



Advanced Ultrasonic Spectroscopy for Improved Inspection of Highly Attenuative Components

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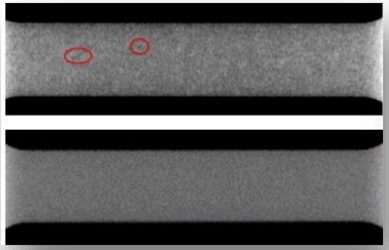
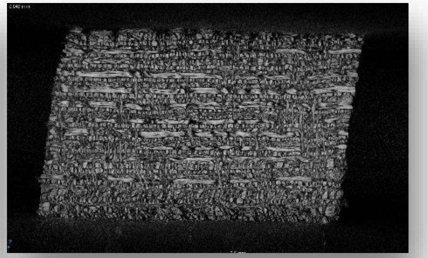
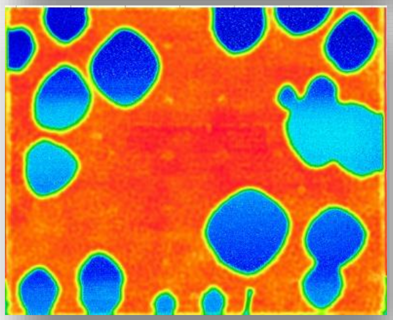
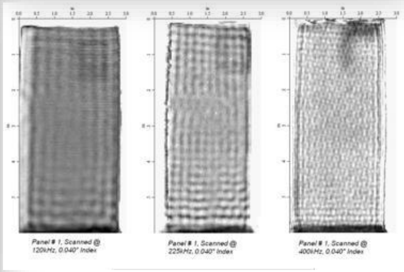
KRATOS SRE: Advanced Materials Characterization

Nondestructive Characterization: Solution Provider for Difficult Inspection Applications

Traditional NDT Methods

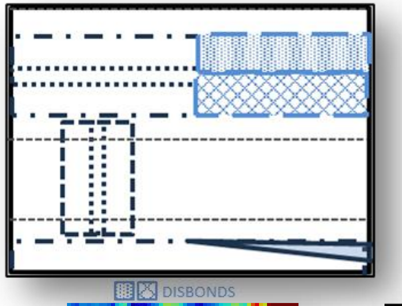
When use of traditional methods not possible or inconclusive

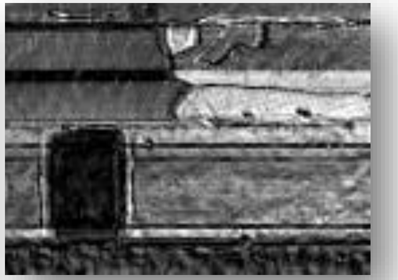
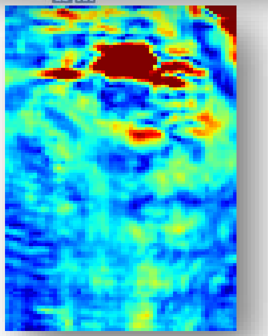
UltraSpec™

<u>Example Inspection Challenges:</u>

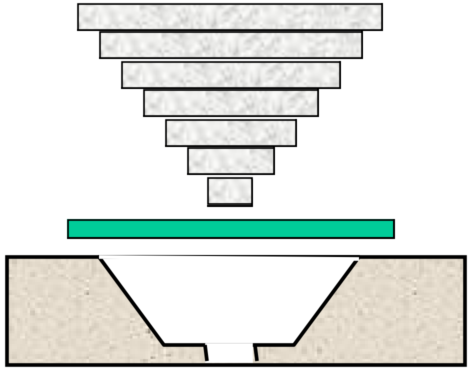
Highly attenuative materials
Highly variable material properties
Complex material structures
Multi-layered dissimilar materials
High depth of penetration requirement



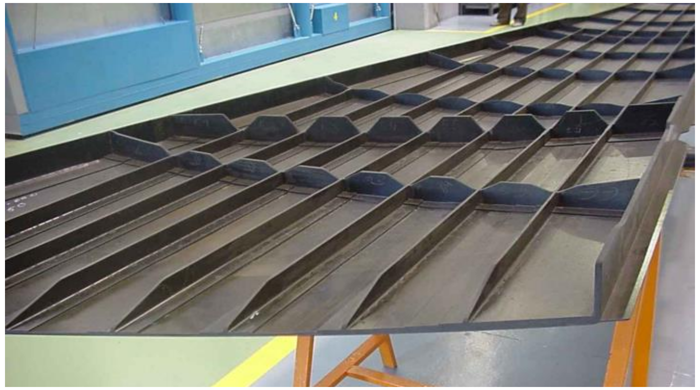




Area	Centroid	W x H	Approx. Area	Approx. Depth from TOP*
1	(1.9, 0.7)	1.0 x 0.5	0.3	20%
2	(4.5, 0.7)	0.8 x 0.4	0.2	21%
3	(1.5, 1.6)	0.7 x 0.8	0.4	33%
4	(3.0, 2.2)	0.6 x 0.6	0.3	40%

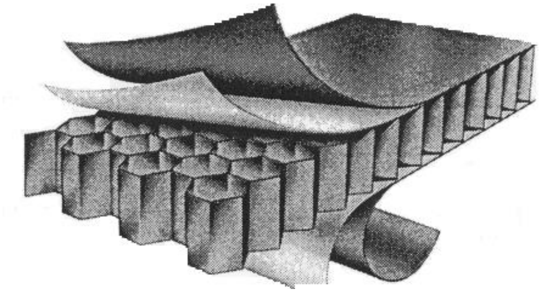
Advanced Ultrasonic Spectroscopy for Improved Inspection of Highly Attenuative Components



