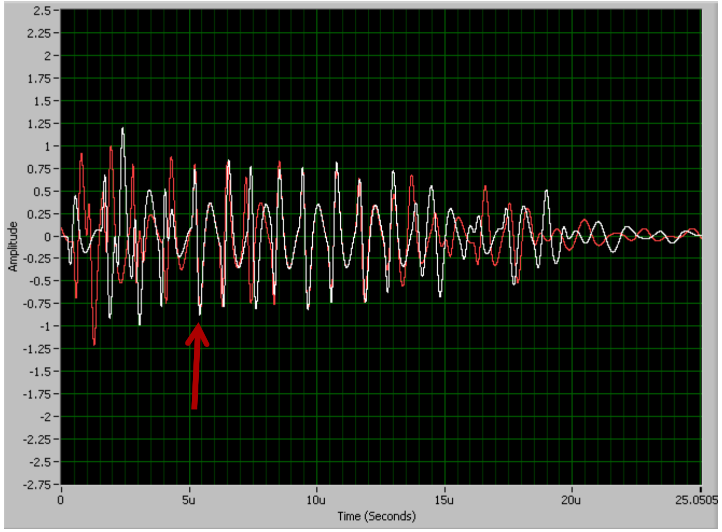


PLY #	Density (kg/m^3)	2x Thickness (mm)	Longitudinal ToF (µsec)	Longitudianl Velocity (mm/µsec)	Shear ToF (µsec)	Shear Velocity (mm/µsec)	Poisson Ratio (σ)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)
2	1505.6	1.516	0.55	2.74	0.97	1.57	0.25	9.31	3.71	6.32
4	1505.6	2.999	1.12	2.68	2.24	1.34	0.33	7.21	2.70	7.23
8	1505.6	5.939	2.17	2.74	4.59	1.29	0.36	6.83	2.52	7.92
16	1505.6	11.949	4.26	2.80	8.08	1.48	0.31	8.61	3.29	7.45

