Ultrasonic Characterization of Aerospace Composites

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Nondestructive Evaluation Sciences Branch

NASA Langley Research Center

Advanced Composites Project

- 5 Year Project:
  - Reduce timeline for certification of composite structures
    - Currently takes ~20 years from material development to market use
  - Infuse advanced tools to accelerate regulatory acceptance of advanced composites
- Partnership: NASA, FAA, DoD, Industry, University
- NDE of composites will play a key role in all three technical challenge areas:
  1. Predictive capabilities (e.g., damage progression)
  2. Rapid Inspection
  3. Enhanced Manufacturing

Boeing 787
www.boeing.com

Lockheed Martin F-35
www.f35.com

Northrup Grumman
Fire Scout
www.northropgrumman.com

Airbus
A-350 WXB
www.a350wxb.com

Bombardier
C-Series
wwaw.cseries.com

Comac C919 (China)

Sukhoi Superjet 100
(Russia)

Composites for Space

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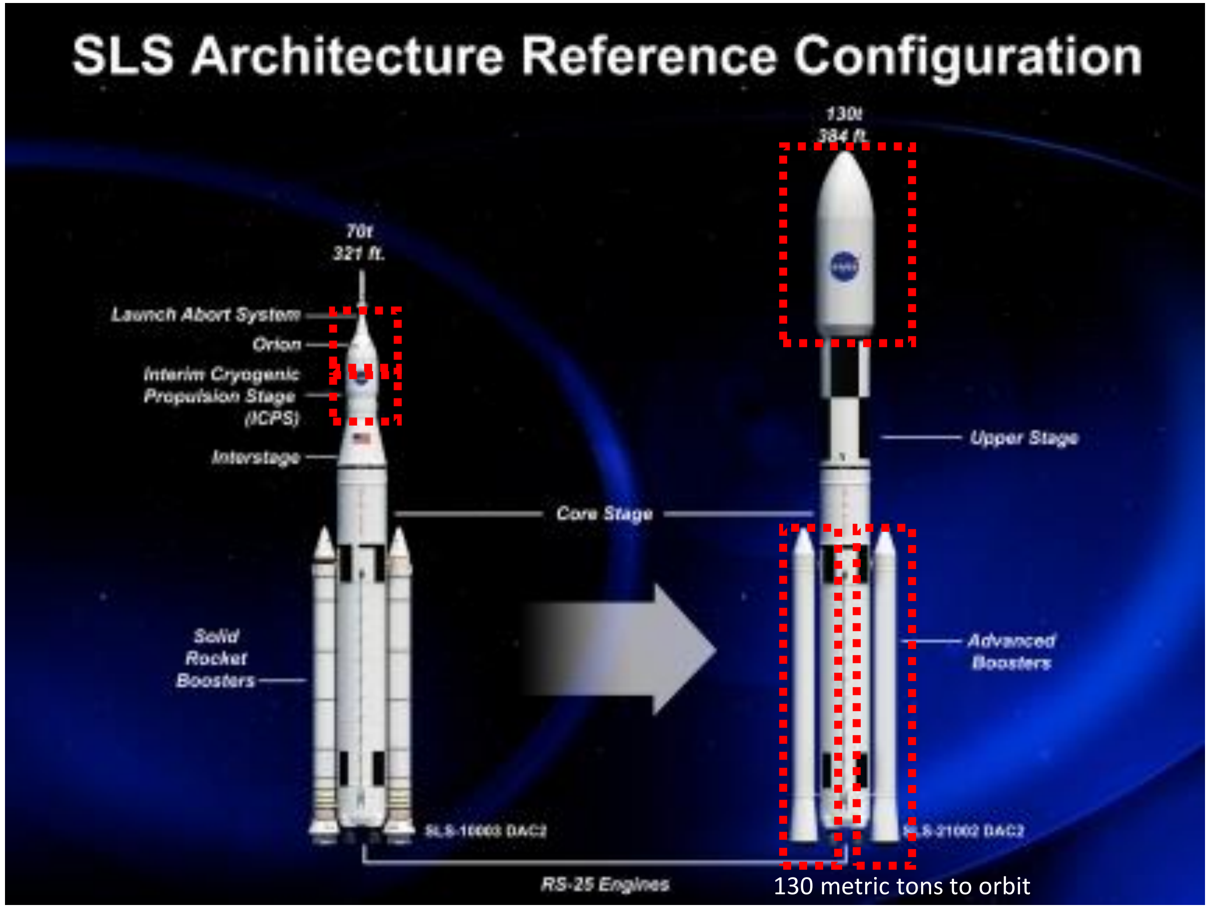
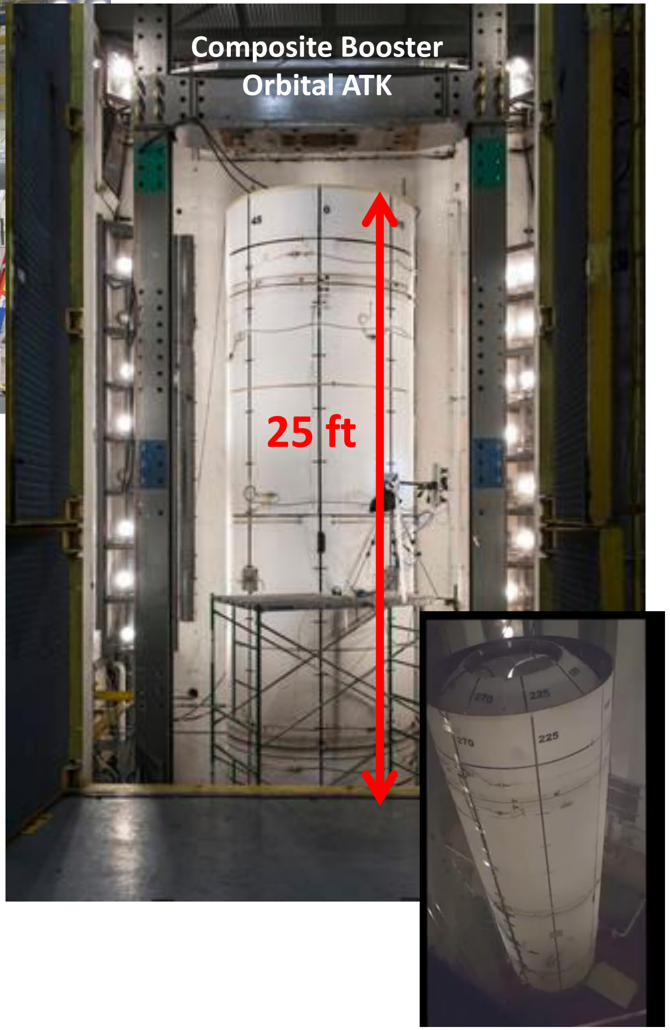


