Secrets Beneath the Surface: The Use of Full Waveform Capture to Quantify Subsurface Features in Laminated Composites

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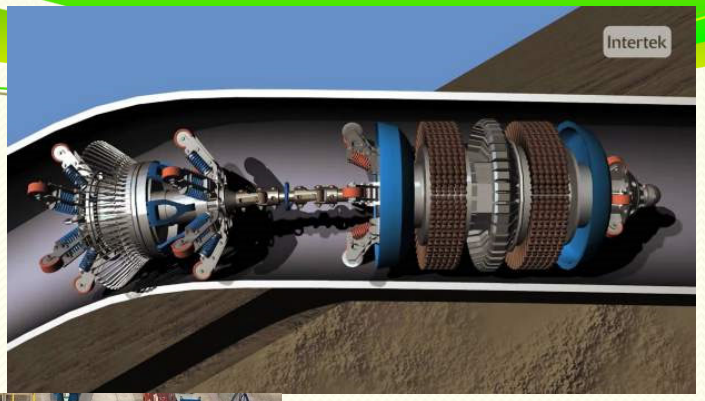
30,000 ft. View

- Want to modify a structure?
- Want to get component material properties?
- Don't have manufacturing documents?
- Only have one part?
- Components are expensive and time consuming to make?
- Properties could vary batch to batch?



[2] https://www.f35.com/news/detail/lockheed-martin-expanding-f-35-assembly-line-capacity-for-production-ramp-u

[3] https://www.greeleytribune.com/news/energy-pipeline-tech-talk-aliso-canyon-gas-leak-renews-pressure-on-pipeline-integrity-measures/

[4] https://www.sampack.com/blog-2019-chevrolet-corvette-offers-excellent-handling-tons-power/

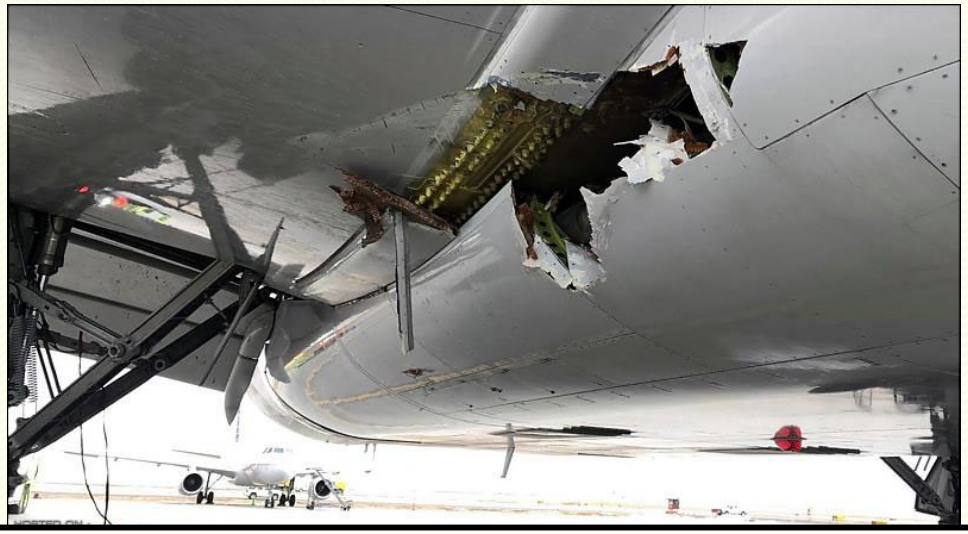
- Technician comes forward and says their tool fell and hit the composite structure, but there is no visible damage.
- Aircraft was left out in a hailstorm
- Desire to check a buried pipeline
- Uncontrolled shopping cart collides with passenger car door

[1] https://www.nasa.gov/content/nasa-declares-sofia-observatory-fully-operational

Non-Destructive Testing and Predictive Modeling

Types of Damage We Want to Prevent

Airbus A310 lost its carbon fiber vertical stabilizer from a gap in the composite that had passed inspection [1]



Impact damage from a "Rapid unscheduled disassembly" of an engine cowling over Denver [2]

Skin separation for Blackhawk blade [3]

[1] – Taken from NewScientist – Composite Aircraft may hide dangers, 22 Nov, 2007.

[2] Engine failure over Denver. https://www.team-bhp.com/forum/commercial-vehicles/233584-usa-engine-failure-united-airlines-boeing-777-a.html - Engine failure over Denver.

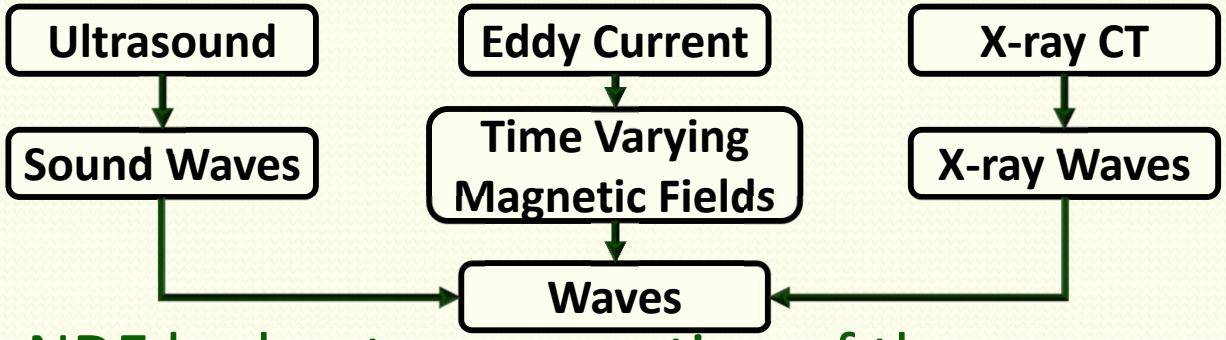
[3] – ArmyTimes, Dec 2014. Black Hawk rotor fails more than a mile high. Pilots land safely.

30,000 ft view of NDT/NDI/NDE/QNDE

- NDT/NDI/NDE/QNDE is the practice of detecting features of a part without altering the part itself. It is often, incorrectly, regulated to the detection of flaws and imperfections, but it may allow the qualification of the as-manufactured part behavior.
- NDT (nondestructive testing), NDI (nondestructive inspection), and NDE (nondestructive evaluation) are often used interchangeably. They are often used as a pass/fail philosophy of "detection". The question posed by the operator is often
  - "Can I **detect** a feature of a given size/type?"
- QNDE, quantitative nondestructive evaluation, changes the concept a bit to where the operator changes the question to:
  - "Can I **quantify** the size/type/number of features?"
- Baylor and Verifi Technologies approach inspection from the latter approach, and we extend the question to
  - "What is the size/type/number of features, and **what will their impact be** on the current and future part performance?"

Types of NDE at Baylor and Verifi

- We use several types of NDE methods



- Most NDE looks at some section of the wave and evaluates some characteristic of the wave over a gate

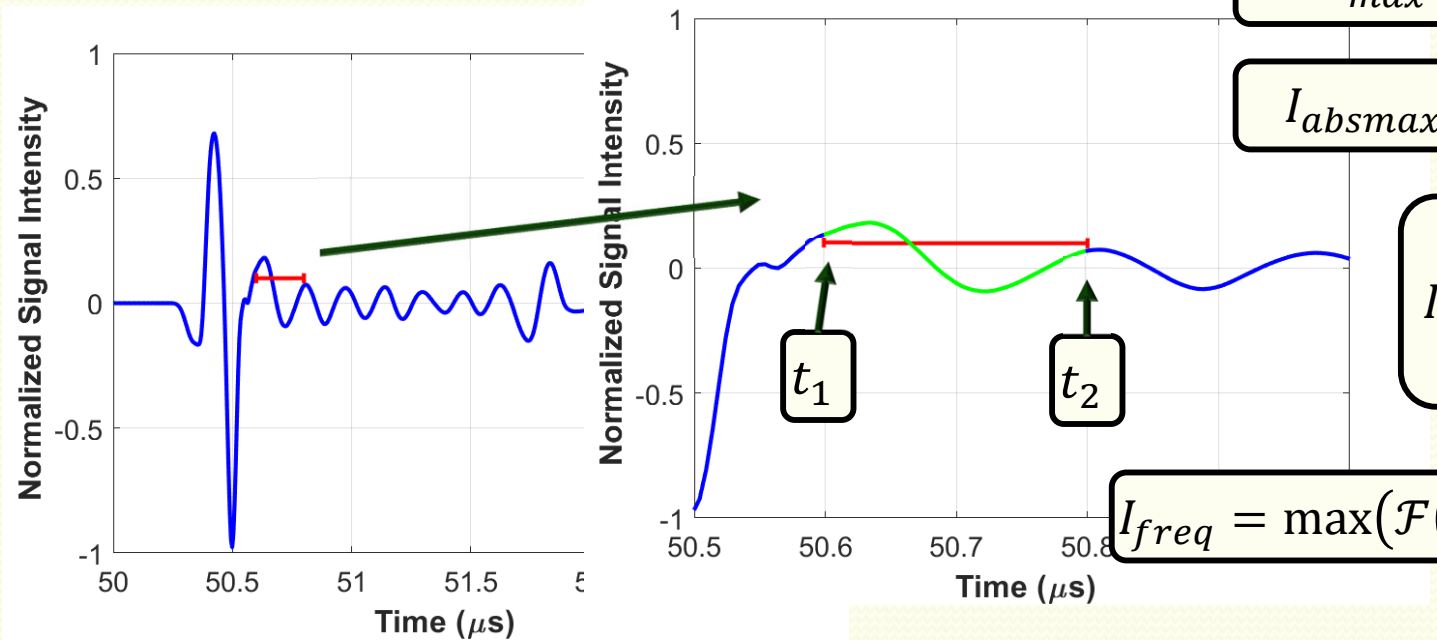
$$I_{1st} = \text{first}(f(t) > \delta, t \in \{t_1, t_2\})$$

$$I_{max} = \max(f(t), t \in \{t_1, t_2\})$$

$$I_{absmax} = \max(|f(t)|, t \in \{t_1, t_2\})$$

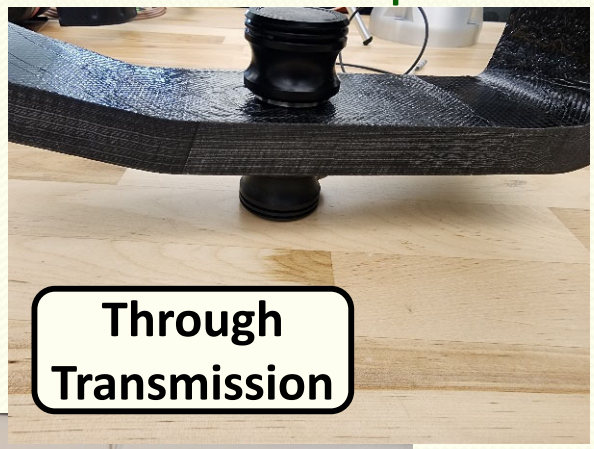
$$I_{energy} = \int_{t_1}^{t_2} f(t)^2 dt$$

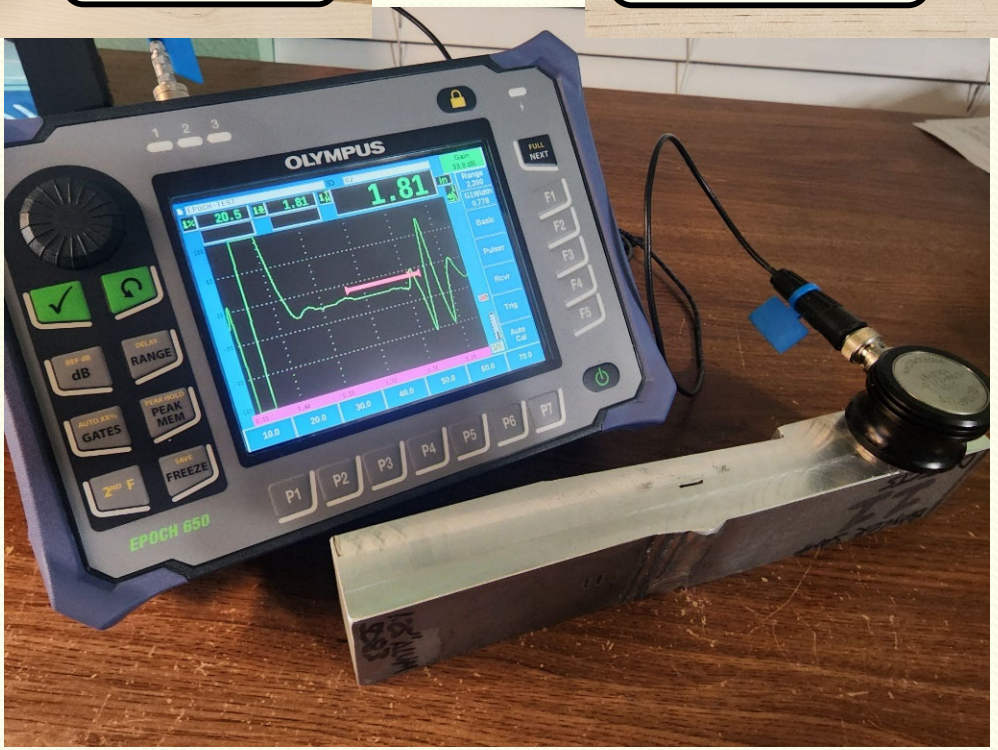
$$I_{freq} = \max\left(\mathcal{F}\left(f(t)\right)(s), t \in \{t_1, t_2\}, s \in \mathbb{R}^+\right)$$



What is Ultrasound?