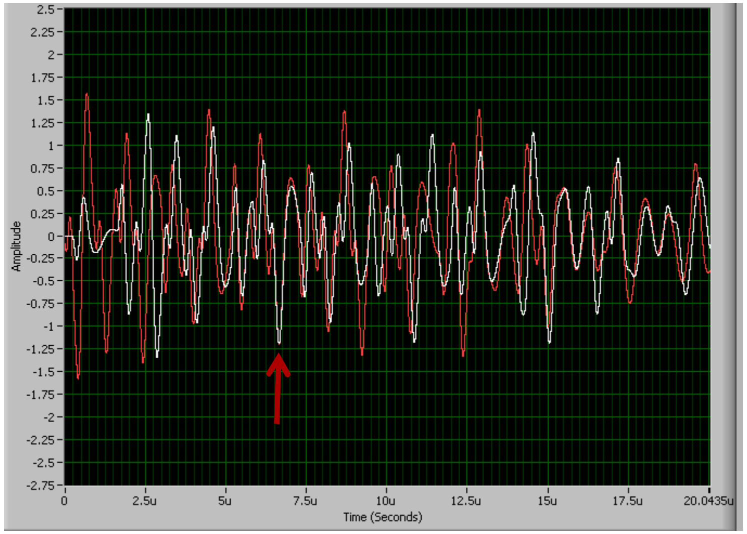
1 MHz Frequency, All Thickness



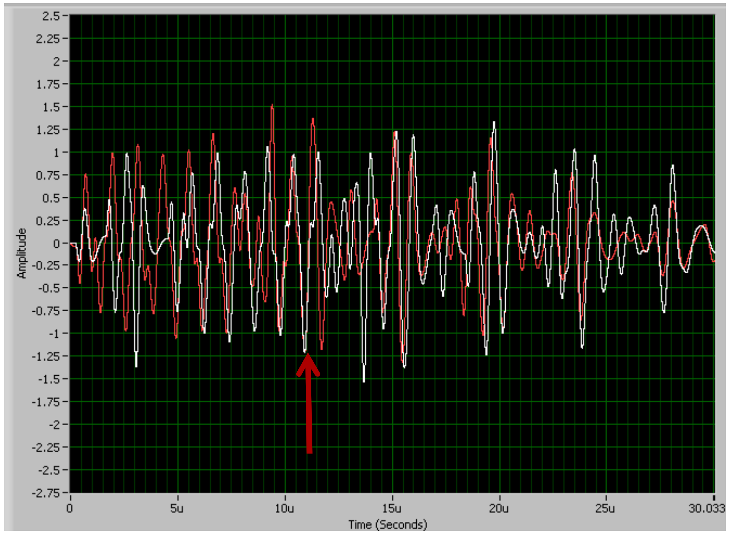
2Ply



4Ply

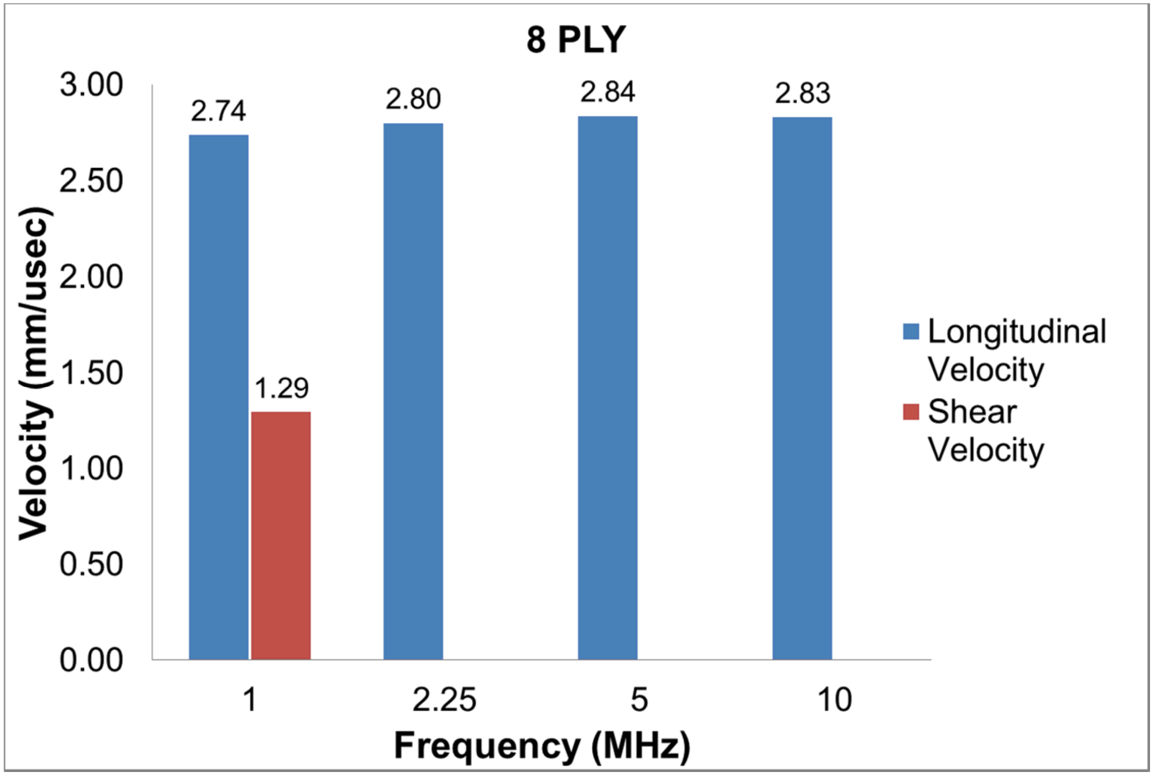


8Ply



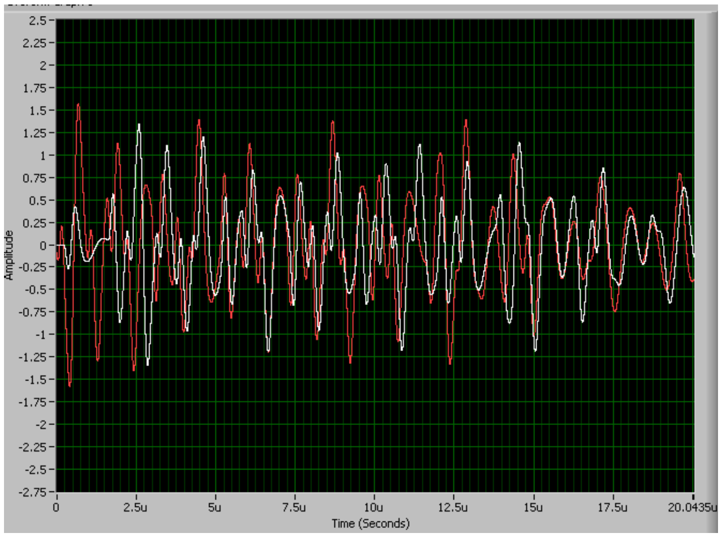
16Ply

8 PLYs, All Frequencies

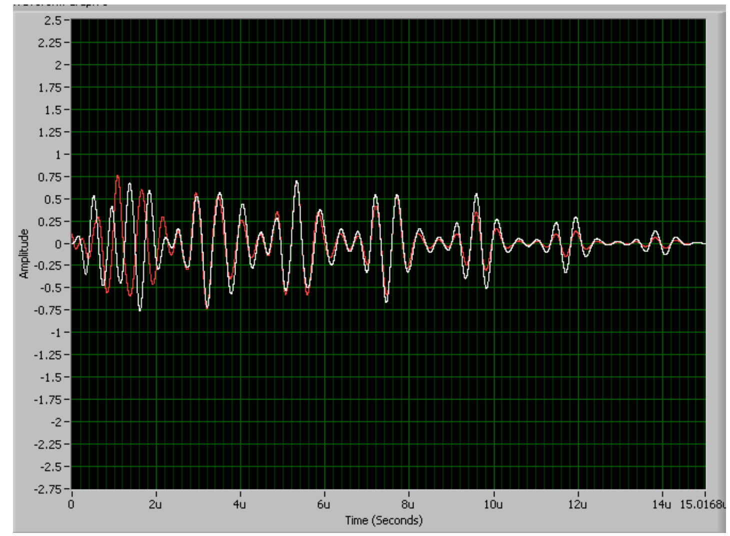


Frequency (MHz)	Density (kg/m^3)	2x Thickness (mm)	Longitudinal ToF (µsec)	