https://www.youtube.com/watch?v=IRutJfOsgII



Composite Damage/Defect Types

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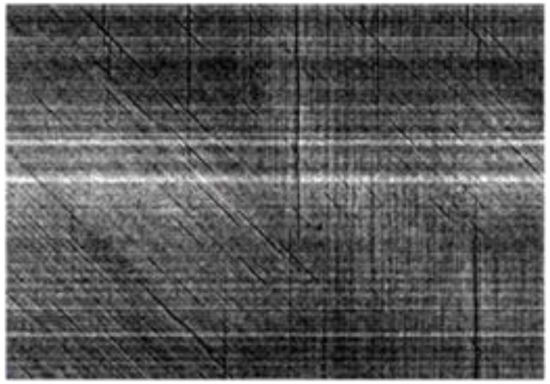
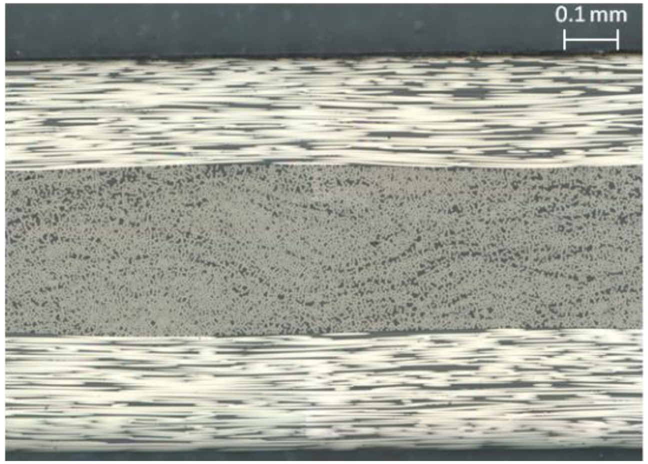
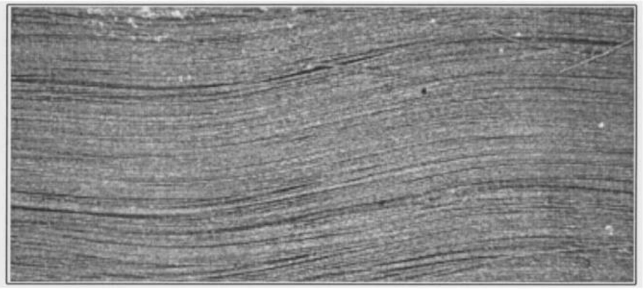
X-ray CT data of microcrack damage



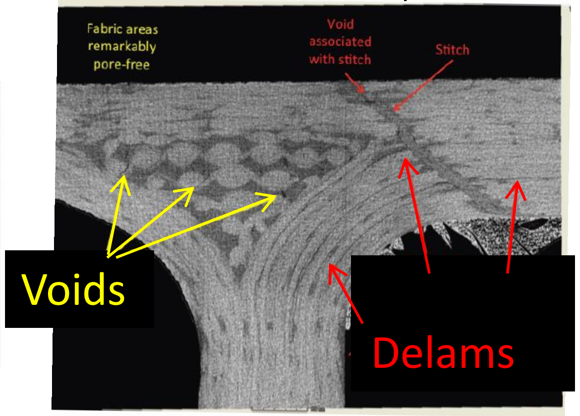
Micrograph showing resin rich regions and fiber misalignment



Fiber waviness (in-plane),
From Kugler and Moon 2002
doi: 10.1177/0021998302036012575