Composite Repairs



Composite Laminates

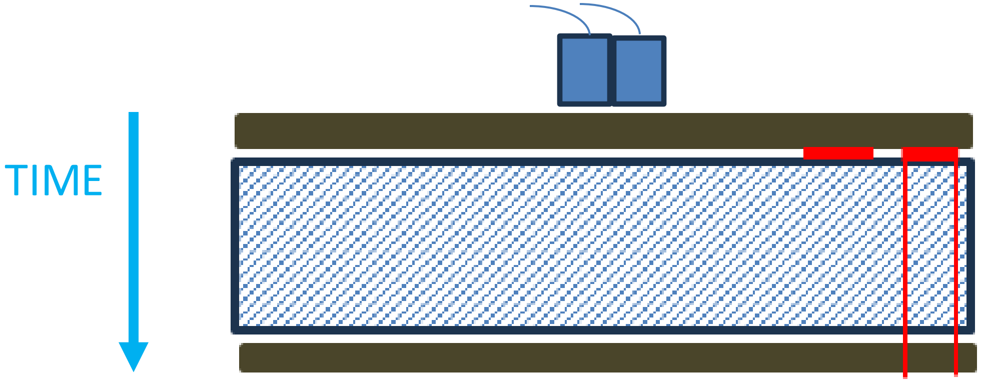


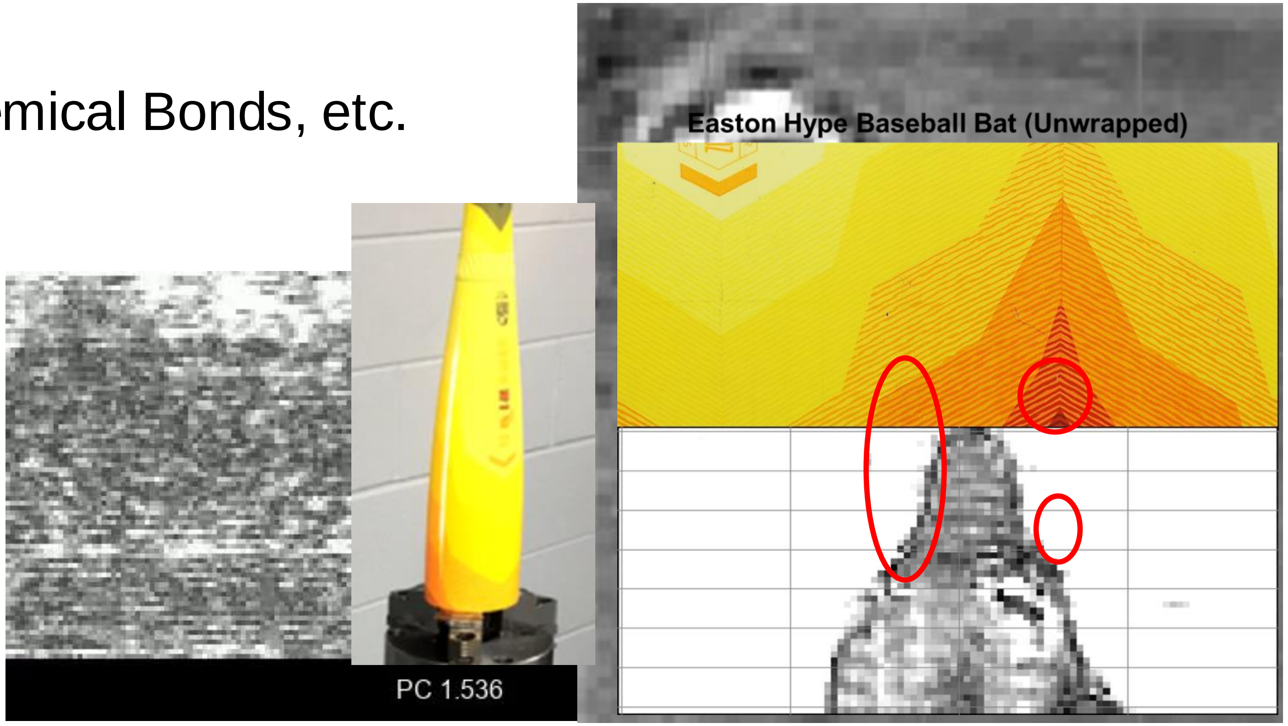
Composite Honeycomb

Composite Impact Damage

Successfully Used UltraSpec™ to Solve Multiple Inspection Challenges

- Composite Subsurface Damage Through Thick Specialty Coatings
  - Other NDE methods were unsuccessful
- Ceramic Matrix Composites (CMC) Characterization – Delaminations, Porosity
  - 0.1” to 2.0” Thicknesses, Rough Surfaces, Complex Geometries
- Challenging Bondline Assessments
  - Assembly Bonds, Adhesive Bonds, Chemical Bonds, etc.
- Complex Stacks of Materials
  - Honeycomb, Dissimilar Materials



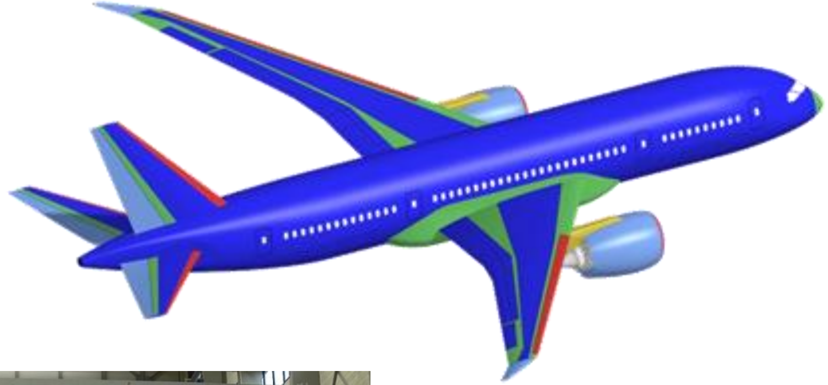


<u>Motivation</u> - Extensive/increasing use of composites on commercial aircraft and increasing use of NDI to inspect them