Longitudianl Velocity (mm/µsec)	Shear ToF (µsec)	Shear Velocity (mm/µsec)	Poisson Ratio (σ)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)
1	1505.60	5.94	2.17	2.74	4.59	1.29	0.36	6.83	2.52	7.92
2.25	1505.60	5.94	2.12	2.80						
5	1505.60	5.94	2.09	2.84						
10	1505.60	5.94	2.10	2.83						

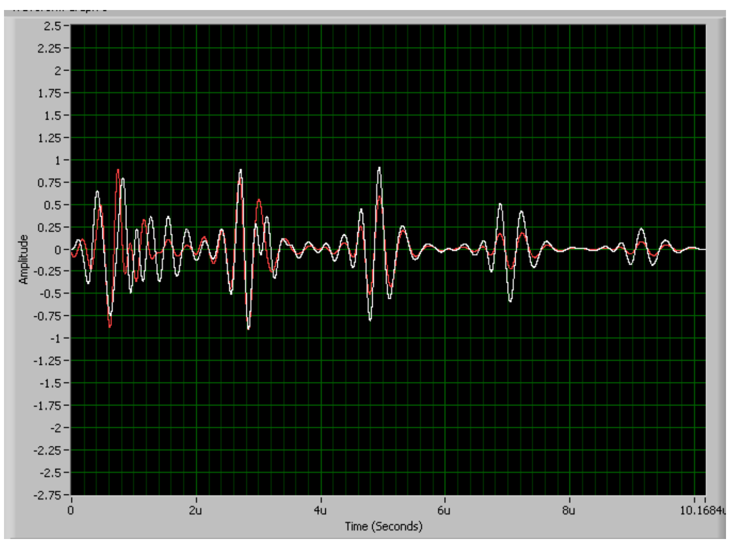
8 PLYs, All Frequencies (longitudinal)