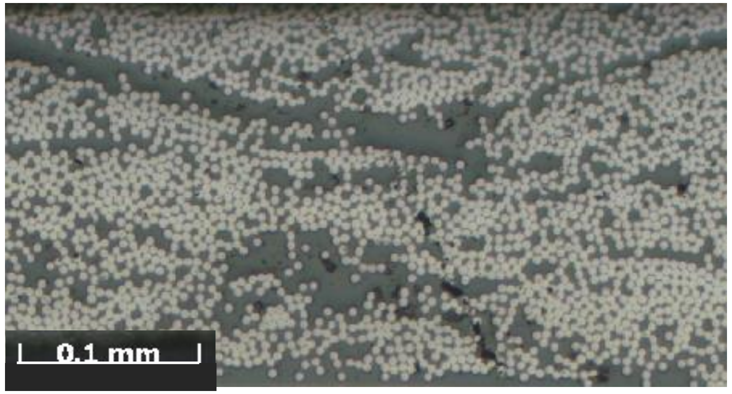


X-ray CT of PRSEUS Joint
From NASA TM-2013-217799 by Patrick Johnston

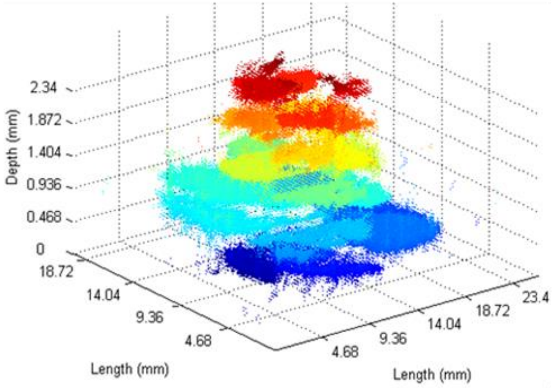


X-ray CT data of microcrack damage

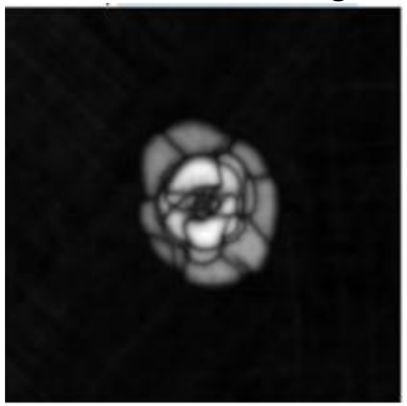
Micrograph showing porosity



X-ray CT data of delamination damage

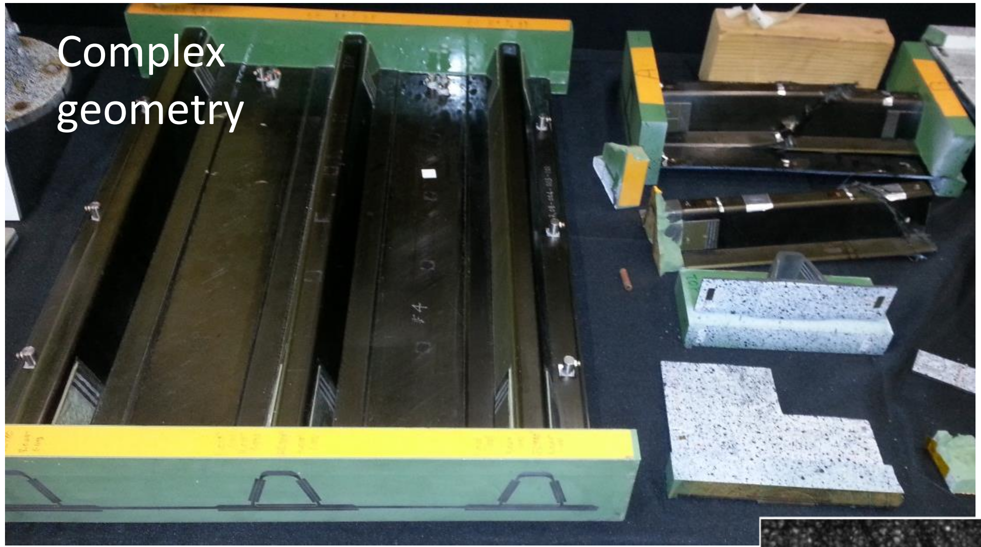


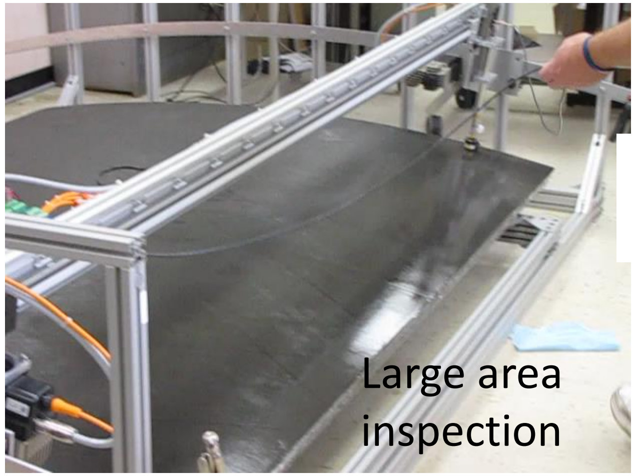
UT data of delamination damage

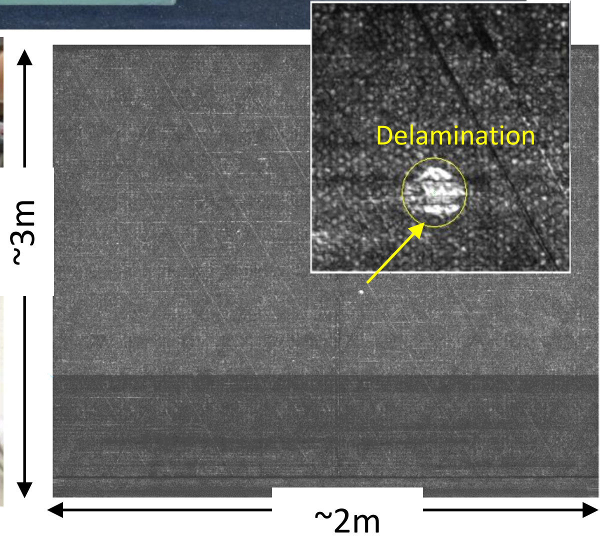


ACP NDE Research

- Carbon fiber reinforced polymer composites
- NDE focus areas:
  - Inspection of complex geometry components
  - Rapid large area inspection
  - Defect/damage characterization
  - Validation of detectability
- Of-interest defect/damage types include:
  - Microcracking, fiber waviness, delamination, porosity, manufacturing variability, etc
- Experiment:
  - Thermography, ultrasound
- Simulation:
  - Enables model based inspection prediction/validation
  - Custom code, 3D simulation

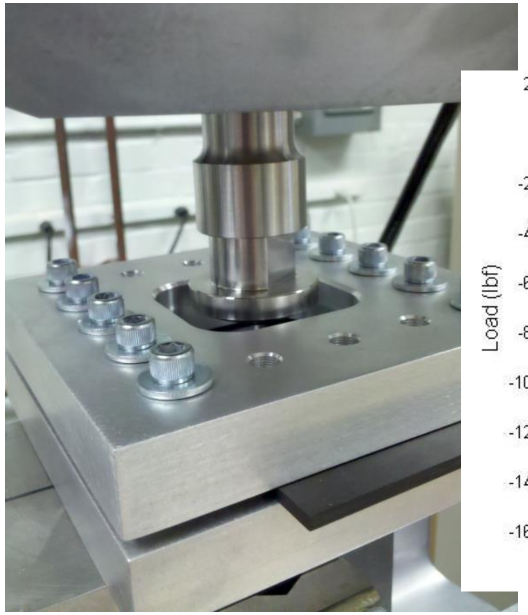


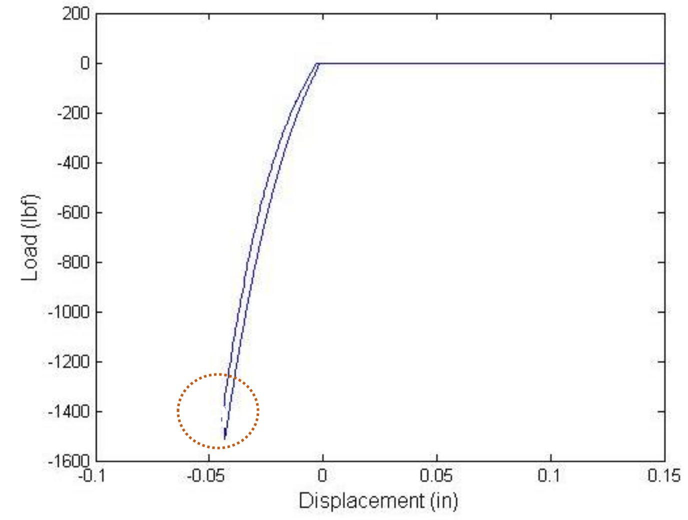


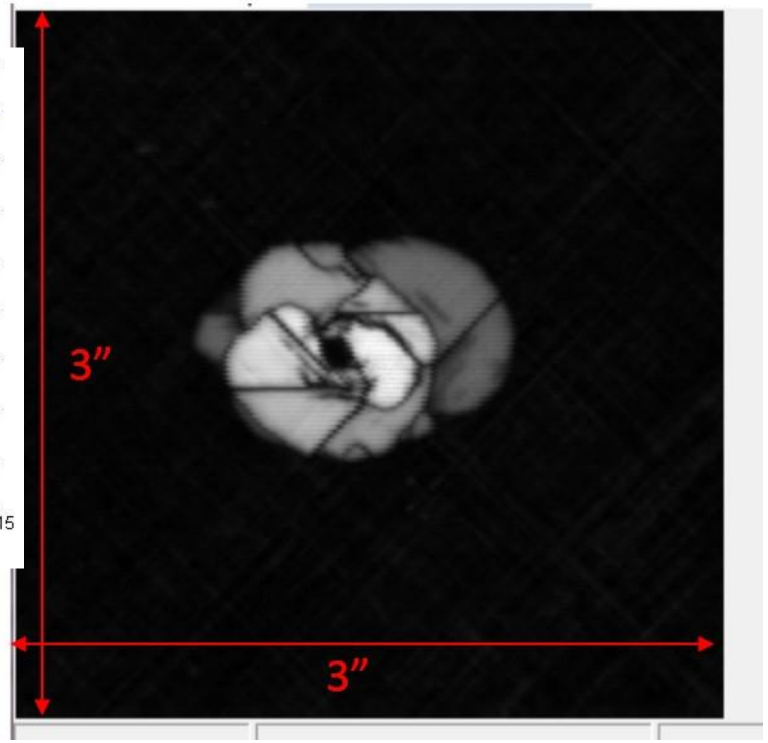


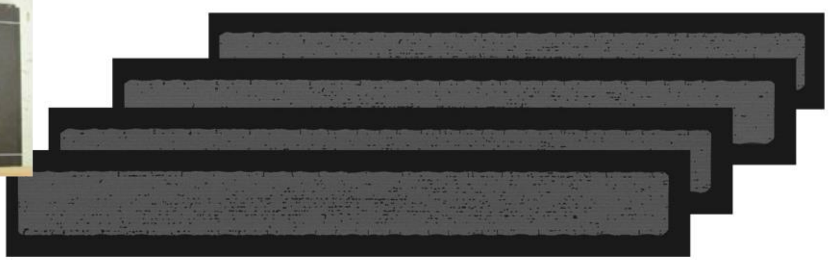
Defect samples

- Delamination
- Cracking
- Overlap
- Gaps
- Waviness
- Misalignment
- Porosity
- Weak bonding