- Ultrasound uses high-frequency sound energy often generated by a piezo-electric element connected to a digitizer
- Two primary methods, through transmission and pulse-echo





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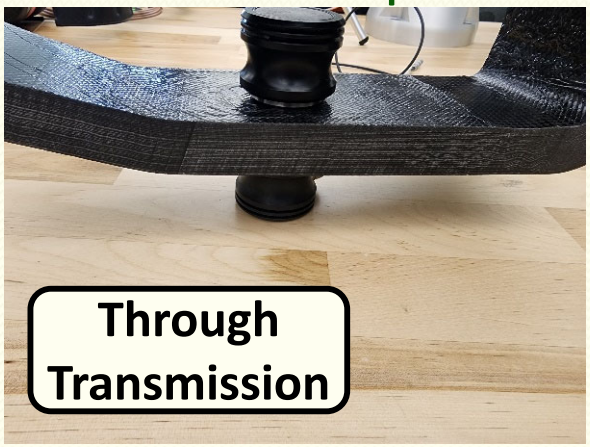
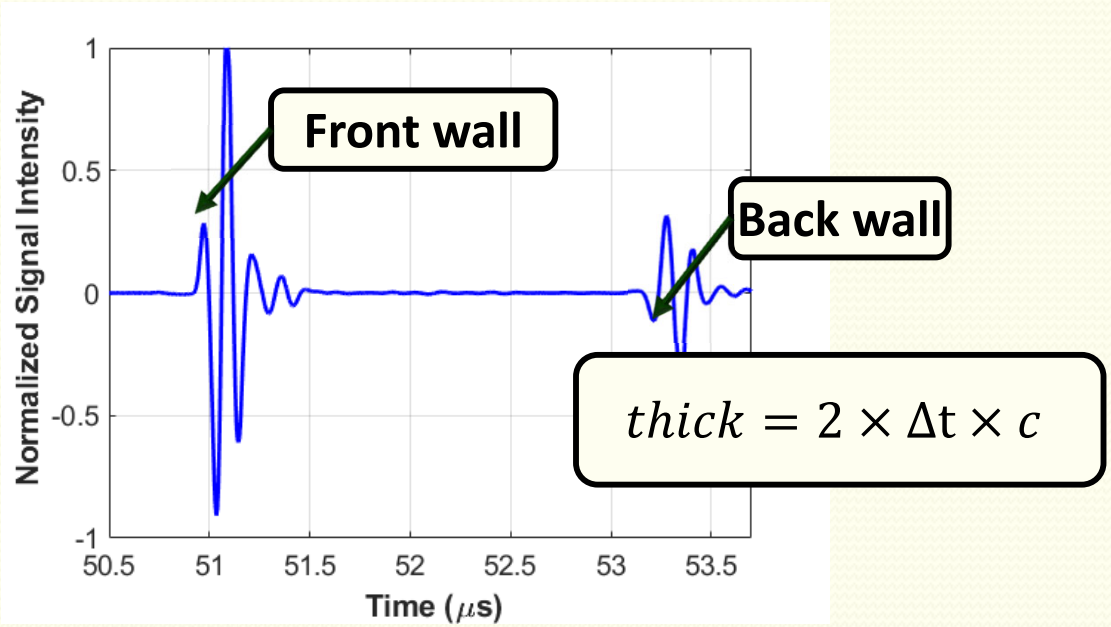
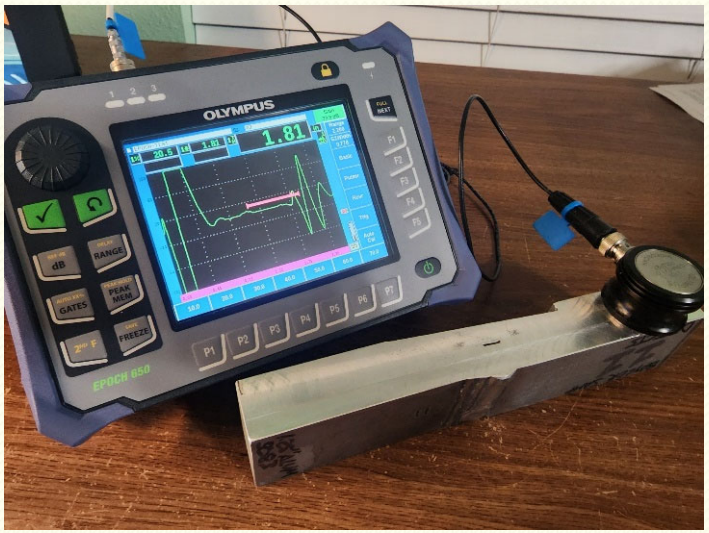


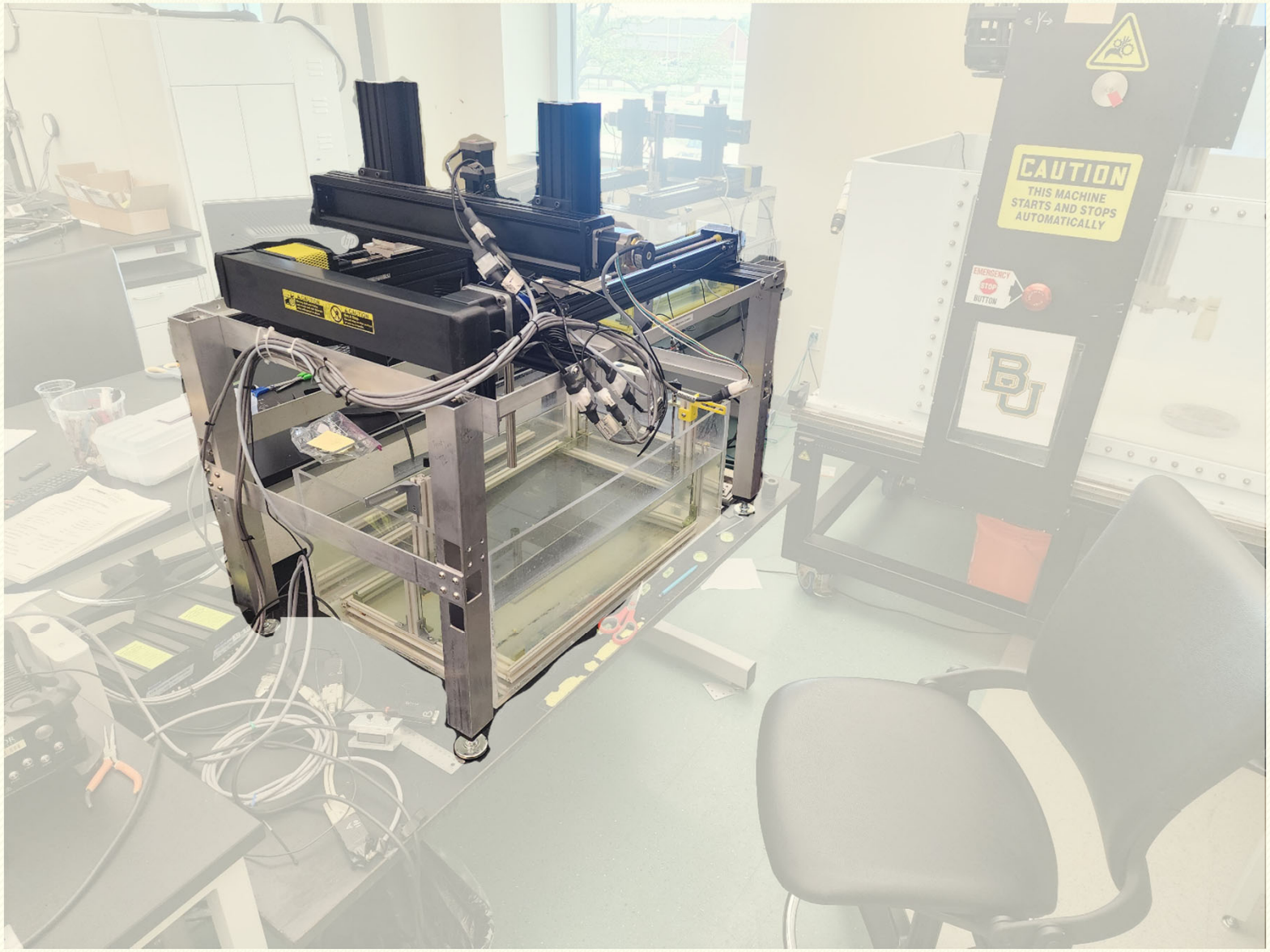
- Great for measuring flat-bottom holes, cracks, part thickness.





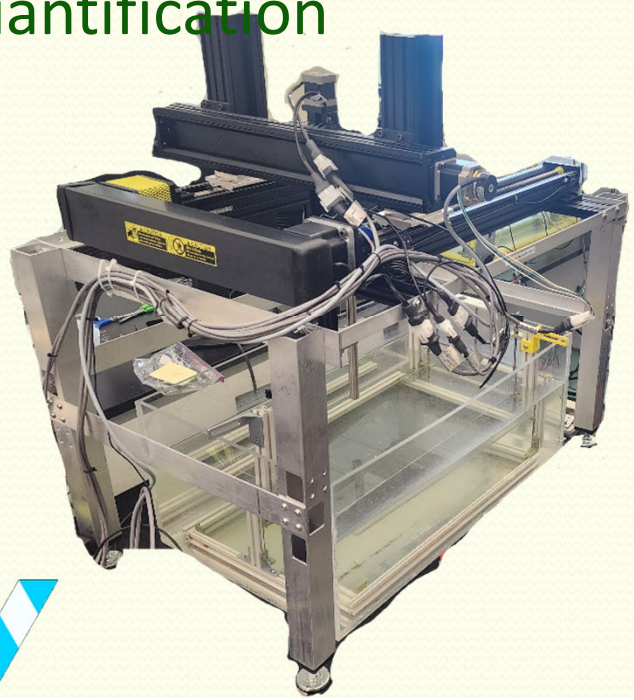
Data Collection System

- Sound travels quite well in water. So, for the best quality images the part is submerged in water



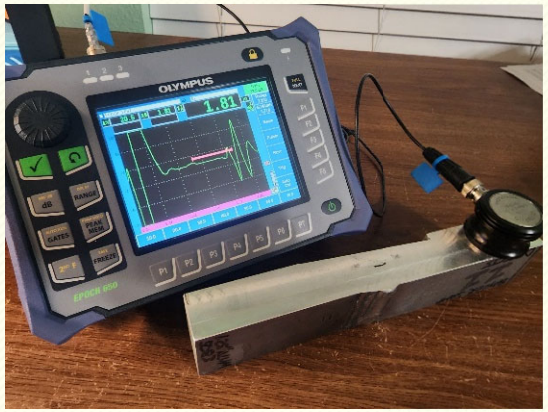
Data Collection System

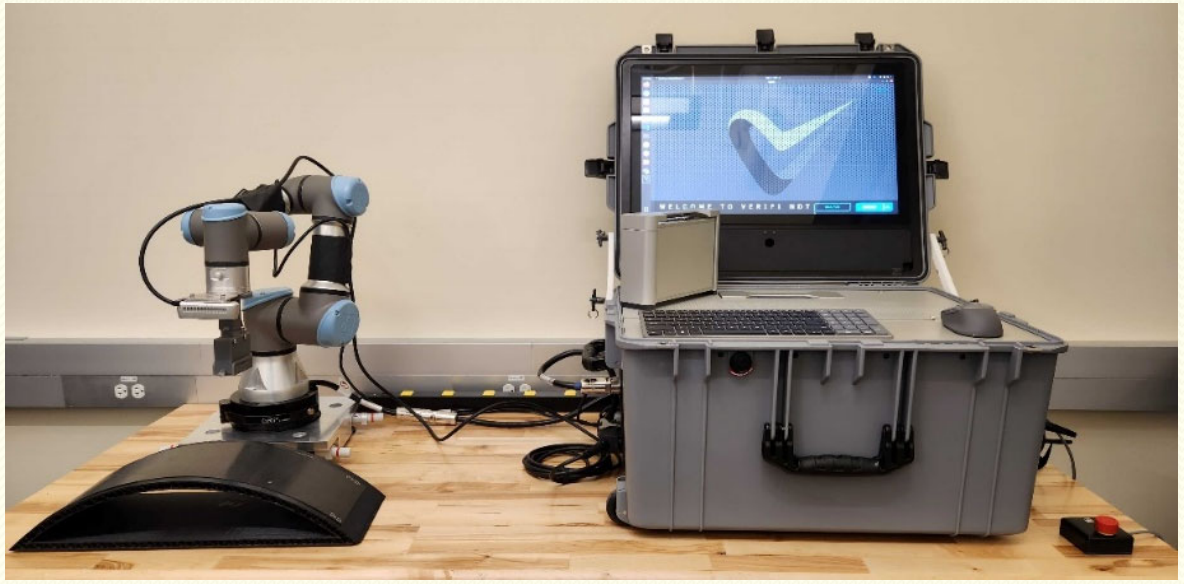
- Sound travels quite well in water. So, for the best quality images the part is submerged in water
- This also allows us to go from the low-resolution flat-front, contact transducers to high resolution spherically focused transducers or even phased array systems
- Immersion scanning enables quantification