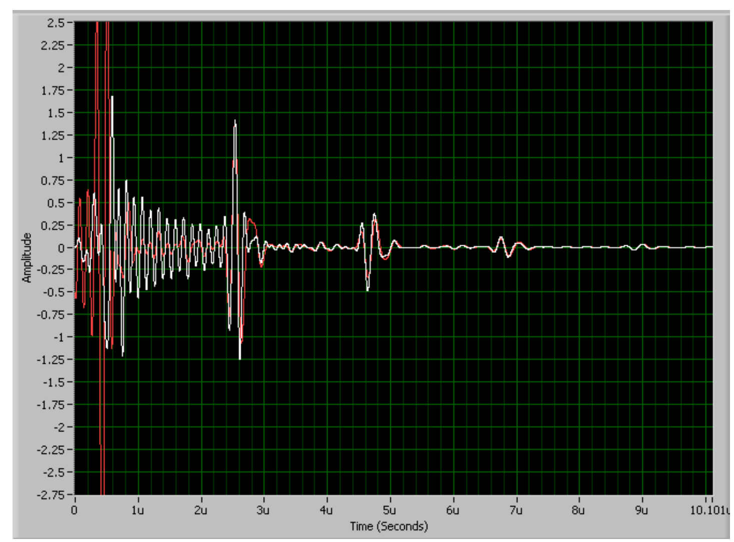
1MHz



2.25MHz

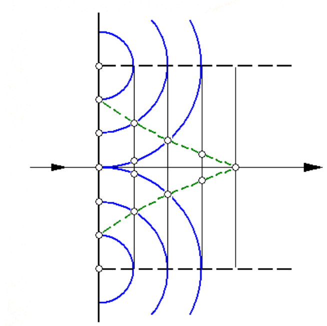


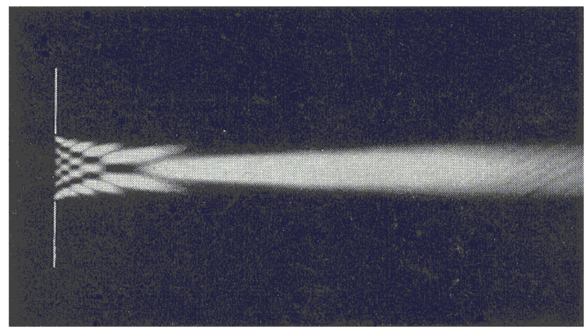
5MHz

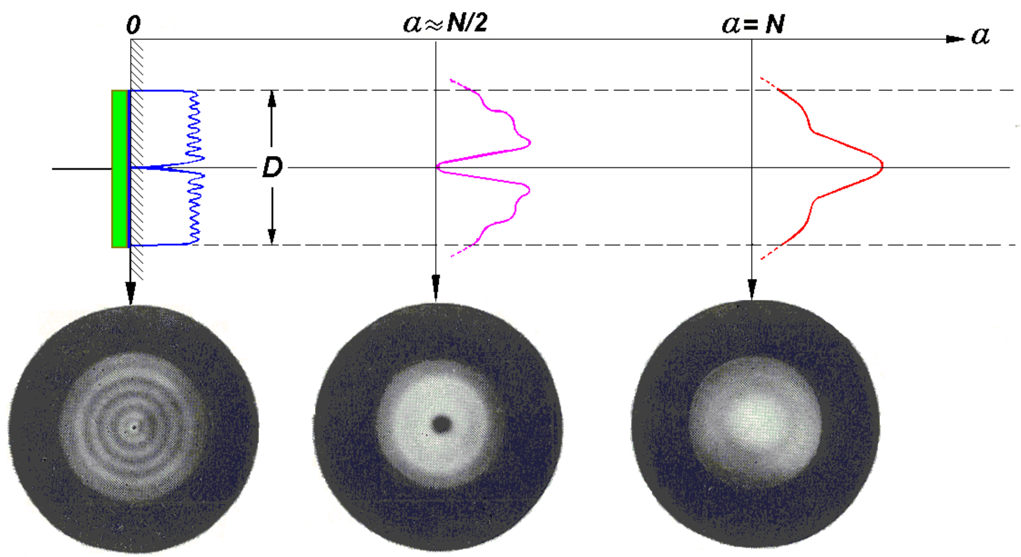


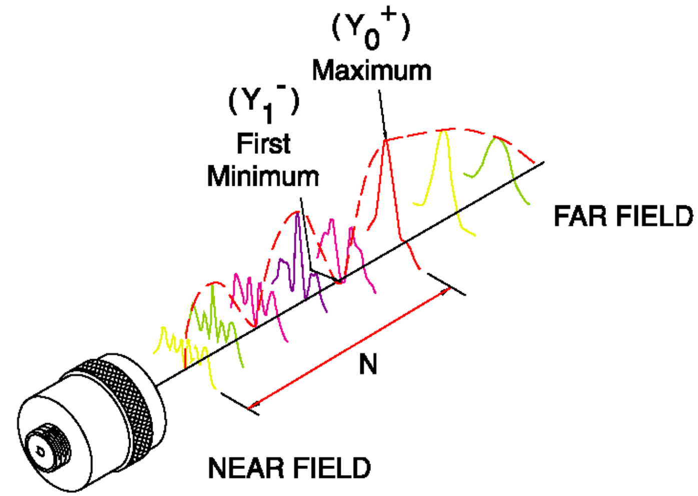
10MHz

Piezoelectric Transducers









$$N = \frac{D^2}{4\,\lambda}\left[1 - \frac{\lambda}{D}\right] \approx \frac{D^2 f}{4\,v}$$

Limitations of Contact UT

- Nearfield
  - Operating in the nearfield causes the signals to be noisier due to the constructive and destructive signals produced by the piezoelectric transducer.
- Couplant
  - Results might change slightly if the type and thickness of the couplant is changed
- Material property
  - The symmetry in our composites and how they cause dispersion of the ultrasonic wave through our composites are still unknown
- Equations
  - Using the same equations that are used for isotropic materials may cause error due to oversimplification.
  - Knowing how the structure of our composites interacts with the ultrasonic pulse can help us to account for the complexity in our equations

Benefits of Contact UT:

- Simple
- Relatively inexpensive
- Quick
- Can inspect thicker parts
- Minimum instrumentation
- Manual testing
- Portable
- No tanks or immersion
- Good for small areas
- Low loss of surface waves
- Used for velocity and thickness measurements

Conclusions

- Longitudinal waves passed through all thicknesses at all frequencies studied.
- Shear waves only propagate through all thicknesses at 1MHz frequency.
- Poisson's ratio, Young's Modulus, Shear Modulus, and Bulk Modulus could only be measured/calculated for all thicknesses at 1MHz frequency.
- There was a slight variation in the velocity of sound of this composite which can be attributed to:
  - dispersive properties of the composite