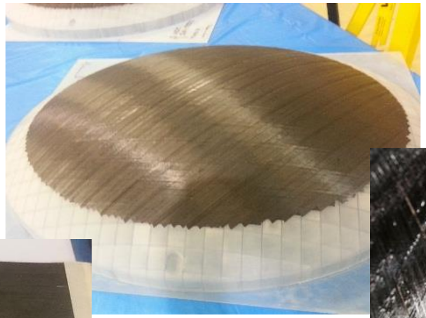


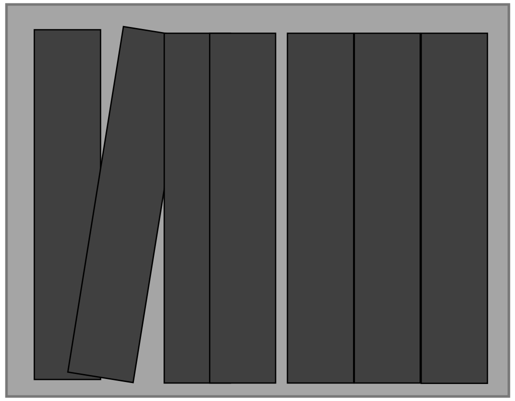
Defect samples

- Delamination
- Cracking
- Overlap
- Gaps
- Waviness
- Misalingment
- Porosity
- Weak bonding


ISAAC Automated fiber placement machine


¼ in. tape prepreg




Overlaps and gaps on order of 1/8” to 1/2”

Defect samples

- Delamination
- Cracking
- Overlap
- Gaps
- Waviness
- Misalignment
- Porosity
- Weak bonding

ACC Partners

Ultrasonic approaches

- Polar scattering
  - Cracking, fiber waviness, fiber misalignment, porosity
- Phase sensitive methods
  - Weak bonding
- Guided waves
  - Delamination, fiber waviness, porosity

Polar Scattering Applications

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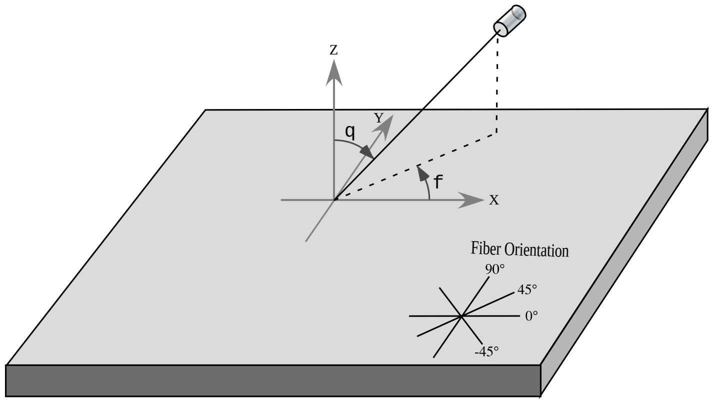
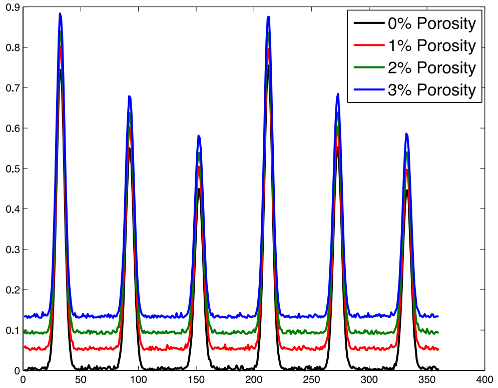
Polar Backscatter Geometry

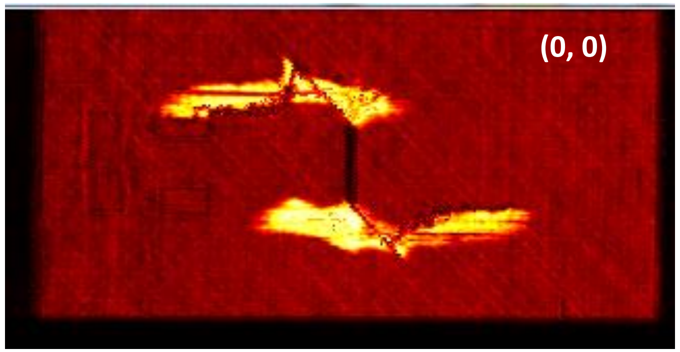


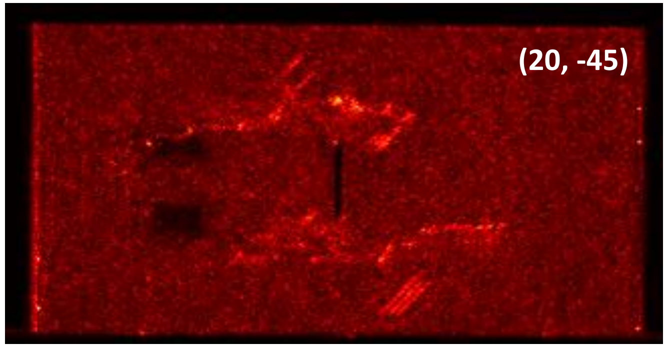
Fixed Polar Angle, Scan Azimuthal Angle
Low Volume-Fraction Porosity



(Schematic data, after Bar Cohen and Crane, 1982, and others)

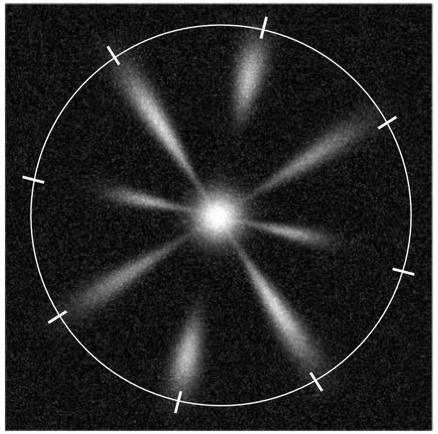
Fixed Polar Angle and Azimuthal Angle
Scan X- Y
Delaminations and Transverse Cracks
In Same Specimen



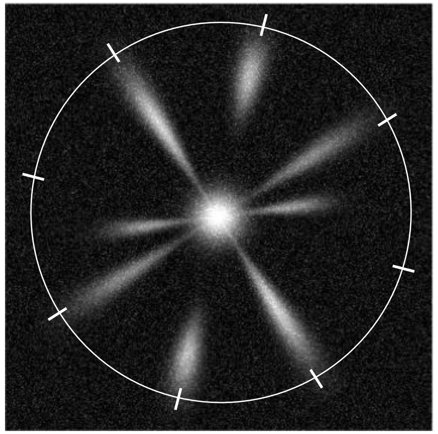


(Measured data, NASA: Johnston, *et al, 2012*)