Data Collection System

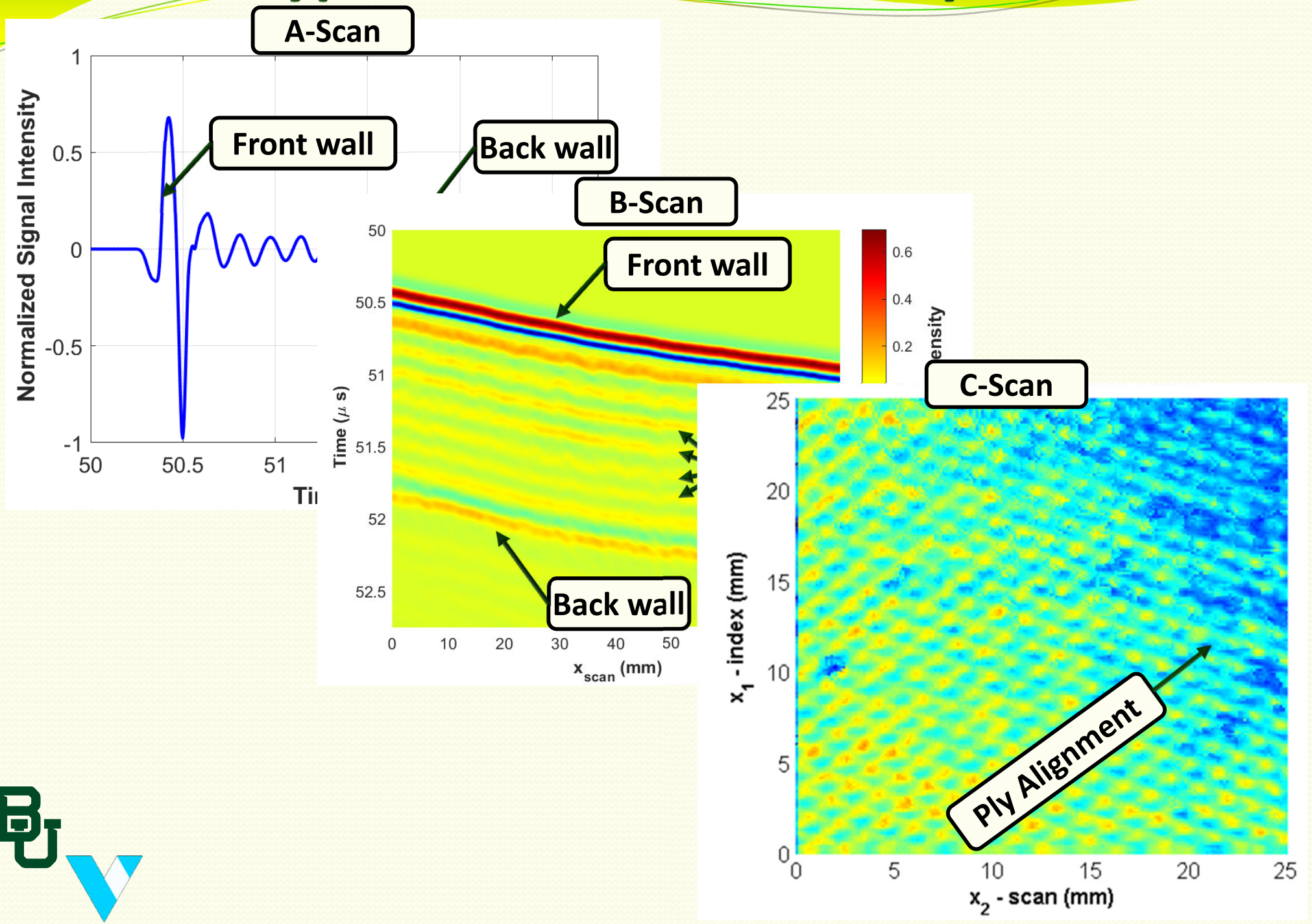
- Handheld systems are convenient, but limited by poor resolution and by near-surface features
- Immersion systems have high resolution capabilities, but are limited by the need to submerge a part in water
- We have developed the patented and patent pending system, termed the ANDE
  - Field portable
  - Manufacturing environment
  - No need for immersion tank, only a light mist
  - From setup to data collection, it takes ~ 15 minutes to capture and analyze a data source





Typical Sequence of Operations for Inspection

Types of Ultrasonic Analysis



Manufacturing Inspection – Ply Orientation

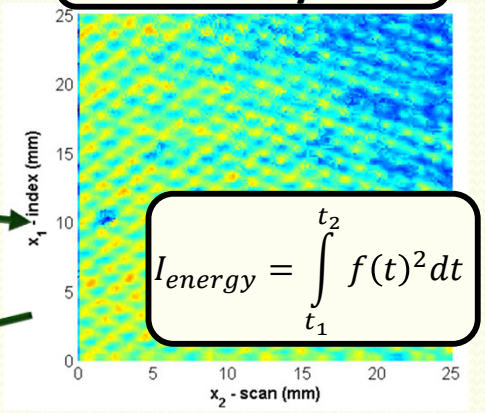
- The composite laminate's structural performance is a function of the number of plies and the relative alignment of each lamina
- The final part performance will depend upon
  - Lamina type and material
  - Subtle changes in the orientation
  - Missing plies
  - Misplaced plies
- This study quantifies the orientation of each individual ply within a laminated composite
  - **The inspection approach has received an FAA 8100-9 Statement of Compliance with Airworthiness Standards**
  - **The approach has an accuracy of $\pm 2^\circ$ for 98% of the lamina inspected**

Manufacturing Inspection – Ply Orientation

Fabricate Coupon

Inspect Part

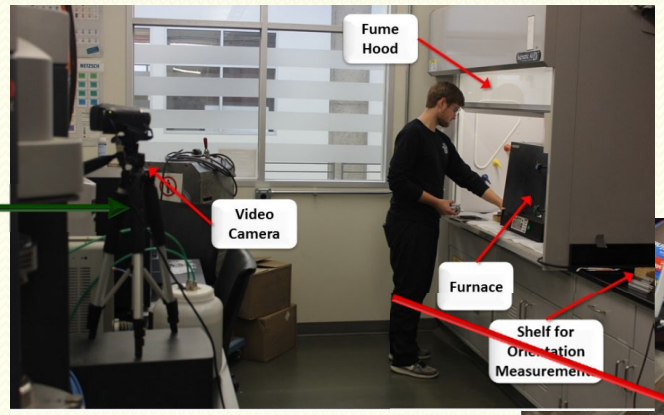
Extract Waveform to Analyze

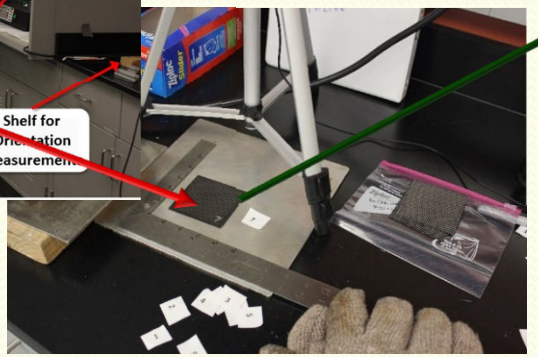


2D Transform in Spatial Domain to Quantify Orientation

Ply #	θ_i (deg)
1	14
2	68
3	2
…	…
N	30

Validation by Thermal Digestion



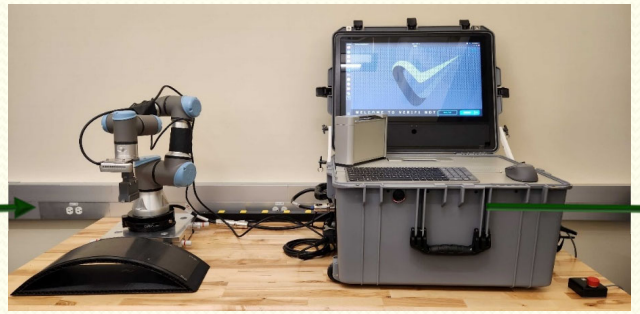


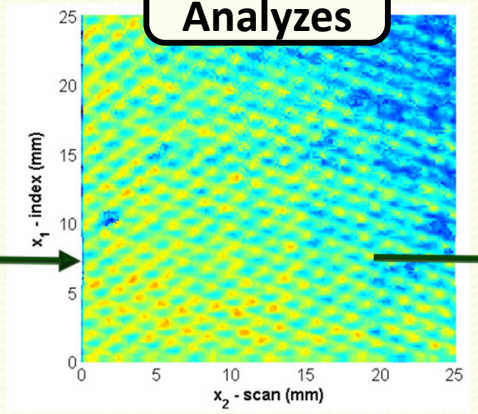
Check Accuracy

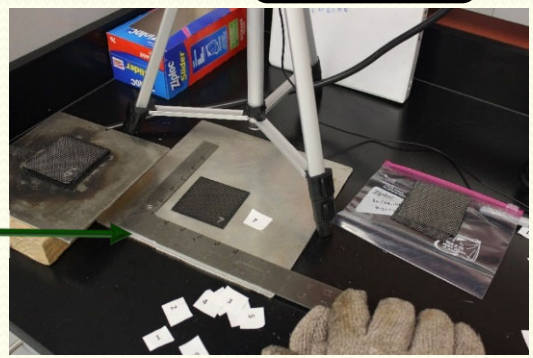
Ply #	θ_i - NDI	θ_i Mfg.
1	14	15
2	68	71
3	2	1
…	…	
N^{th} Lamina	30	31

Manufacturing Inspection – Ply Orientation

Fabricate Coupon → **Inspect Part** → **Waveform Analyzes** → **Validation**







- Full study includes: woven carbon fiber laminates, 3 – 18 lamina coupons, environmental conditioning for > 90 days, inspection in the relevant environment

Number of Lamina (Plies)	CTD Test – Conducted at 40F, RH 20%	CTW Test – Conducted at 40F, RH 80%	RT Test – conducted at 70F, RH 50%	ETC Test – Conducted at 105F, RH 20%	ETW Test – Conducted at 105F, RH 80%	# Tests
3	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	80
6	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	80
9	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	80
12	26 ply stacks	26 ply stacks	26 ply stacks	26 ply stacks	26 ply stacks	130
15	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	16 ply stacks	80
18	17 ply stacks	17 ply stacks	17 ply stacks	17 ply stacks	17 ply stacks	85
Total # Tests						535

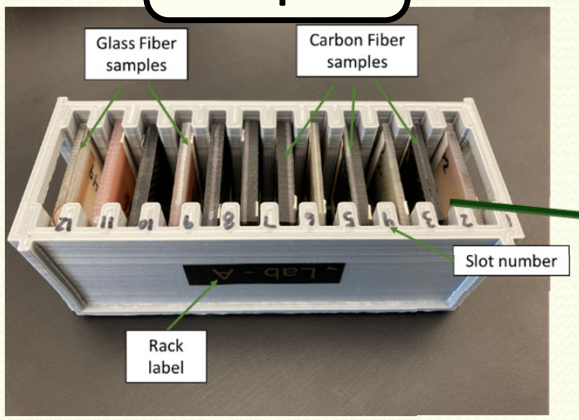
- **Currently sitting at a >98% accuracy to within $\pm 2^{o}$**