<u>Goal</u> - Improve flaw detection performance in composite aircraft structure with UltraSpec™

- Carbon laminate
- Carbon sandwich
- Fiberglass
- Aluminum
- Aluminum/steel/titanium pylons

Composite Structures on Boeing 787 Aircraft



Composite Center Wing Box

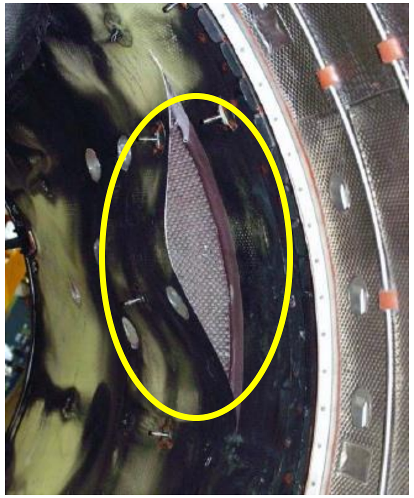
A380 Pressure Bulkhead

Sources of Damage in Composite Structure

One airline reports 8 composite damage events per aircraft (on avg.) with 87% from impact

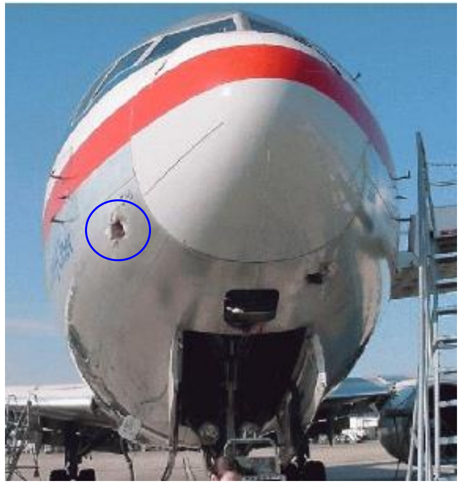
Cost = $200K/aircraft

Lightning Strike on Thrust Reverser



Disbonding at skin-to-honeycomb interface

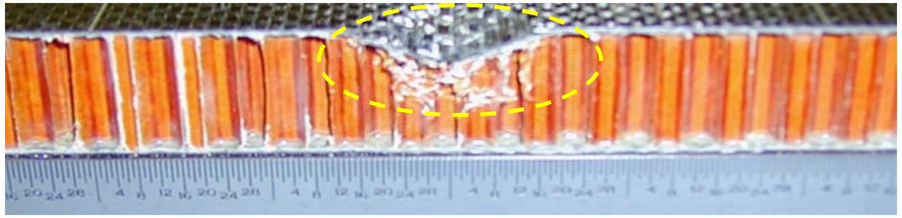
Towing Damage



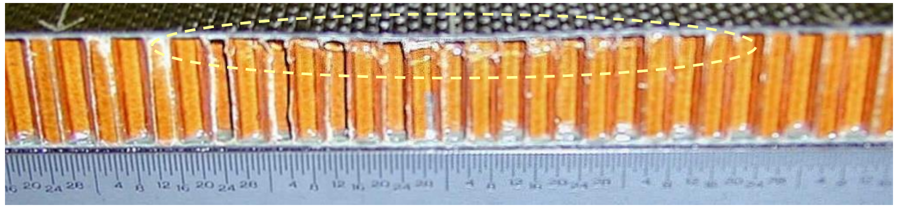
Bird Strike

Inspection Challenge – Hidden Impact Damage

Backside fiber failure from ice impact

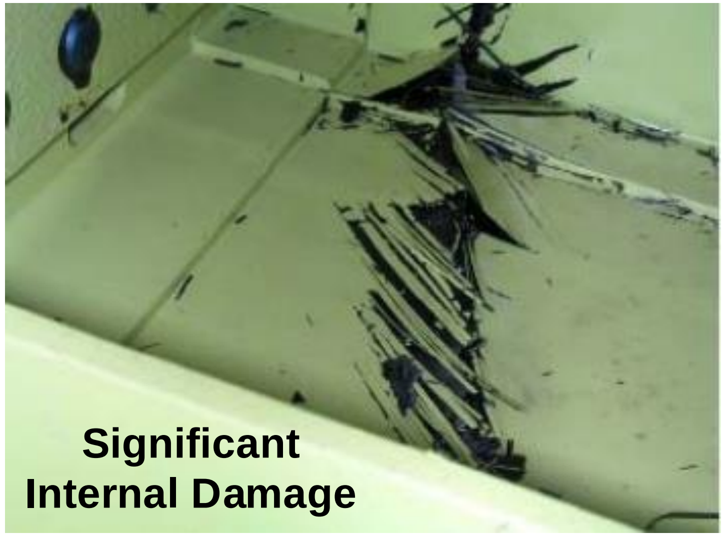


Visible Impact Damage – external skin fracture



Backside Damage – internal skin fracture & core crush

Damage from ground vehicle

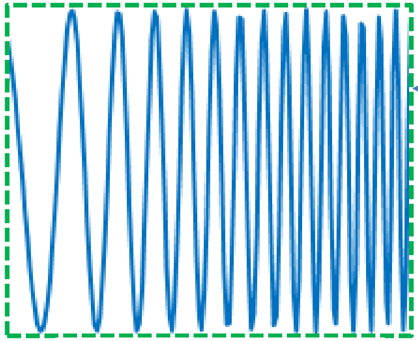


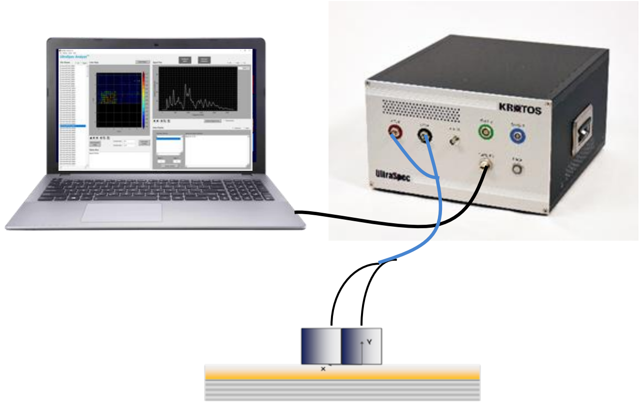
How UltraSpec™ is Different from Traditional UT