Scan Polar Angle and Azimuthal Angle
Fiber Direction at an X-Y Location



Quasi-Isotropic Lay-up

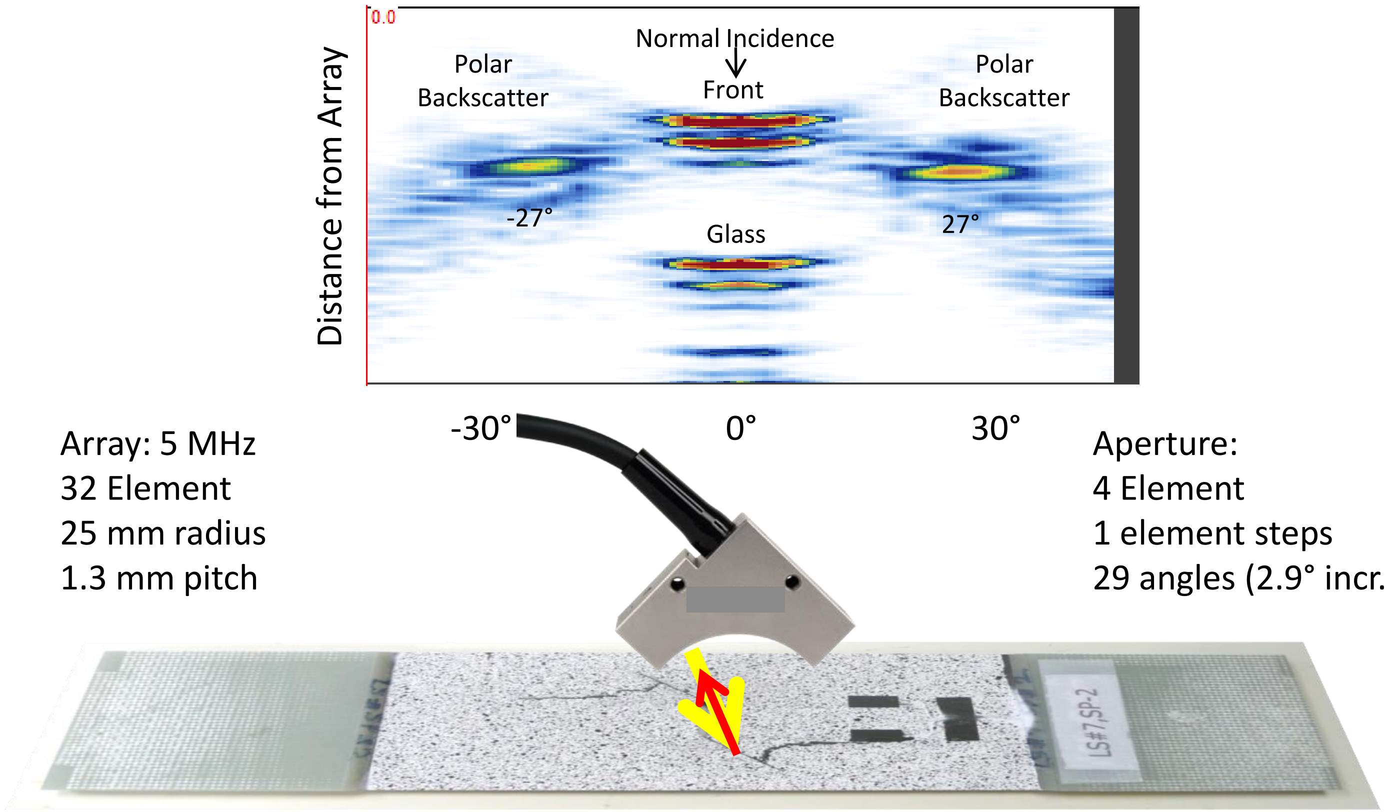


Quasi-Isotropic Lay-up with Misaligned Lamina

(Schematic data, after Declercq, *et* al, 2006)

Array Approaches

Curved Linear Array

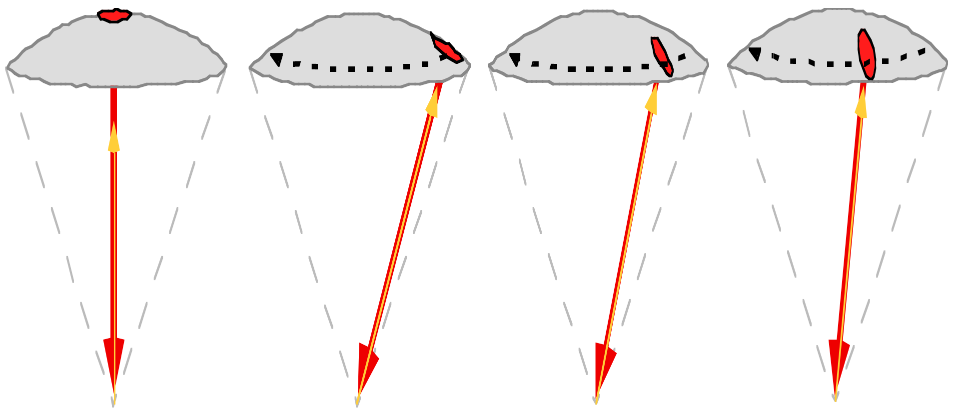


Array: 5 MHz
32 Element
25 mm radius
1.3 mm pitch

Aperture:
4 Element
1 element steps
29 angles (2.9° incr.)

Spherical Shell 2-Dim Array

2-Dimensional array can scan polar and azimuthal angles to interrogate a location to obtain data on fiber orientation, and presence of flaws such as porosity, transverse matrix cracks, in addition to delaminations



Goals:

- More quantitative data improves characterization of composite
- Efficiency is gained by gathering multiple scans worth of information during a single scan using one probe

Planned Work: Characterization of Fiber Waviness

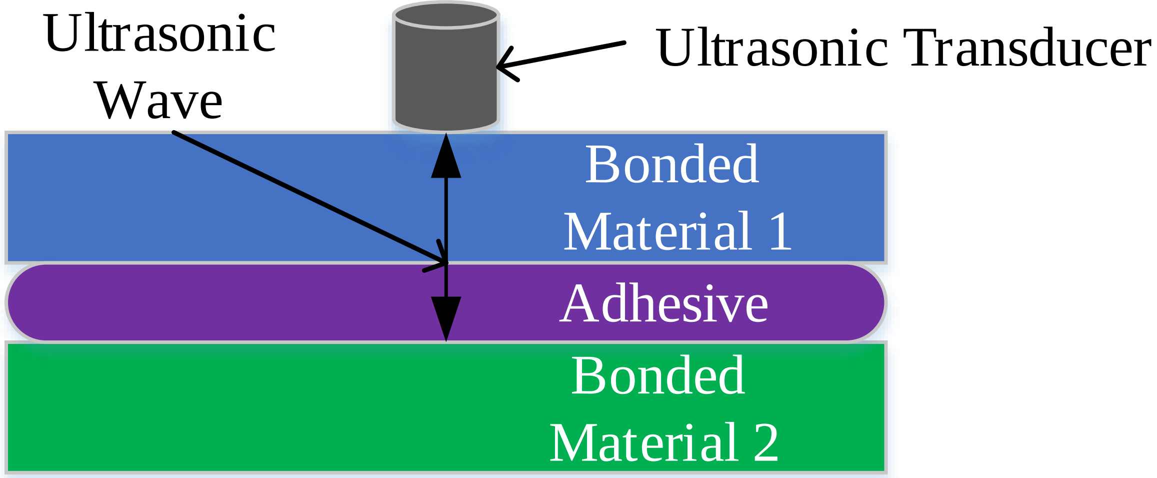
- Previous work has demonstrated the principle of polar backscatter and wide-angle scattering measurements
- Work planned under ACP:
  - Understand the interdependence of ultrasonic, measurement, and composite material variables:
    - *Ultrasonic:* F-number, focal length, beam width, center frequency, bandwidth
    - *Measurement*: Polar angle, azimuthal angle, Z-offset, scattering angle, time-gating
    - *Composite material:*
      - Stacking sequence, lamina thickness, fiber and matrix material
      - Lamina depth, lamina thickness, separation of parallel lamina, surface roughness
      - Fiber waviness, micro-cracking, porosity, delamination, transverse cracks
  - Develop verified design parameters for wide-angle, curved, 2-D array probe to optimize measurement performance
  - Design, fabricate, and demonstrate 2-D array probe
  - Involves theory, experiment, and modeling and simulation