Manufacturing Inspection – Bondline Qualification

- Many manufactured composite laminates are bonded to each other or to a structure using an adhesive
- Knowledge of the domain of the adhesive, thickness, and any defects (i.e., weak bonds or kissing bonds) is essential for confidence in the final part performance
- The final part performance will depend upon
  - Adhesive type
  - Adhesion bonding
  - Adhesive thickness
  - Adhesive surface area
- This study quantifies the spatial variations of the adhesive thickness between panels
  - **The inspection approach has received an FAA 8100-9 Statement of Compliance with Airworthiness Standards**
  - **The approach has an accuracy of ± 0.0034"± 0.002" over all 660 coupons**
  - Approach was validated for carbon-carbon composite, fiberglass-fiberglass composite, and aluminum-aluminum bonded panels

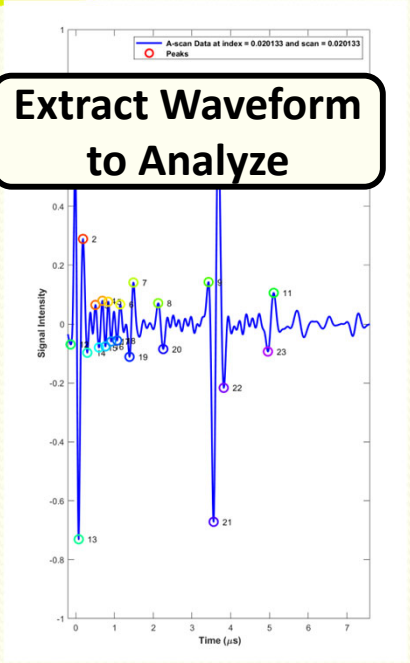
Manufacturing Inspection – Bondline Qualification

Fabricate Coupon

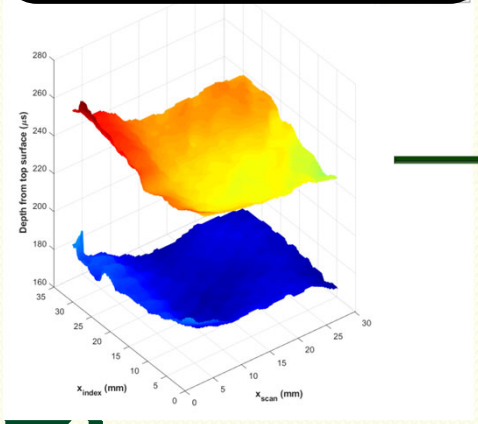


Inspect Part

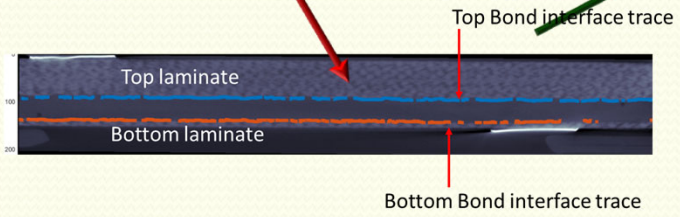
Extract Waveform to Analyze



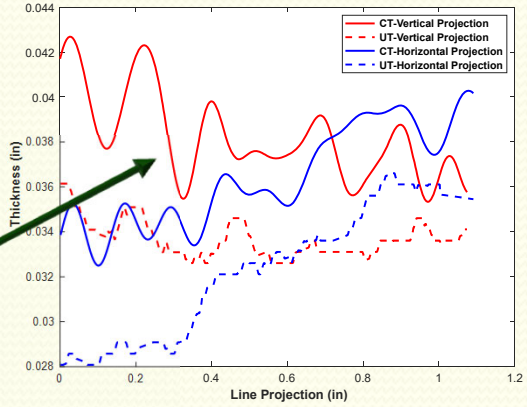
Automated Extraction of the Adhesive Surfaces



Validation by X-ray CT

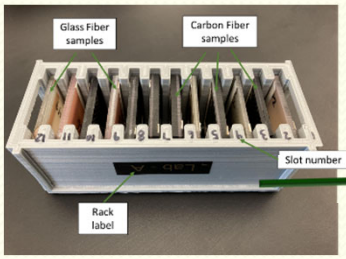


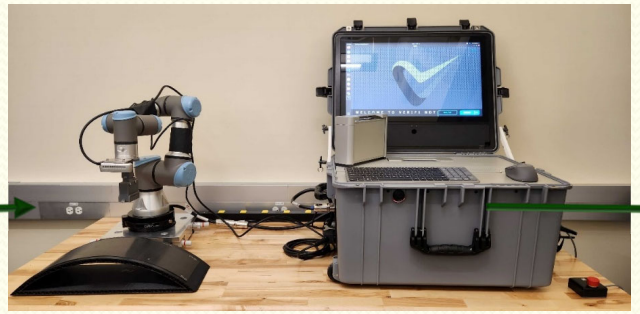
Check Accuracy

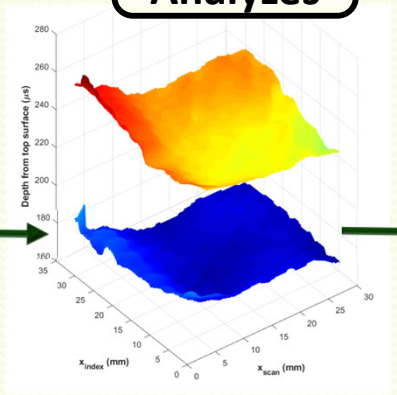


Manufacturing Inspection – Bondline Qualification

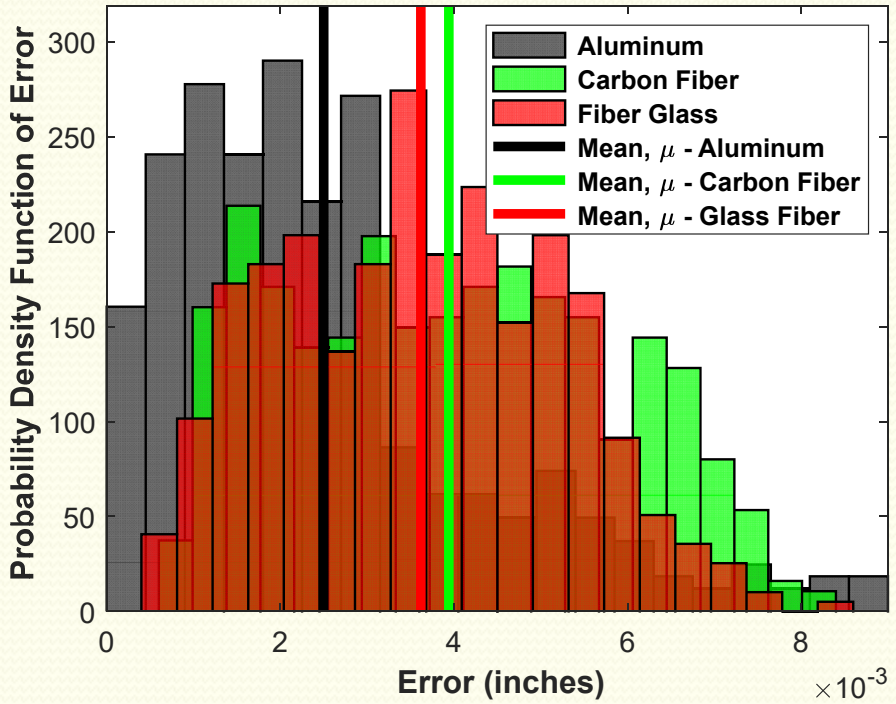
Fabricate Coupon → **Inspect Part** → **Waveform Analyzes** → **Validation**







- Full study includes
  - Carbon fiber, fiberglass and aluminum bonded coupons
  - 660 total coupons
  - adhesive thickness from 0.004”-0.060”
  - Single side thickness of 3 ~ 18 lamina
  - Environmental conditioning for > 90 days
  - Conditions of 4°C ~ 50°C and 10%RH ~ 90%RH
  - Inspection in the relevant environment
  - **Accuracy of ± 0.0034”± 0.002”**

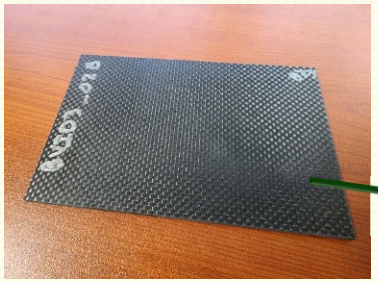


In-Service Inspection – Barely Visible Impact Damage

- Composites are susceptible to service induced impact damage
  - Bird-Strike
  - Hail impact
  - Worker tool impact
  - FOD from ground surface
  - Etc.
- Knowledge of the geometry of the 3D damage zone will allow for proper decisions for when and where to repair
- This study quantifies the damage zone layer-by-layer for carbon fiber composite panels
  - **The inspection approach is completing an FAA 8100-9 Statement of Compliance with Airworthiness Standards (est. June 2023 finish)**
  - **The approach was successful in identifying and quantifying the 3D damage zone for every single panel**
  - Approach was validated using X-ray CT

In-Service Inspection – Barely Visible Impact Damage

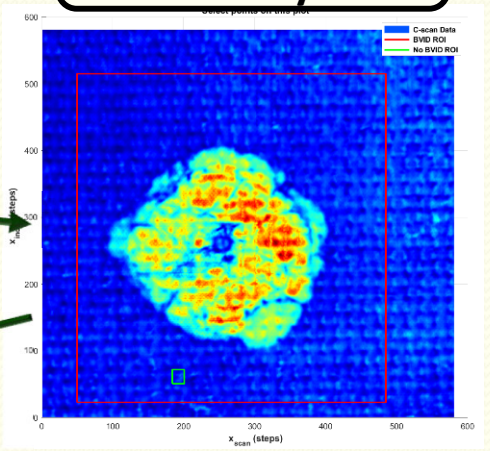
Fabricate Coupon



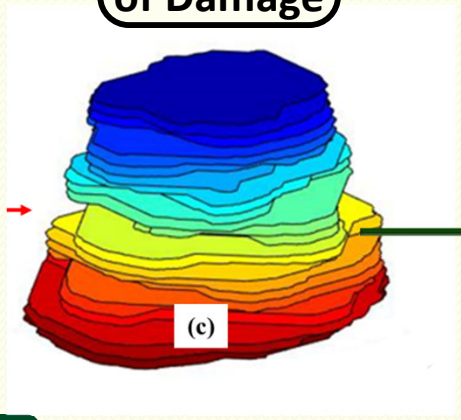
Impact Part

Inspect Part

Extract Waveform to Analyze

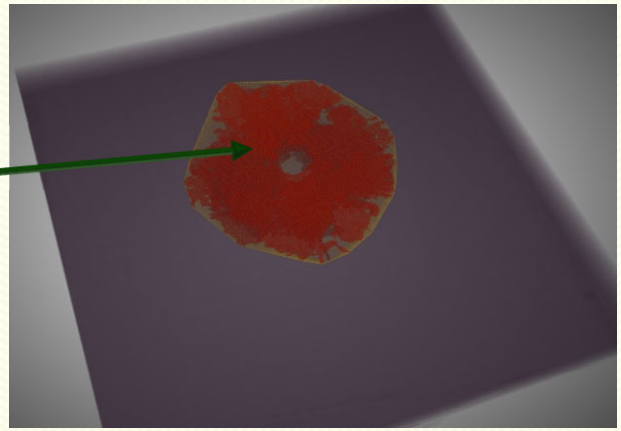


Automated Extraction of Damage



Validation by X-ray CT

Check Accuracy



In Service Inspection – Barely Visible Impact Damage

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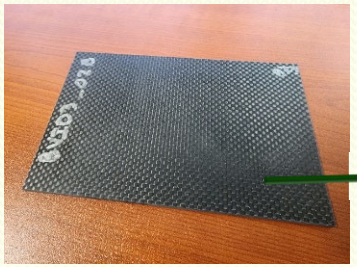
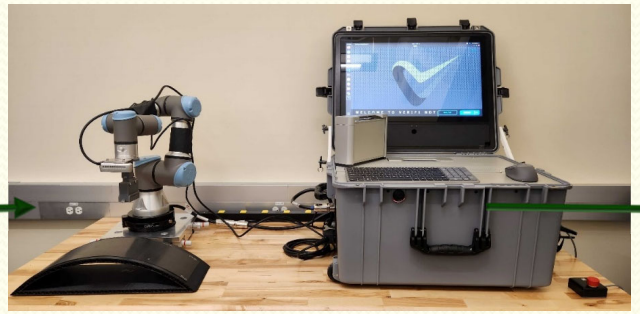
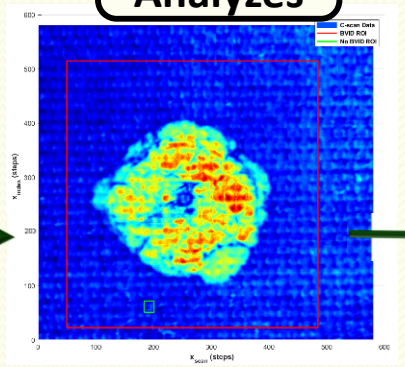