US Patent# 10605789

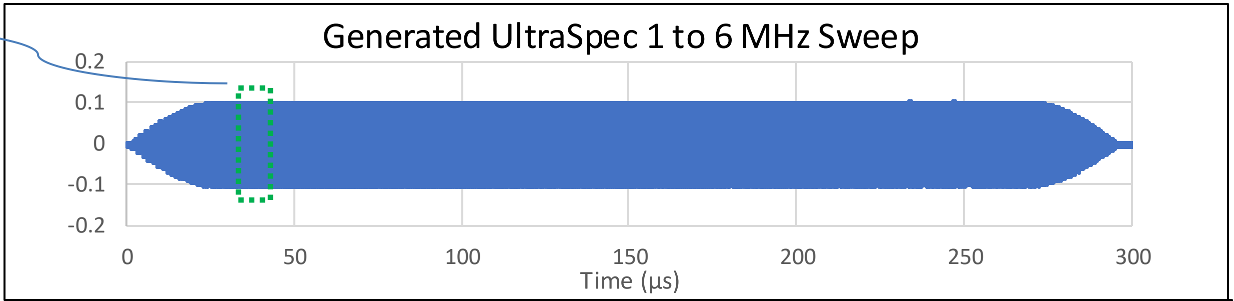
Long Duration Pulse

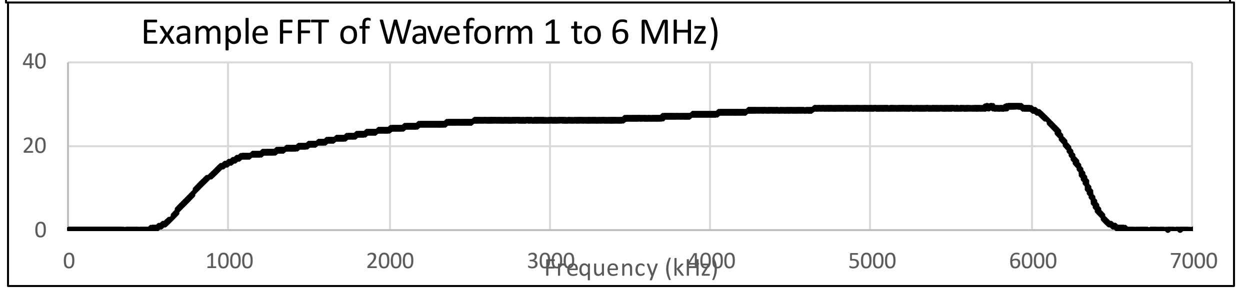
- User-defined frequency range
- Based on material
- Improved signal-to-noise
- **MORE ENERGY** into and out of the material structure





UltraSpec



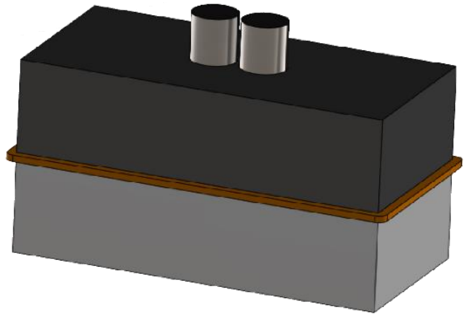


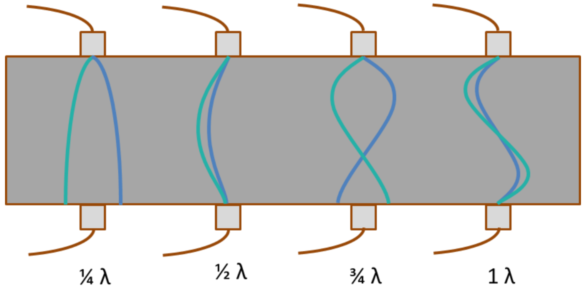
Traditional UT: Single Frequency
Time-of-Flight
Amplitude

UltraSpec™ – Swept-frequency ultrasonic spectroscopy

- **Dry-coupled**, automated scanning of complex geometries
- Proven to be effective at evaluating a wide range of composite materials and highly attenuative materials
- Unique ability to provide frequency, resonance and time reflections for *<u>enhanced material understanding</u>*
- Advanced analytical tools for delamination detection, crack detection, porosity evaluation and bond evaluation