Phase based methods for quantitative adhesive bond strength measurement

- Important method of joining composite parts is through adhesive bonding
- Currently no proven method for measuring absolute bond strength
- Bonded repair currently only approved for certain factory conditions
- Quantitative bond strength measurement could allow:
  - Bond quality to be known at any point in bonded structures life
  - Detection of degraded bonds that have proved undetectable with current NDE
  - Inspection and improvement of bonding processes without needing destructive tests

Adhesive Bond Strength Monitor

- Developing an interferometric, phase-based ultrasonic technique for measuring bond strength
- Quality of adhesive bond will affect the amount of phase shift
- Received wave is compared to reference wave to determine phase shift in bonded specimen
- Much more sensitive than conventional ultrasonic measurement techniques
- Attempting to quantitatively measure adhesive bond strength

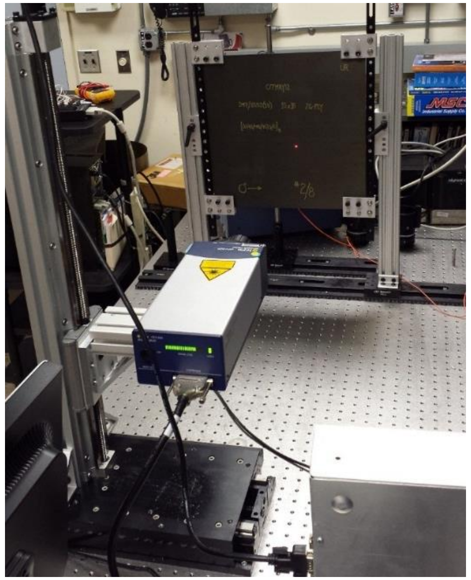


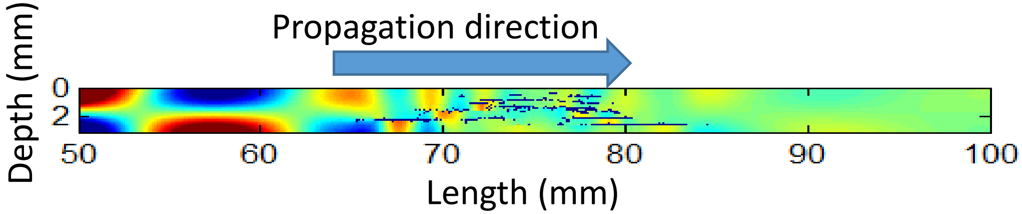
- Phase shift due to each layer:
  - $\phi_{layer} = \frac{4\pi L}{\lambda}$
  - L is length of each layer, λ is acoustic wavelength in each layer
- Complex reflection coefficient of imperfect adhesive interface modelled as massless spring system*:
  - $R = \frac{Z_1 - Z_2 + i\omega\frac{Z_1 Z_2}{K}}{Z_1 + Z_2 + i\omega\frac{Z_1 Z_2}{K}}$
  - Z is acoustic impedance of each interfacing layer, ω is angular frequency of ultrasonic wave, K is effective spring constant of interface
  - Perfect interface: $K \to \infty$
  - Complete disbond: $K \to 0$
- Total phase response will be combination of phase shift in each layer and phase shift induced by imperfect interface

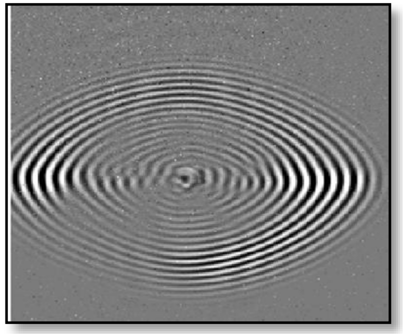
*H G Tattersall 1973 *J. Phys. D: Appl. Phys.* **6** 819

Guided waves

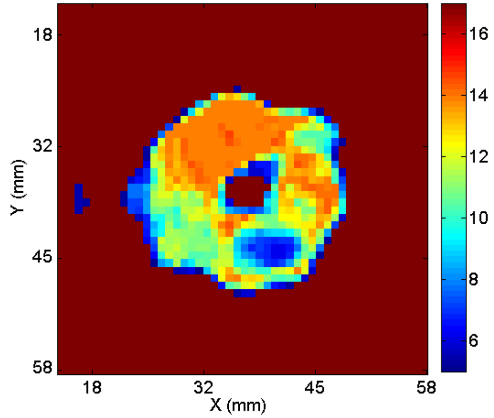
- Laser Doppler Vibrometry measurement
- Later in this session:
  - Characterizing delamination size, shape, and depth with guided wave methods (contactless measurement)







Wavenumber analysis from LDV data



Guided Wave Energy Trapping

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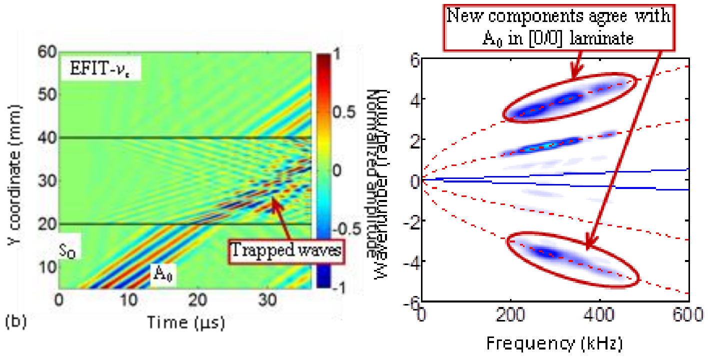
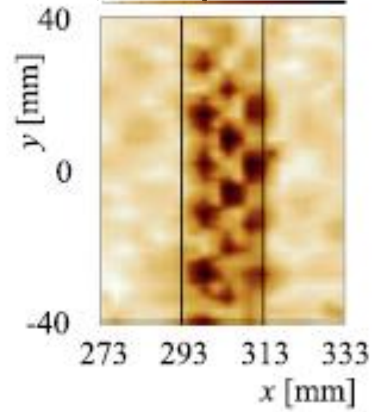
- Studied previously by several authors via LDV and simple simulations
  - Prior studies focused on single layer delamination
- Current NDE methods (Cscan etc) allow for single-sided delamination sizing
  - But not single sided multi-layer damage characterization

Tian, Composite, single delam



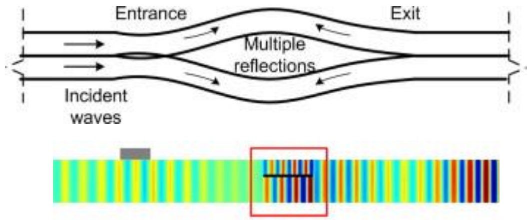
[3]Zhenhua Tian ; Lingyu Yu ; Cara A. C. Leckey; Proc. SPIE 9063, (2014), doi:10.1117/12.2044927.