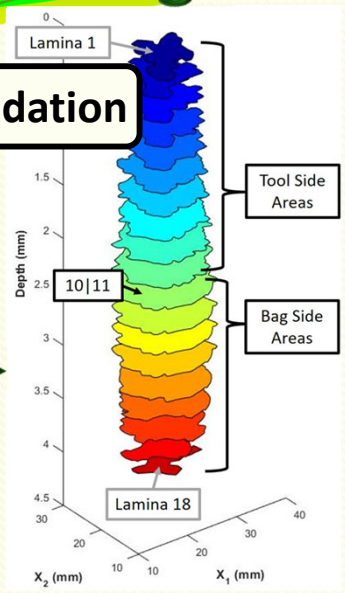
Inspect Part



Waveform Analyzes



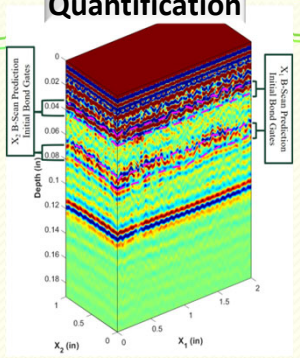
Validation



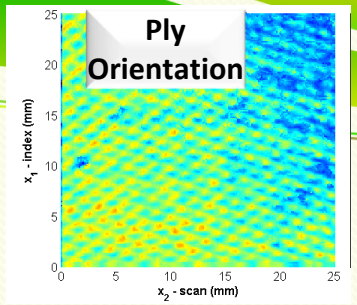
- Full study includes
  - Hybrid carbon fiber panels
  - 45 total coupons
  - Damage ranges from low, 8J – “undetectable”, to 16J “detectable”
  - Method goes beyond detection and quantifies the region of damage as a function of depth
  - Environmental conditioning for > 90 days
  - Conditions of 4°C ~ 50°C and 10%RH ~ 90%RH
  - Inspection in the relevant environment
  - **Accuracy of ? ? ?**

Need image from Dr. Pulipati or Dr. Kokkada

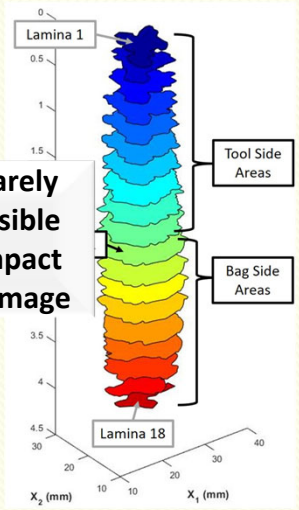
Bondline Quantification



Ply Orientation

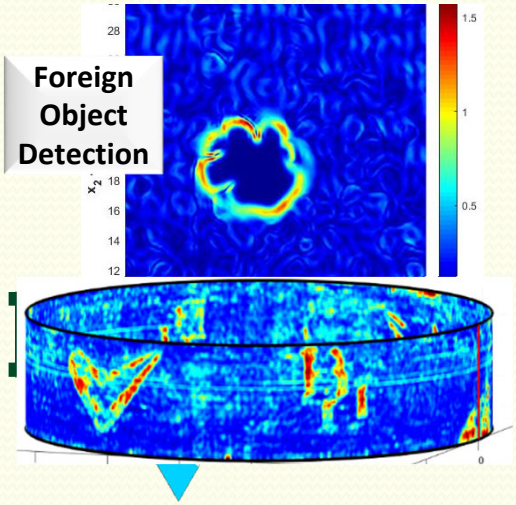


Barely Visible Impact Damage

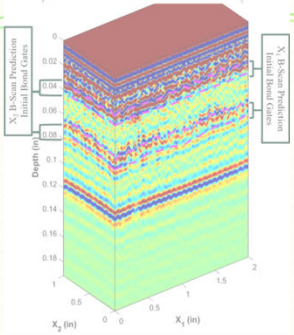


What else can we see?