UltraSpec™: Three Classes of Data Example

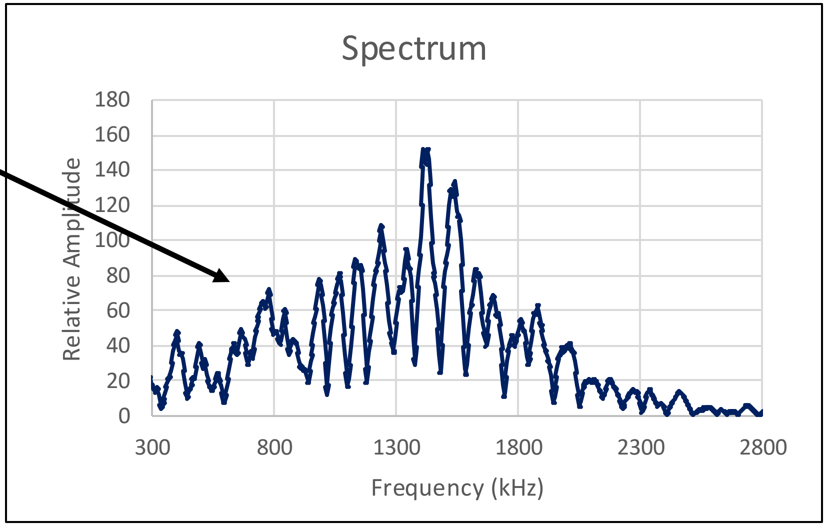


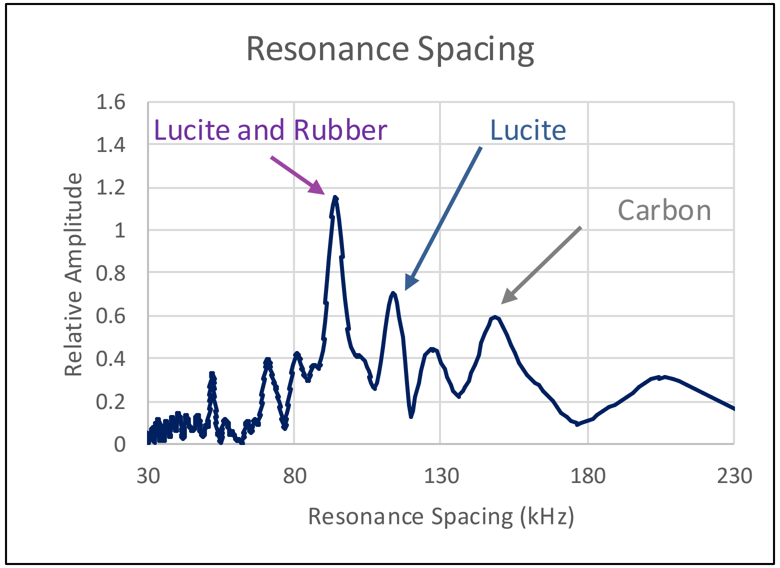


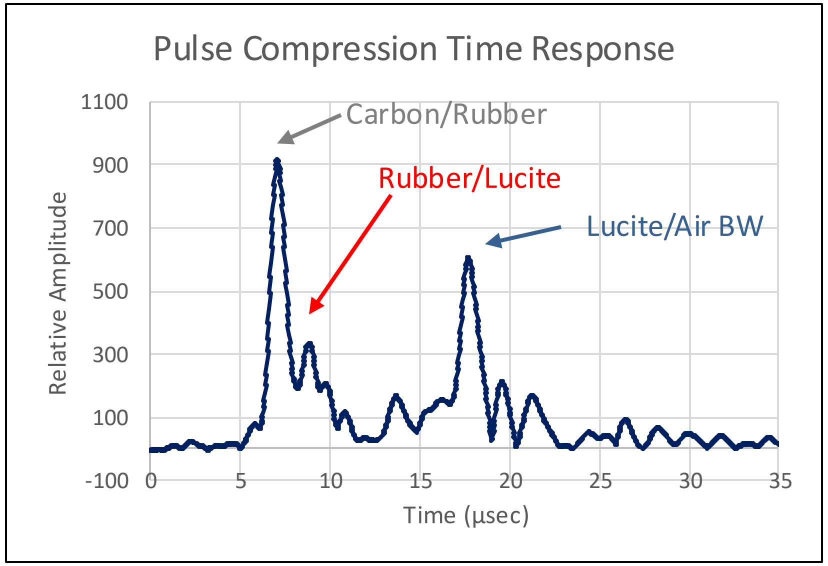
$$\text{Resonant Frequency} = \frac{velocity}{2*thickness}$$

Spectral Response (Signature)

- Very Repeatable
- Contains Resonances of Each Layer Individually
- Contains Resonances of Full Thickness or Combinations of Layers



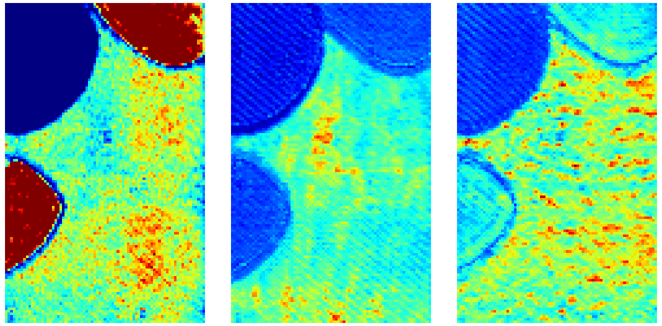




KRATOS
READY FOR WHAT'S NEXT™

Advanced Interpretation Module (AIM)

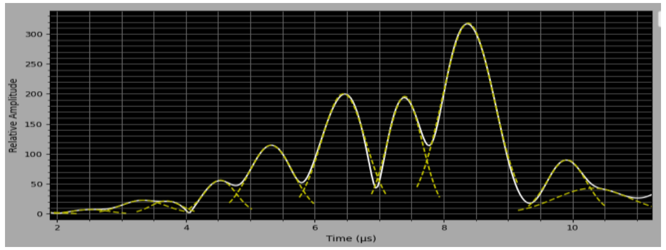
Data Cube "Slices"
Structure/Feature Identification



UltraSpec

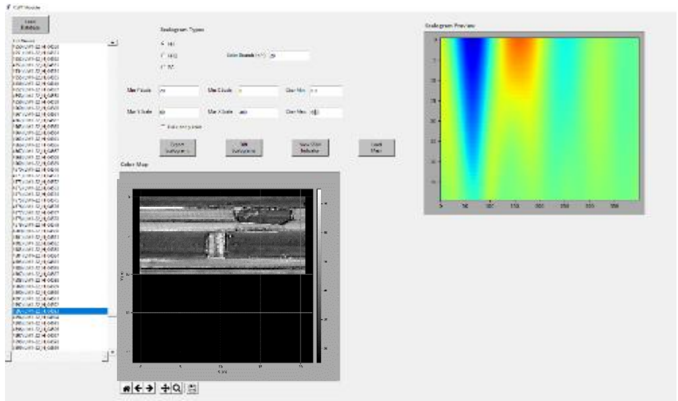
Advanced Interpretation Module (AIM)