Glushkov, Two layer aluminum



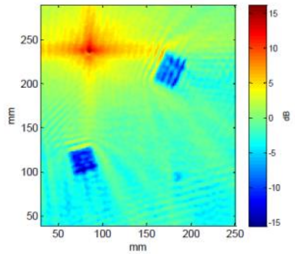
[1]Glushkov, E, Glushkova, N, Golub, M, Moll, J, Fritzen, CP. *Smart Materials and Structures* 21.12 (2012): 125001.

Sohn, Composite, single delam



[2]Sohn, H., Dutta, D., Yang, J. Y., Park, H. J., DeSimio, M., Olson, S., & Swenson, E. (2011). *Composites science and technology*, *71*(9), 1250-1256.

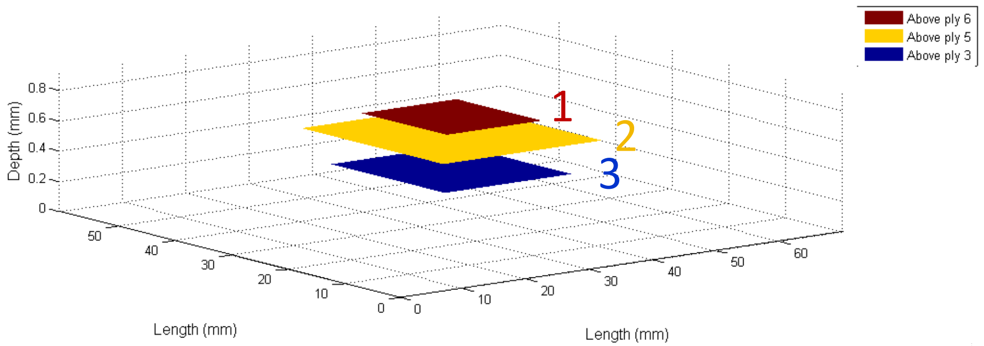
Michaels, Composite, *simulated* single delam

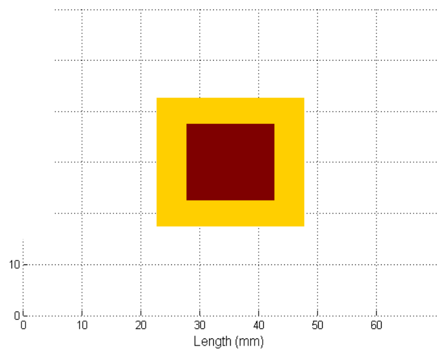


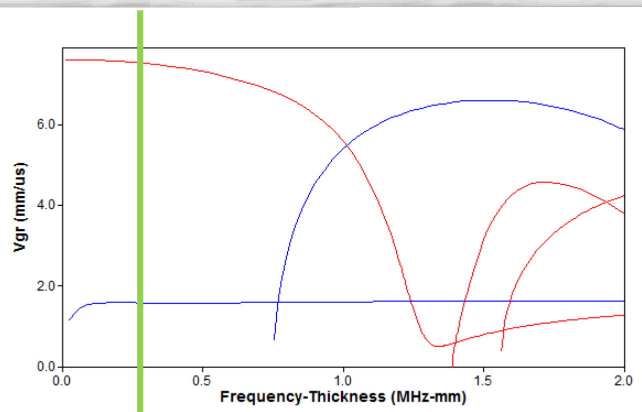
Michaels , J; Dawson, A ; Michaels, T ; Ruzzene, M. Proc. SPIE 9064, (2014); doi:10.1117/12.2045172.

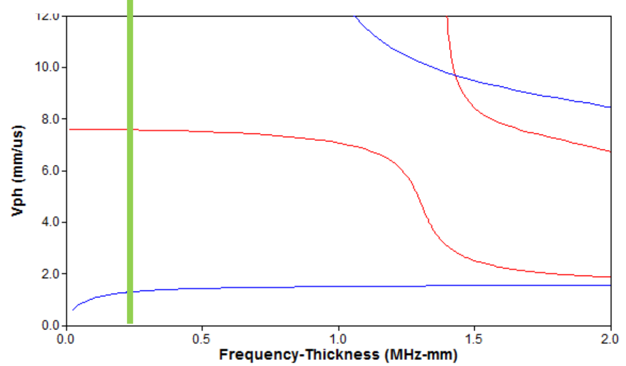
Energy Trapping Study

- Can energy trapping be leveraged for multi-ply delamination characterization?
- Simulation based study:
  - 8 ply, IM7/8552 CFRP sample $[(0/90)_2]_s$, 0.92 mm thick
  - 3 simple delamination cases: 1, 2, and 3 delaminations (+ pristine case)
  - 300 kHz, 3 cycle Hann windowed sine wave
  - dx=19 μm, dt analysis = 0.29 μs (dt/200)