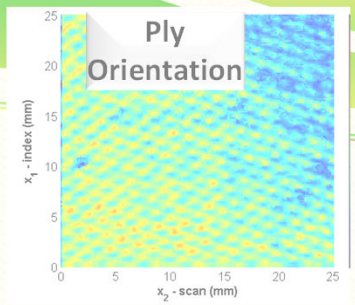
Foreign Object Detection



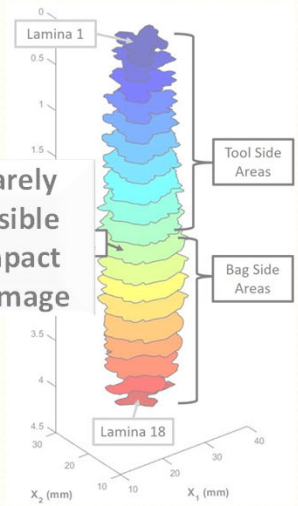
Bondline Quantification



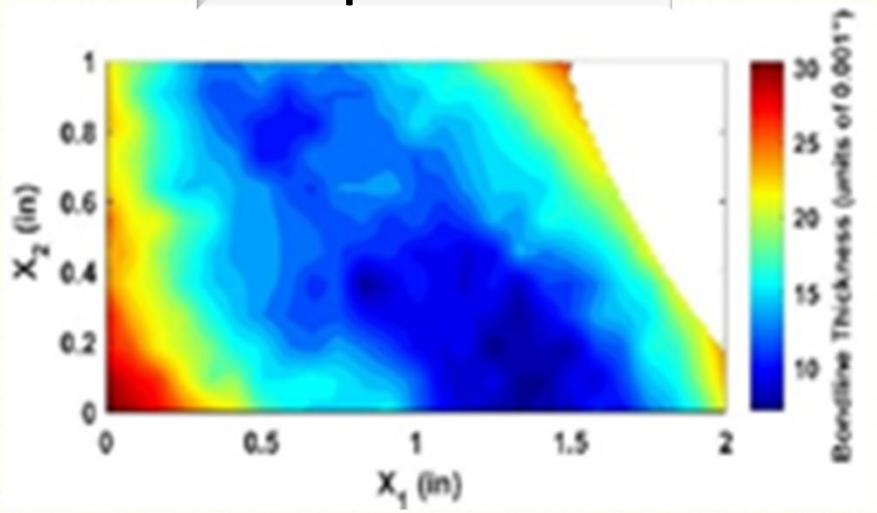
Ply Orientation



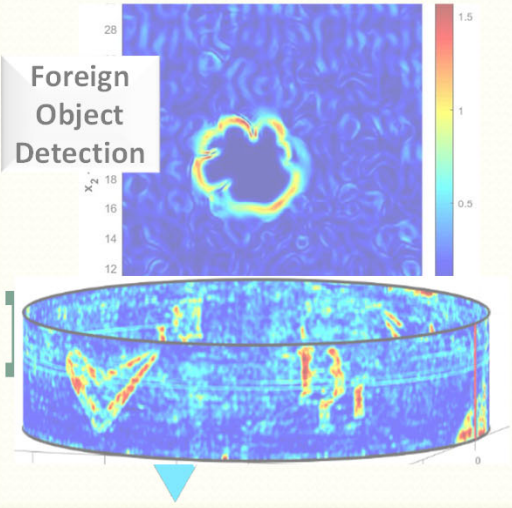
Barely Visible Impact Damage



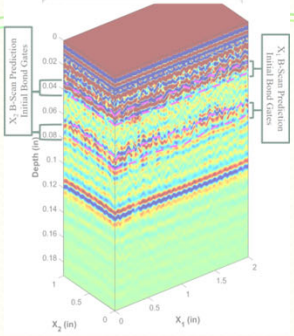
Incomplete Bondline



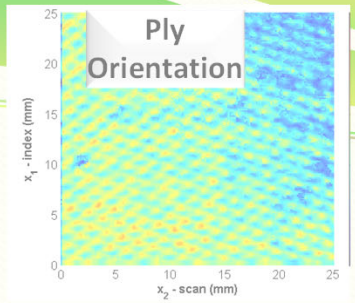
Foreign Object Detection



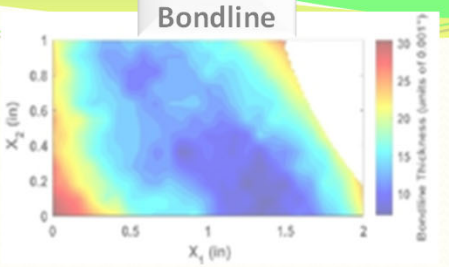
Bondline Quantification



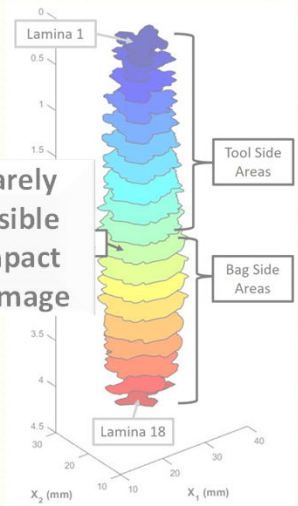
Ply Orientation



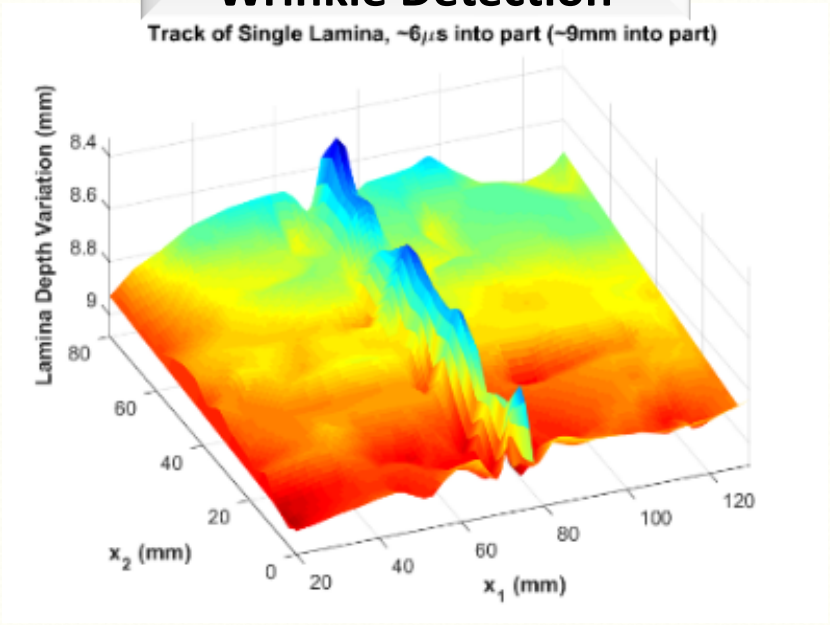
Incomplete Bondline



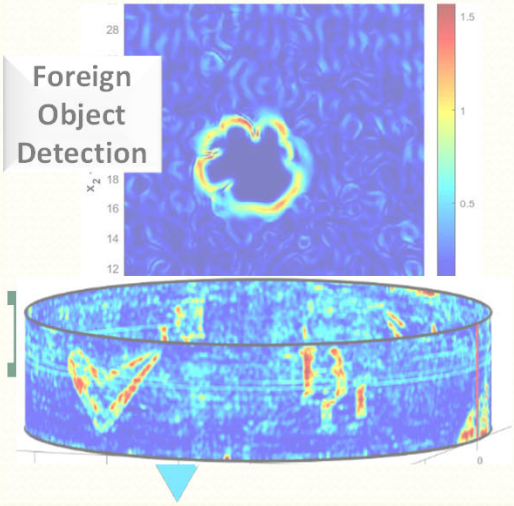
Barely Visible Impact Damage



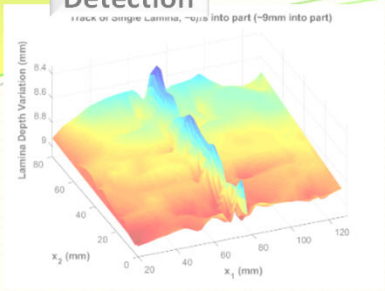
Wrinkle Detection



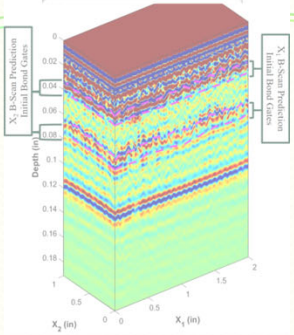
Foreign Object Detection



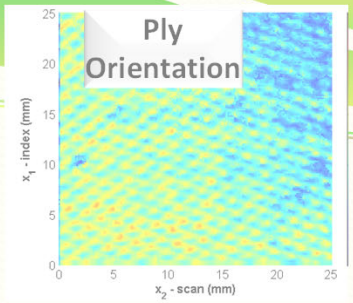
Wrinkle Detection



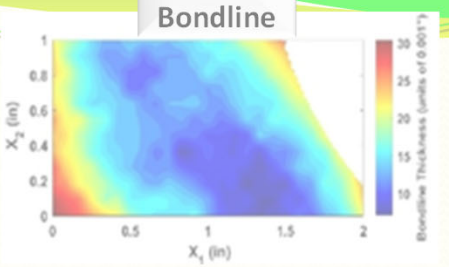
Bondline Quantification



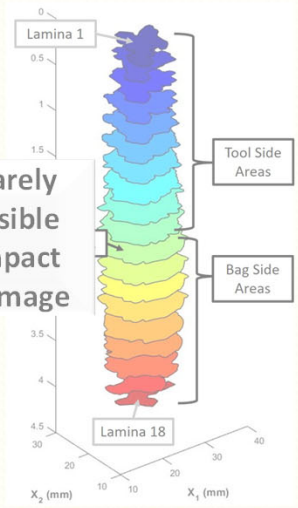
Ply Orientation



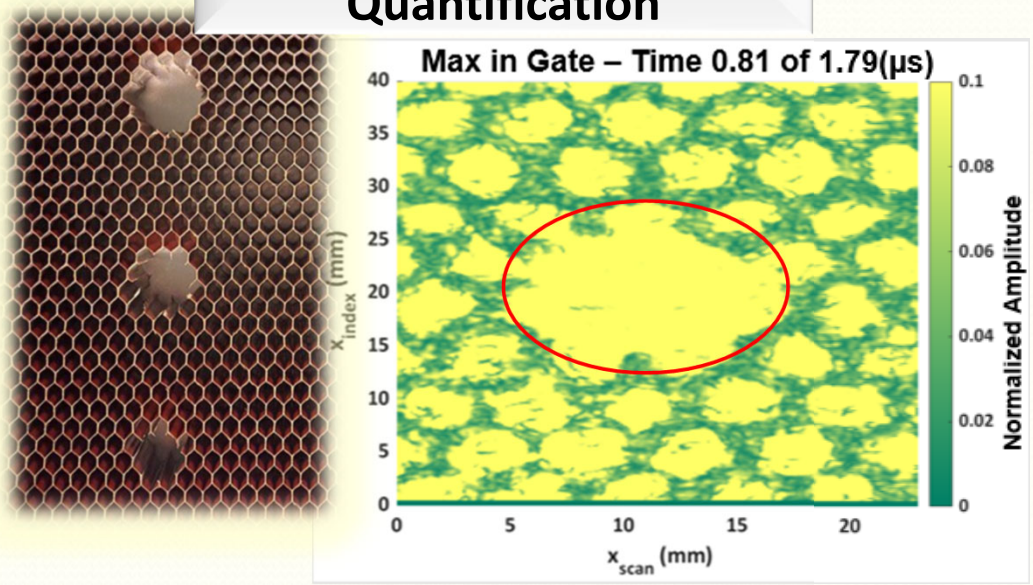
Incomplete Bondline



Barely Visible Impact Damage



Honeycomb Adhesion Quantification



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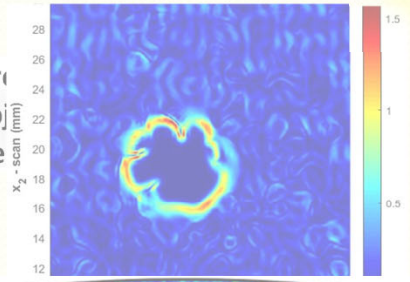
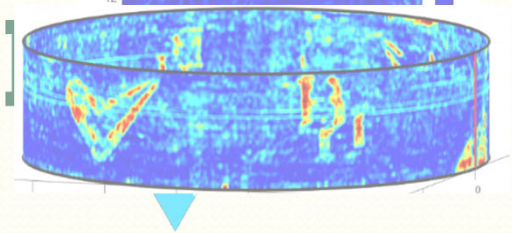
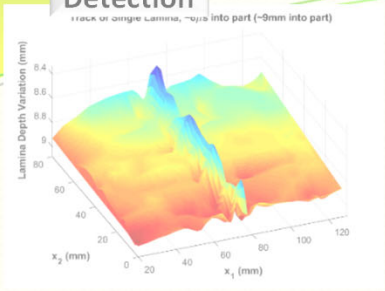
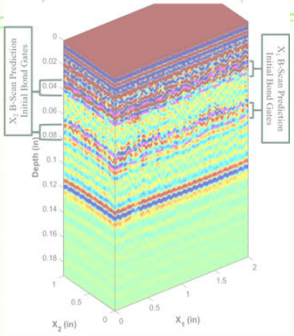




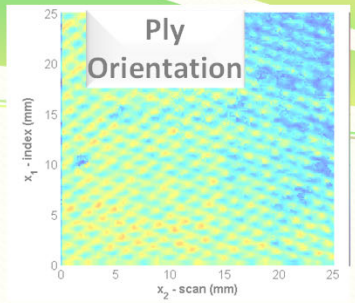
Wrinkle Detection



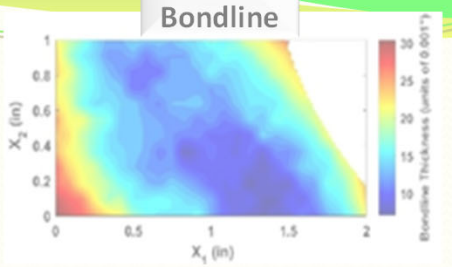
Bondline Quantification



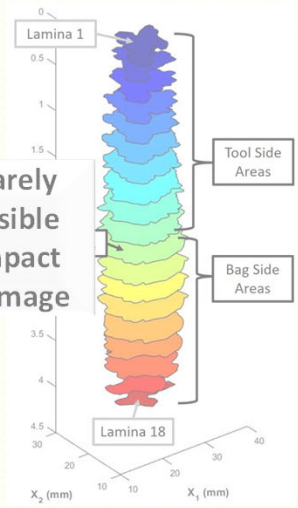
Ply Orientation



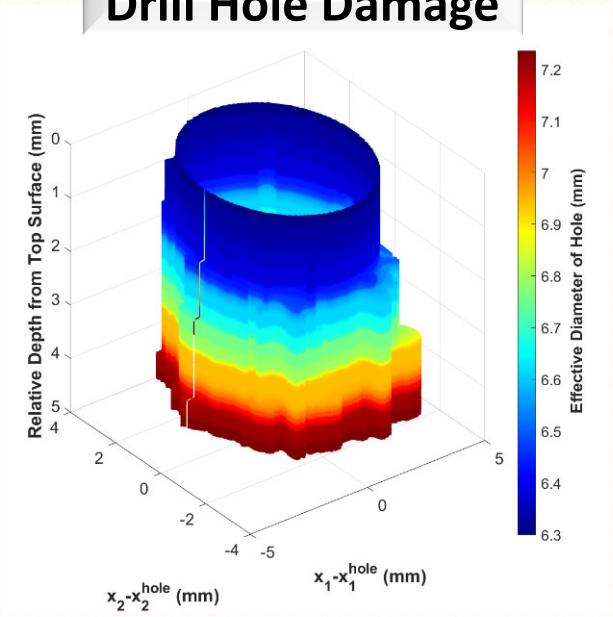
Incomplete Bondline



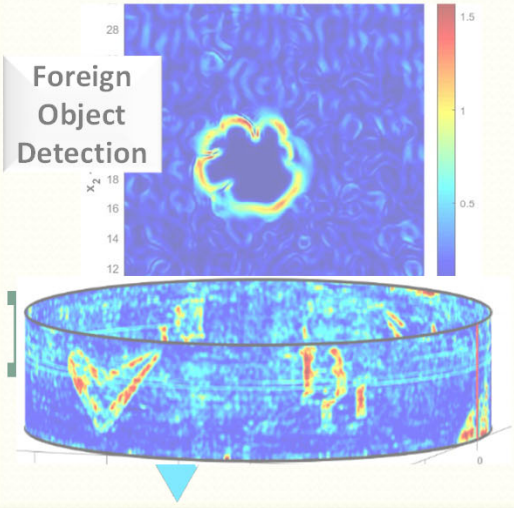
Barely Visible Impact Damage



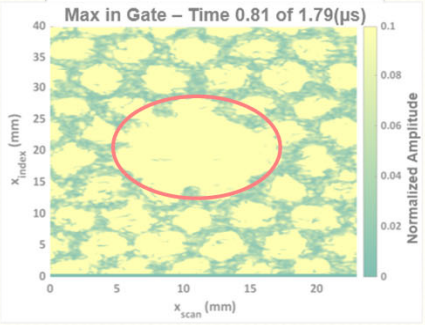
Drill Hole Damage



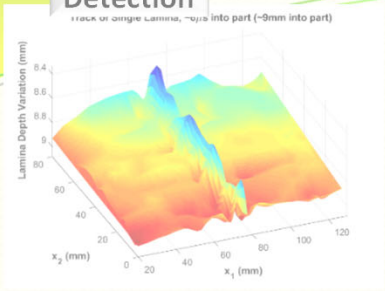
Foreign Object Detection



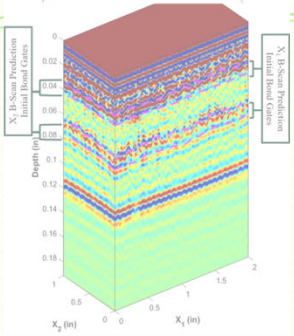
Honeycomb Adhesion Quantification



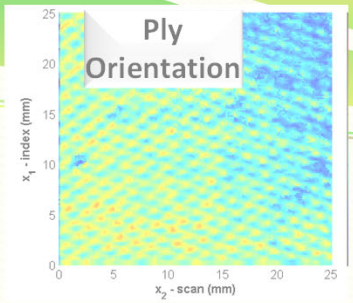
Wrinkle Detection



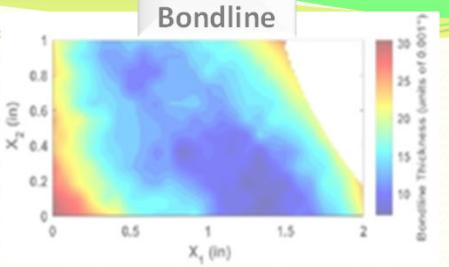
Bondline Quantification



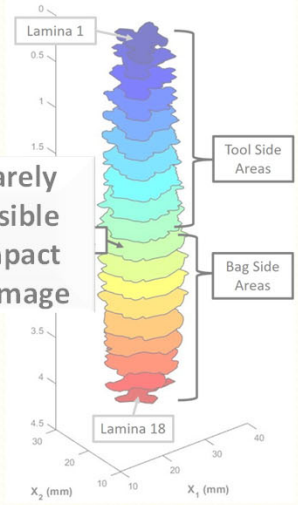
Ply Orientation



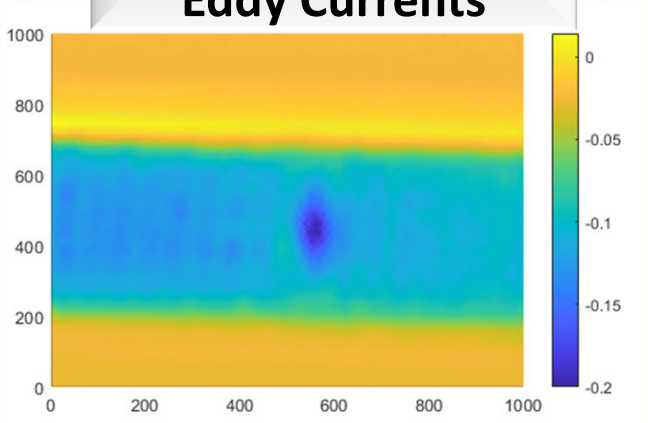
Incomplete Bondline



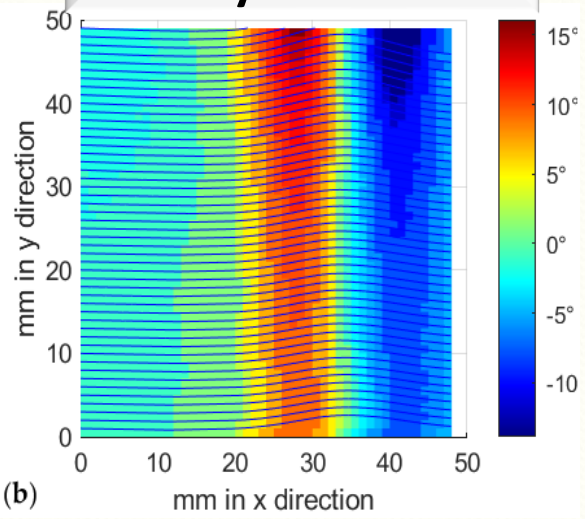
Barely Visible Impact Damage



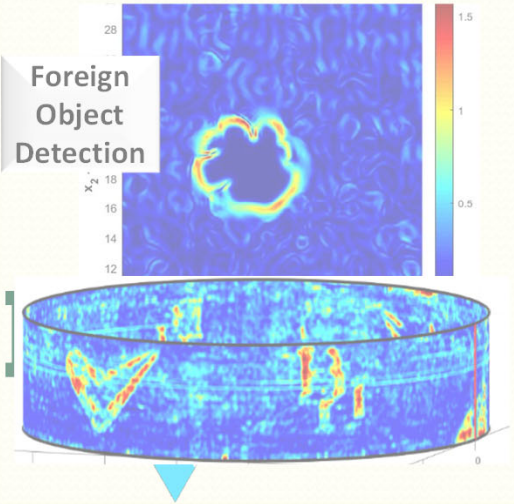
Sub-surface Cracks in Composites Using Eddy Currents