Peak/Valley Fits with Physics Calculator

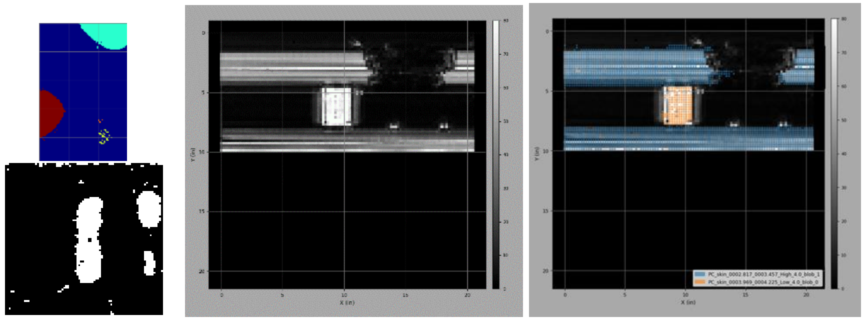


	FREQ (kHz)	TIME (µs)
1 Layer	900	3.8
2 Layers	450	4.9
3 Layers	300	6.0
4 Layers	225	7.1
5 Layers	180	8.2
6 Layers	150	9.3

Self-Referencing Algorithm
Identifies Areas of Change

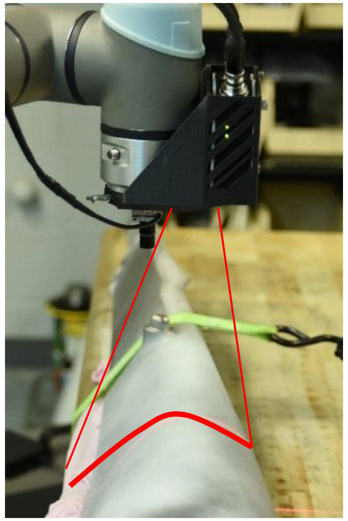


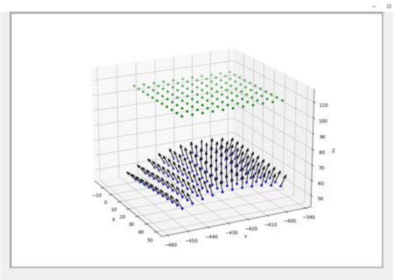
Spatial Comparisons
Blob Detection, Grouping

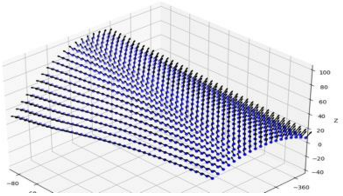


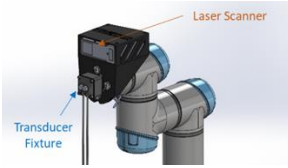
UltraSpec Scanning Options: UR5e Collaborative Cobot, XY Encoder