  - working in the nearfield
  - using mathematical equations that assumes the material is isotropic

Questions??

References

[1] Crampin S., Taylor D.B., “The propagation of Surface Waves in Anisotropic Media”, Geophys. J. R. astr. Soc., 1971, Volume 25, pp. 71-87.

[2] Crampin S., “An Introduction to Wave Propagation in Anisotropic Media”, Geophys. J. R. astr. Soc., 1984, Volume 76, pp. 17-28.

[3] Carcione J.M., “Wave Propagation in Anisotropic Linear Viscoelastic Media: Theory and Simulated Wavefields”, Geophys. J. Int., 1990, Volume 101, pp. 739-750

[4] Wang C.Y., Achenbach J.D., “Elastodynamic Fundamental Solutions for Anisotropic Solids”, Geophys. J. Int., 1994, Volume 118, pp. 384-392.

[5] Xiaomin L., Zhen W., “The Riemann Problem for the Nonlinear Degenerate Wave Equations”, Acta Mathematica Scientia, 2011, Volume 31B, pp. 2313-2322

Future Work

- Need to understand how the ultrasonic sound interacts with the fibers in the resin matrix
- Need to modify the equations used to calculate Young's Modulus, Shear Modulus, and Bulk Modulus to account for the complexity

Contact UT:

Benefits

- Simple
- Relatively inexpensive
- Quick
- Can inspect thicker parts
- Minimum instrumentation
- Manual testing
- Portable
- No tanks or immersion
- Good for small areas
- Low loss of surface waves
- Used for velocity and thickness measurements

Limitations

- Flat transducers - less areal resolution
- Slow (usually manual) testing speed. Can miss areas
- Thin couplant layer required
- Coupling variations
- Rough surfaces can be difficult
- Transducer or part wear
- Data interpreted from A-scan. Difficult to record data
- Manual record
- Delay line transducer required for near surface resolution
- Angle inspection requires wedge
- Special shoe required for curved parts