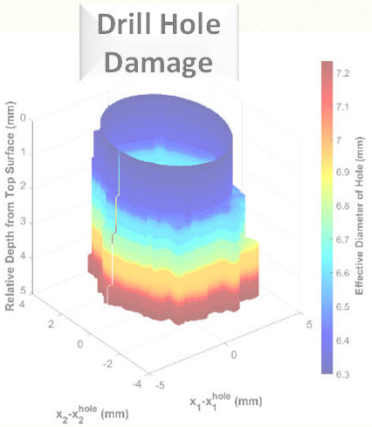
Marcelling Using Eddy Currents



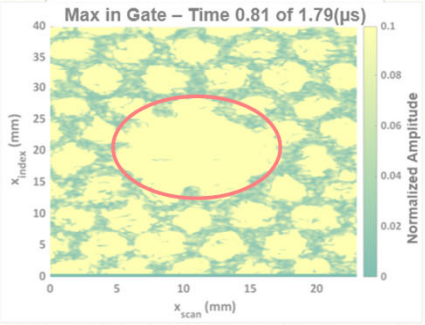
Foreign Object Detection



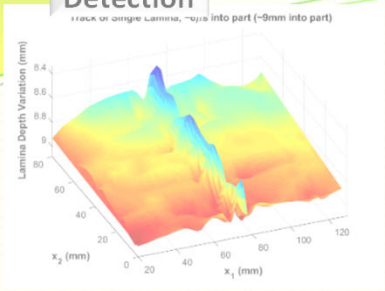
Drill Hole Damage



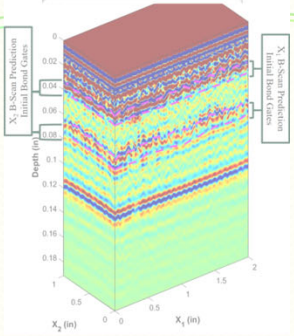
Honeycomb Adhesion Quantification



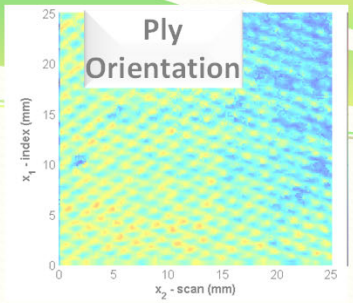
Wrinkle Detection



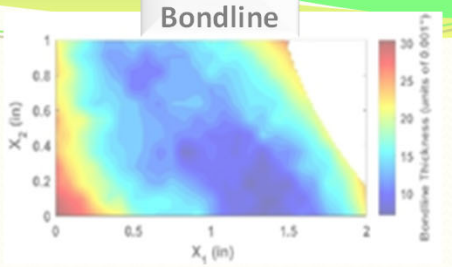
Bondline Quantification



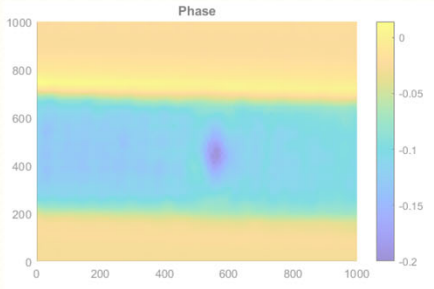
Ply Orientation

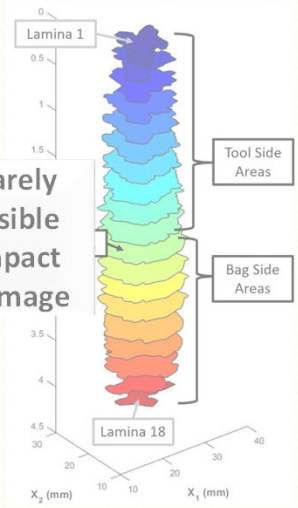


Incomplete Bondline



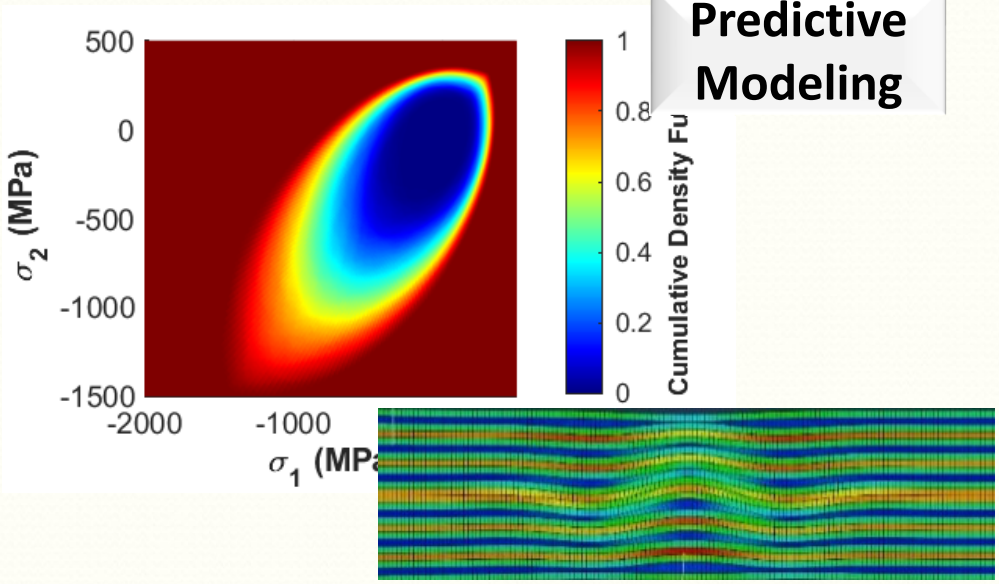
Sub-surface Cracks in Composites Using Eddy Currents