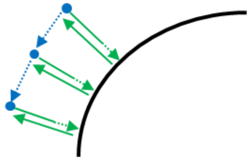
Automated



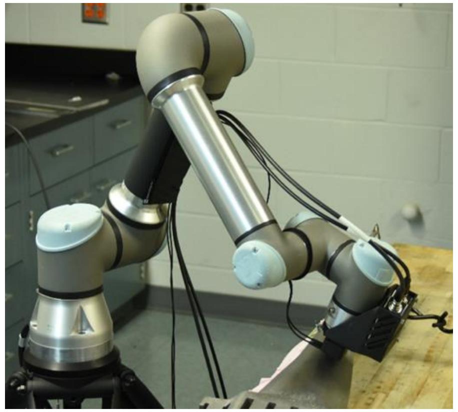




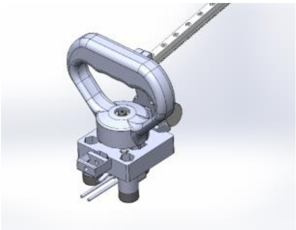




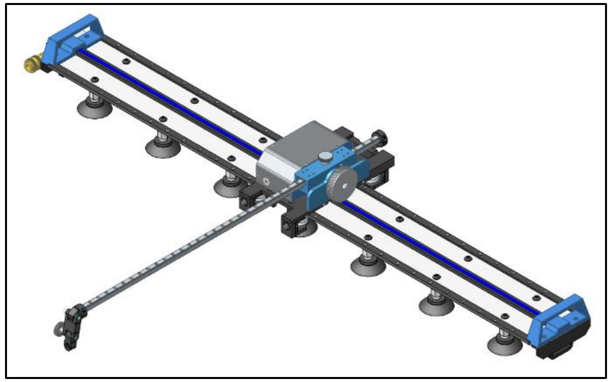
Universal Robots UR5e



Manual



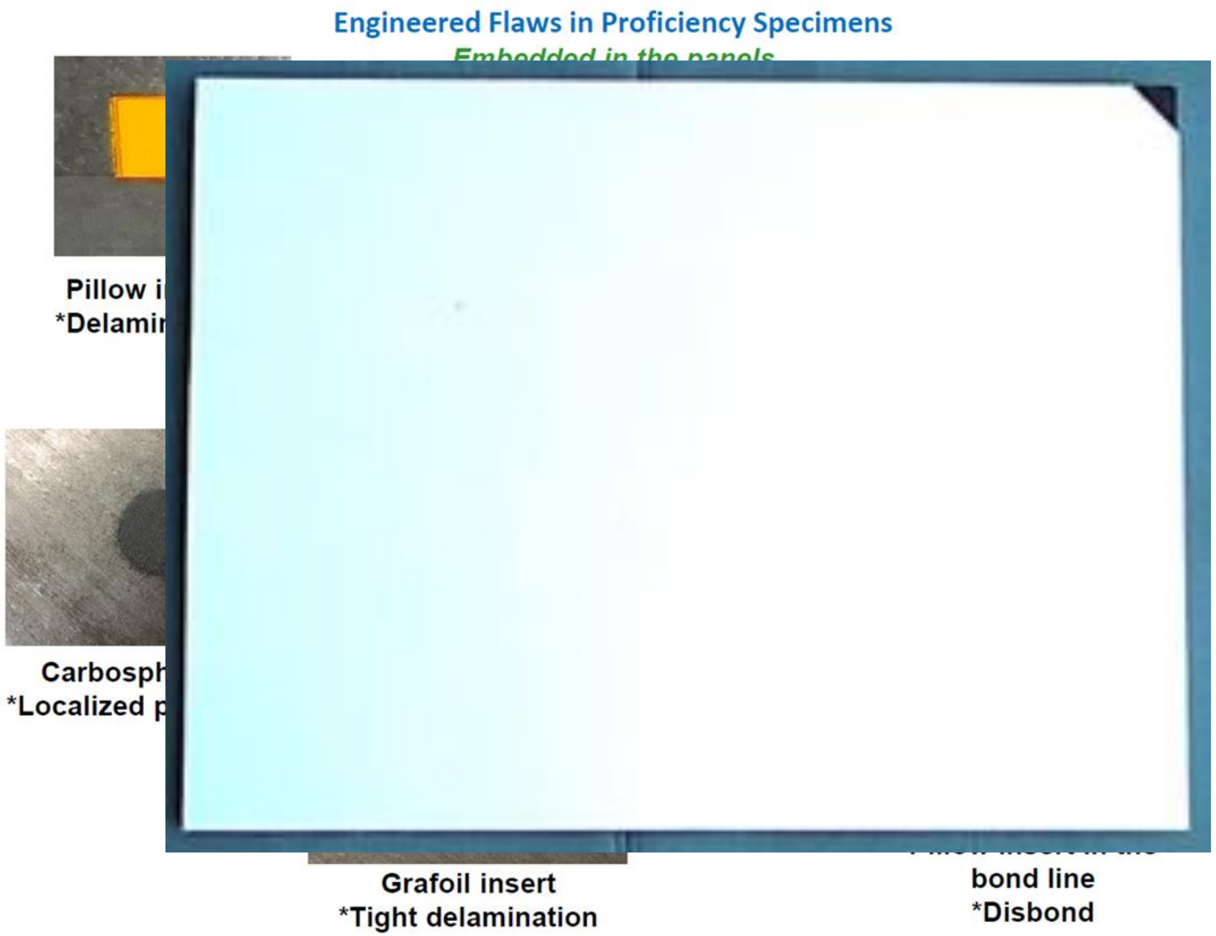
TecScan TecFlex

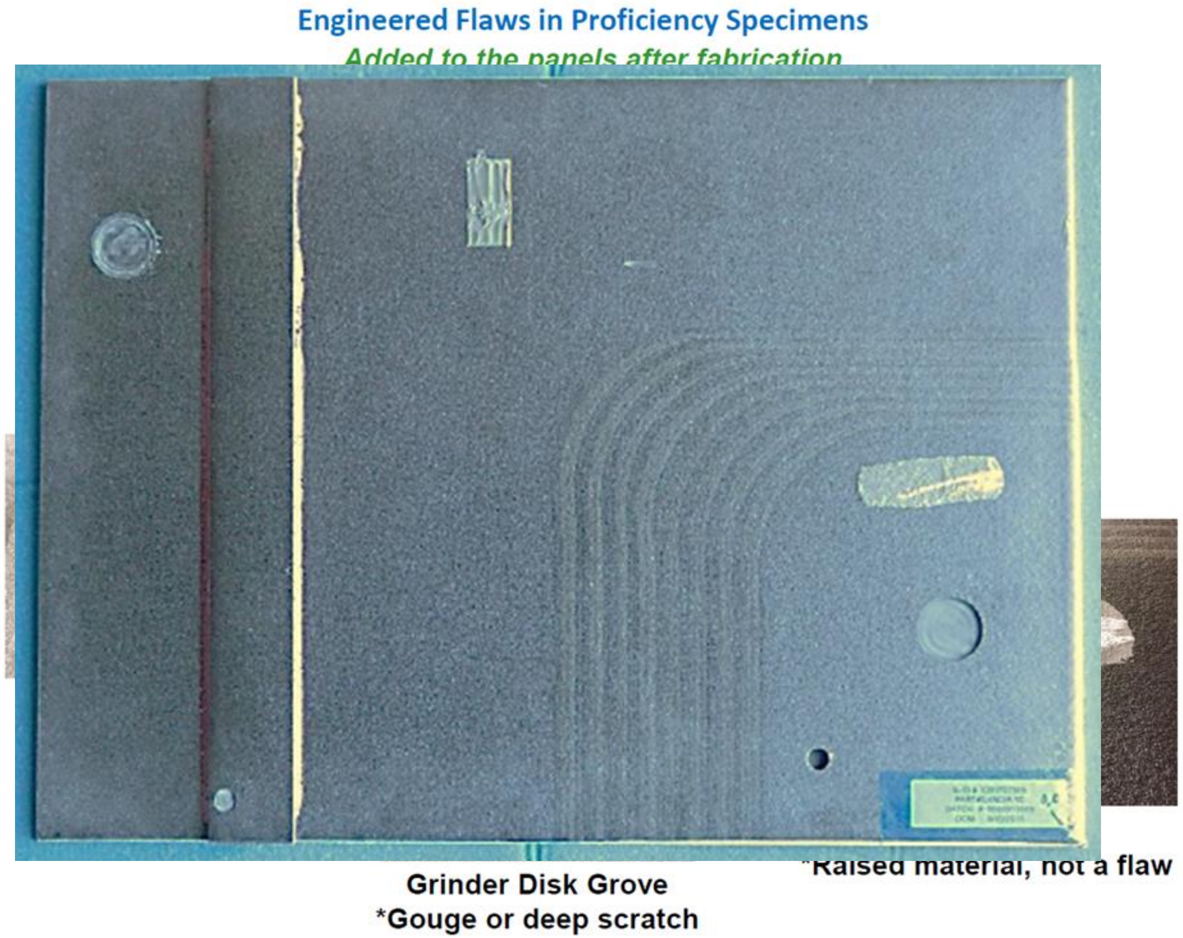


Customized Probe Fixture
TecFlex: Improved Design for Aircraft Mounting (Complex Curvatures)