Results

- Result for cases 2 and 3: wavefields visually appear the same from top surface

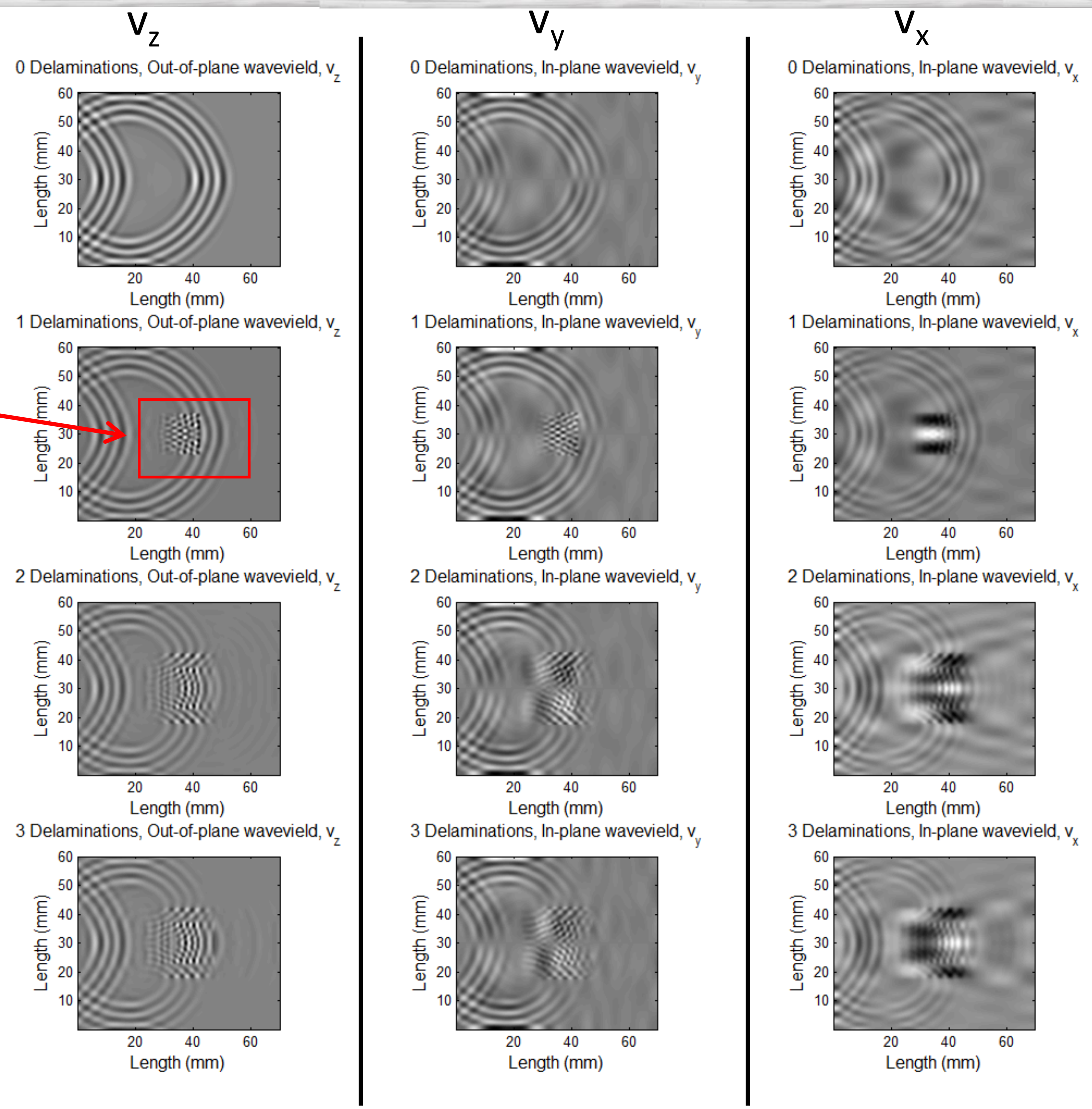
Energy trapping clearly observable

Pristine

Case 1

Case 2

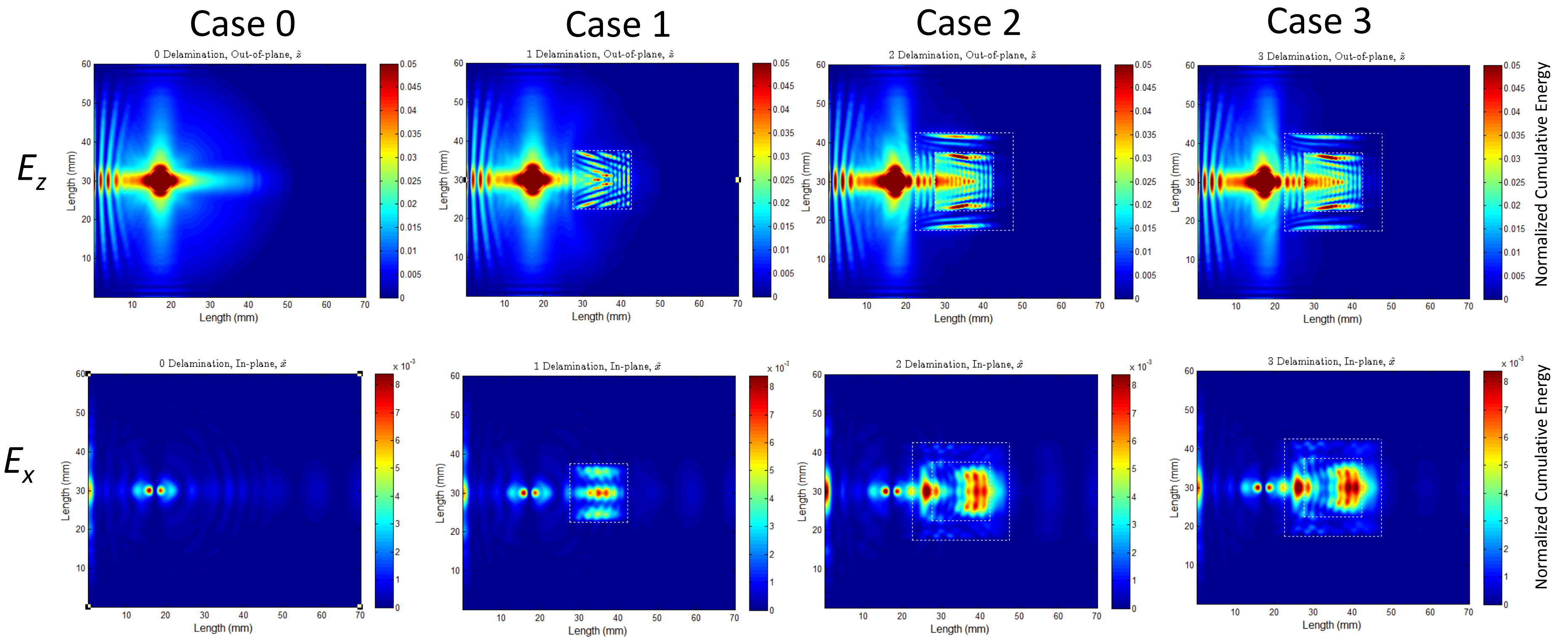
Case 3



Results

- Study difference in cumulative energy (KE) between cases, experimental work underway

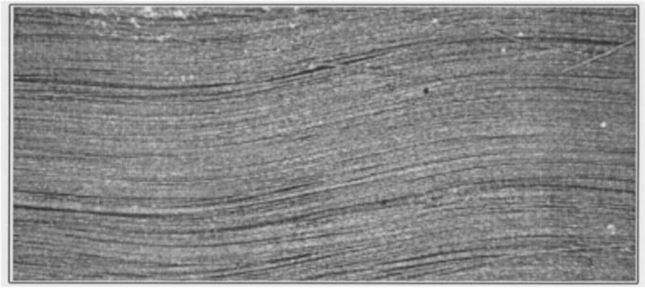
$$E_i(x,y,z,t) = \int_{t_1}^{t_2} \frac{1}{2} {v_i}^2 dt$$



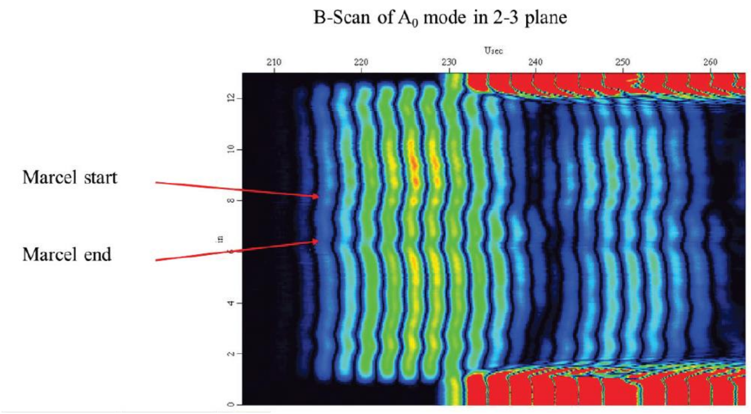
Guided waves: Fiber waviness

- Plans to study methods for guided wave based techniques to detect fiber waviness
- Literature reports changes in group velocity[1], 15˚ fiber wave → 4% change velocity (↓)
- Study other processing approaches, use LDV to image wave behavior

Fiber waviness (in-plane)



From: Kugler and Moon 2002
doi: 10.1177/0021998302036012575



From: [1]Chakrapani, et al. "Detection of in-plane fiber waviness in composite laminates using guided Lamb modes." *Rev Prog QNDE* Vol. 1581. No. 1. AIP Publishing, 2014.

Conclusion

- Characterization of composite defects, degradation, and damage is of-interest to NASA for aeronautics and space missions
- Advanced composites project currently focused on quantitative methods for aeronautics manufacturing and in-service defects
- LaRC NESB is performing and planning upcoming research into various ultrasonic composite characterization methods

Questions?