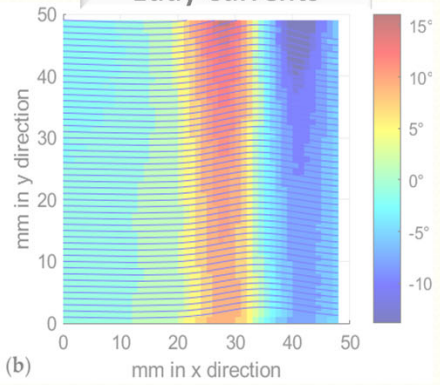


Barely Visible Impact Damage

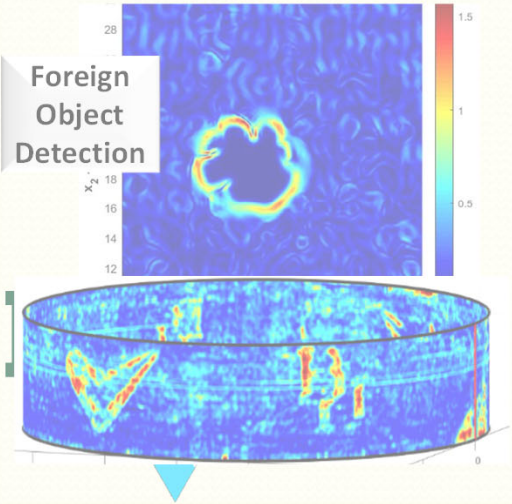
Predictive Modeling



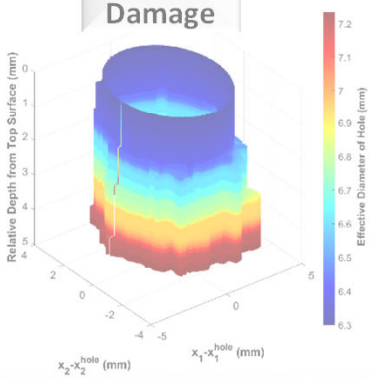
Marcelling Using Eddy Currents



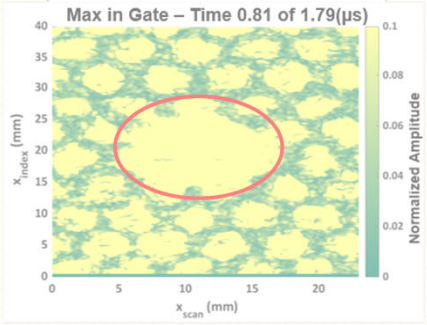
Foreign Object Detection



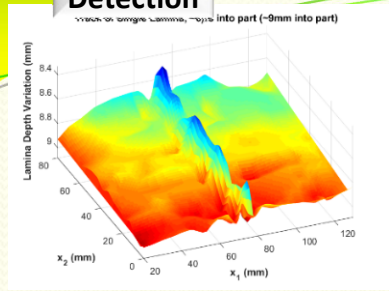
Drill Hole Damage



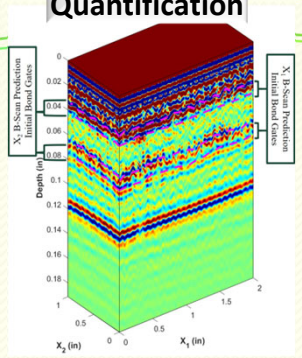
Honeycomb Adhesion Quantification



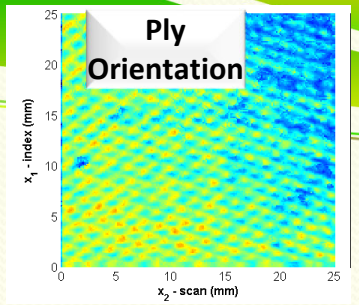
Wrinkle Detection



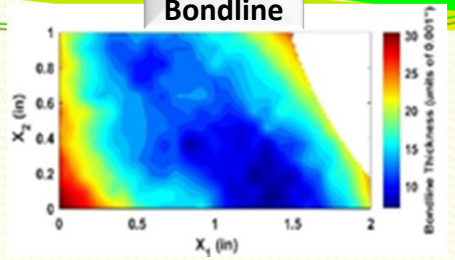
Bondline Quantification



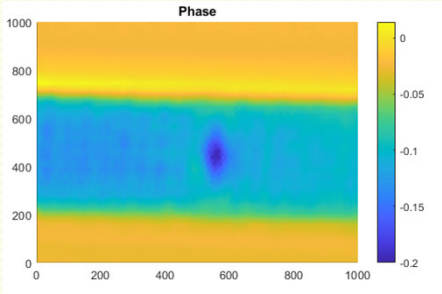
Ply Orientation



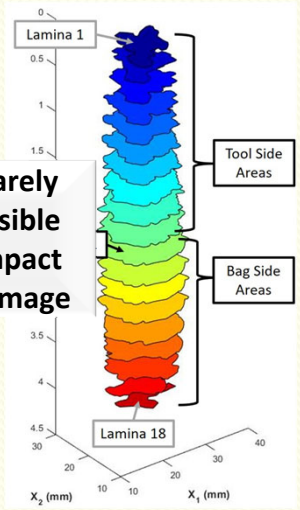
Incomplete Bondline

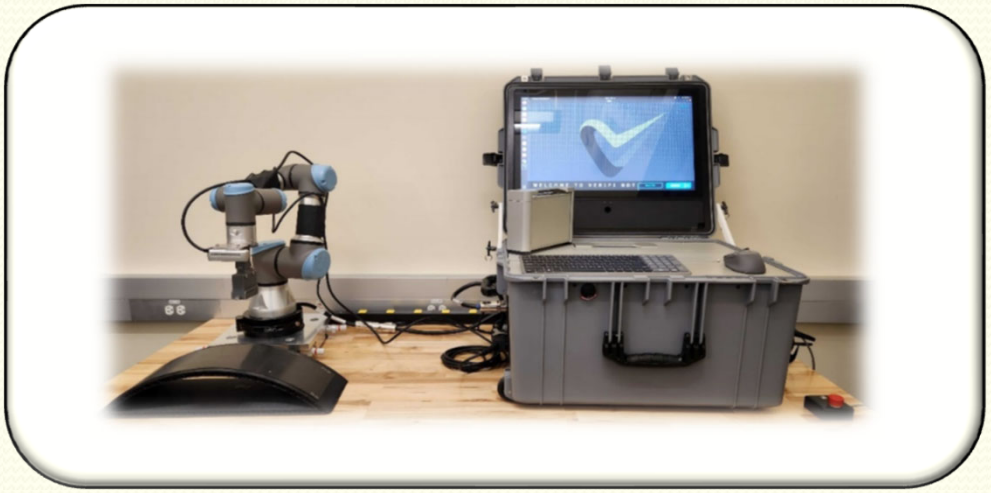


Sub-surface Cracks in Composites Using Eddy Currents

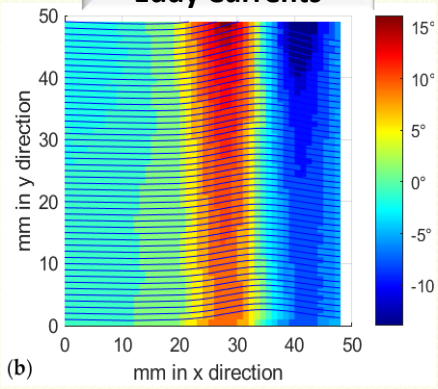


Barely Visible Impact Damage

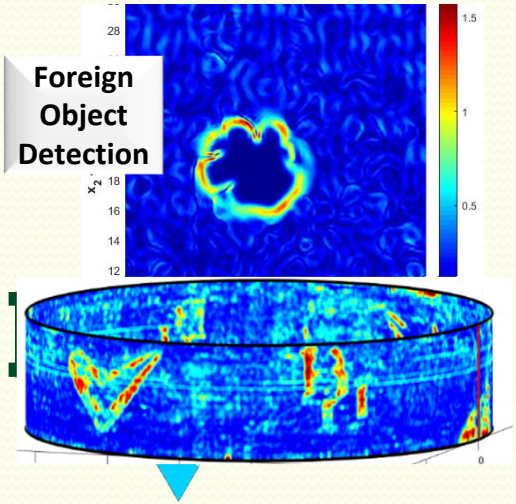




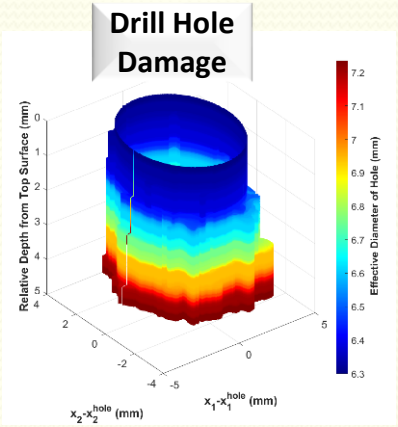
Marcelling Using Eddy Currents



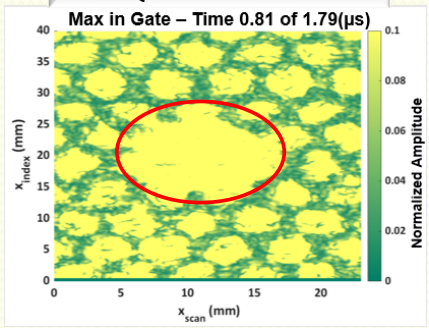
Foreign Object Detection



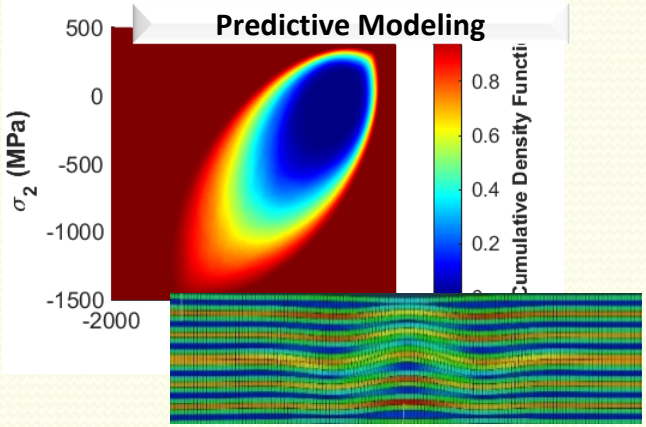
Drill Hole Damage



Honeycomb Adhesion Quantification



Predictive Modeling



Conclusions

- Developed and certified a portable inspection system capable of a resolution equivalent to that of an water immersion system

- Completed FAA 8011-9's on multiple technologies
  - Ply count and orientation
  - Bondline quantification
  - Foreign object detection and quantification (est. June 2023)
  - Barely visible impact damage (est. June 2023)

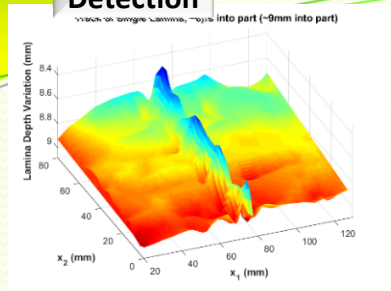
- Deployed the technology to quantify
  - Drill hole damage, incomplete bondline, delaminations, honeycomb core adhesion, subsurface cracks, marcelling, etc.

Special Thanks

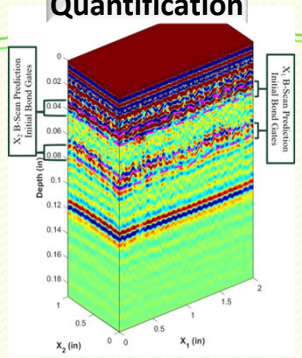
- Dr. Nate Blackman, Kurtis DeVries, Irrtisum Khan, Luke Battershell

- Dr. Daniel Pulipati, Dr. Pruthul Kokkada, Dr. Douglas Smith, Dr. Trevor Fleck, Dr. Ian Gravagne, Dr. Scott Koziol, Dr. Zhao, Ron Nadeau, Nate Emerson, Cameron Coker, Julie Williams, Kirtunia Rahul, Rifat Nargis, Admay Amif, Rachel Van Lear, Joshua Norlin, Matthew Newton, Mahsa Khademi, Savannah Rose, Atik Amin, Khalid,

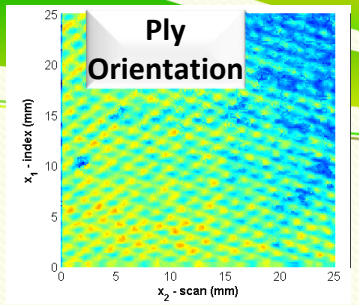
Wrinkle Detection



Bondline Quantification



Ply Orientation



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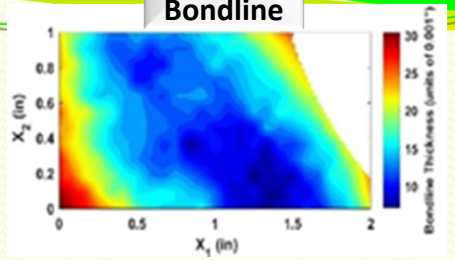

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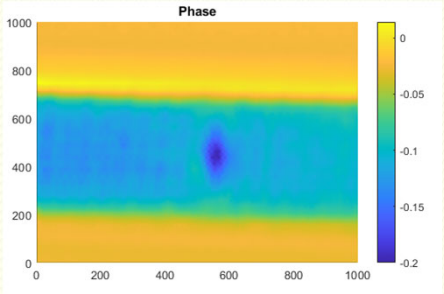
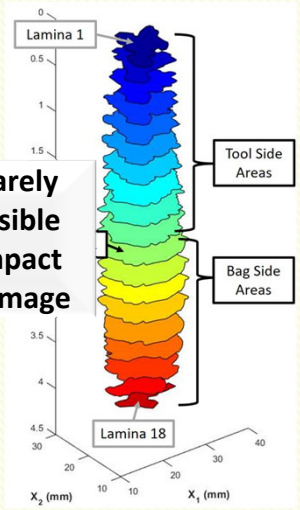
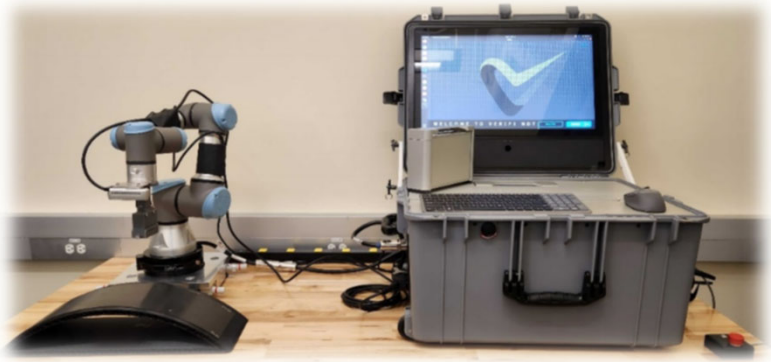


Barely Visible Impact Damage



Thank you for your time!



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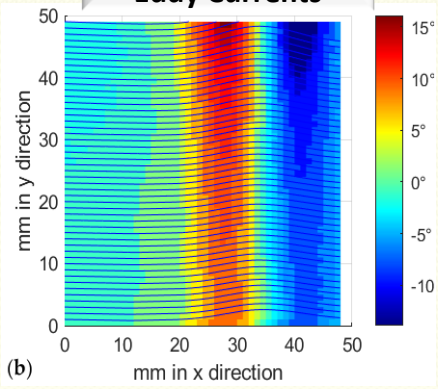
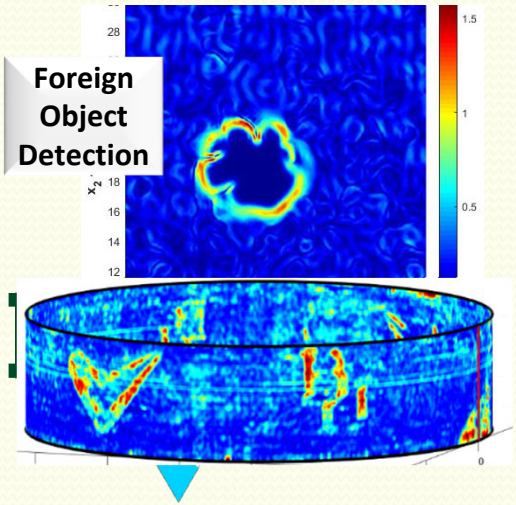
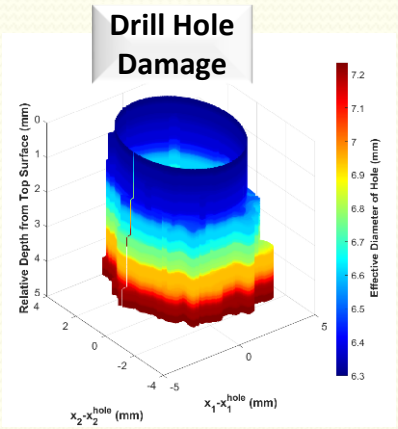


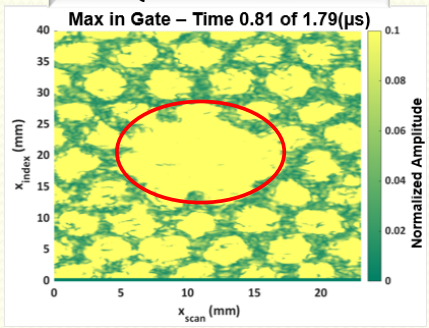
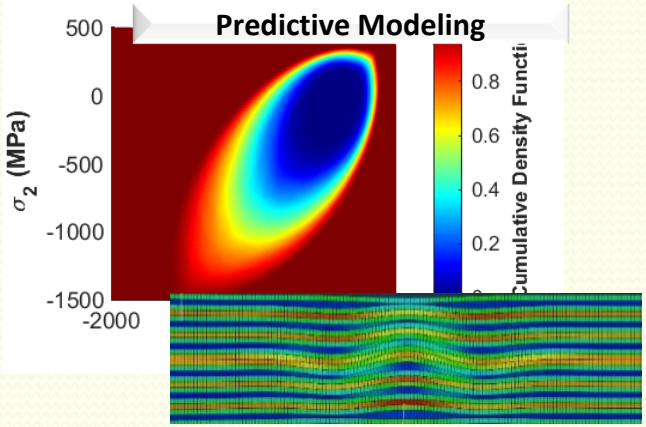
Foreign Object Detection



Drill Hole Damage



Honeycomb Adhesion Quantification



Predictive Modeling