Assess UltraSpec Flaw Detection Performance
Composite Laminate Proficiency Specimen 1C

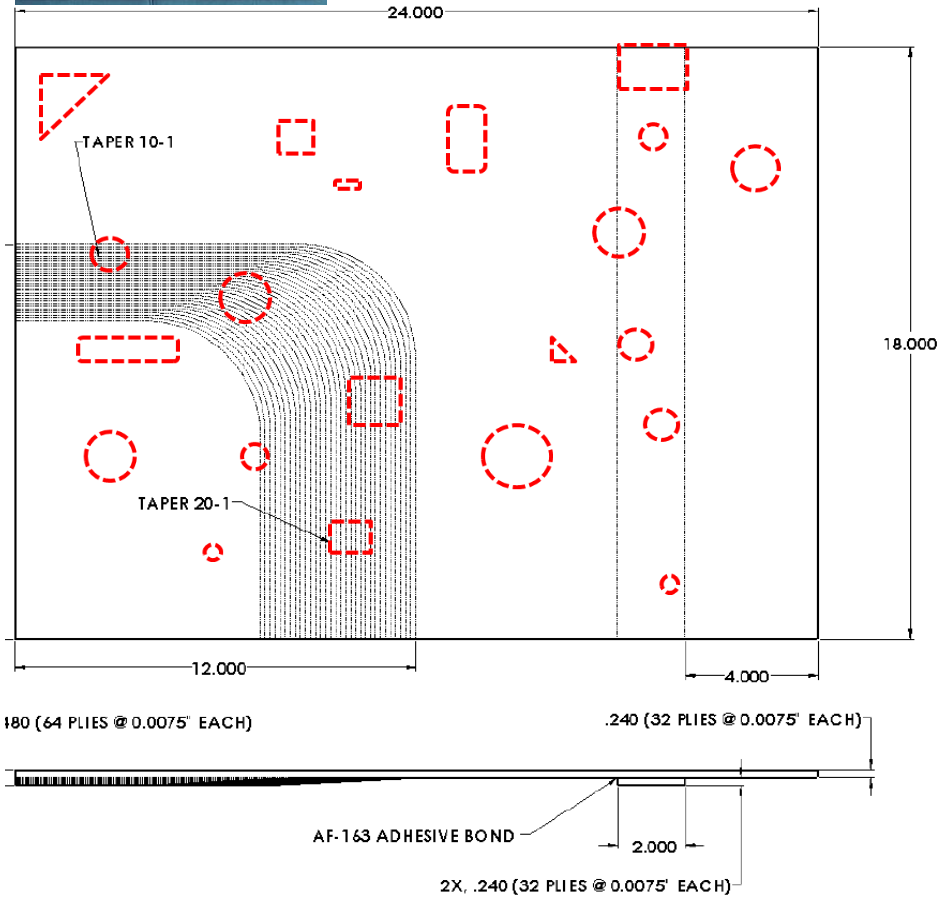
(Developed to train and refresh inspectors for composite laminate structures – challenging flaws)



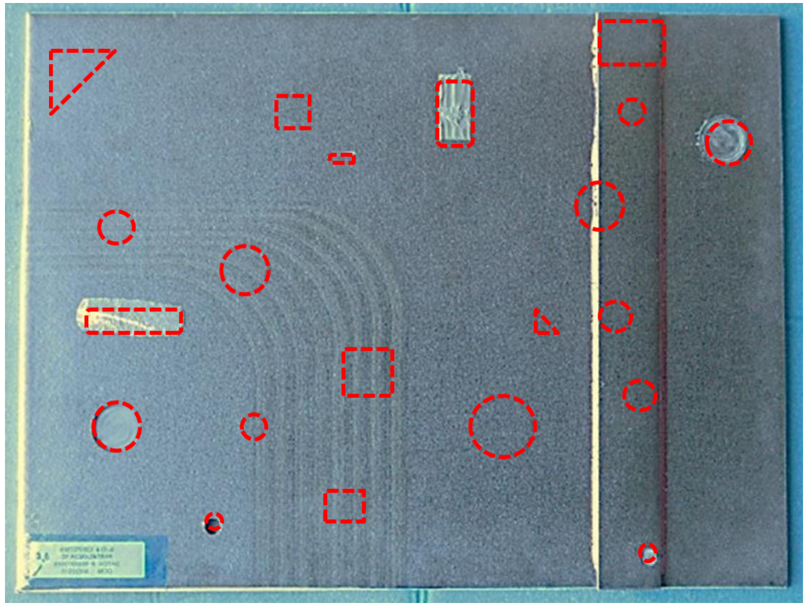


FAA-AANC NDI Test Specimen Library Sample

Assess UltraSpec Flaw Detection Performance Composite Laminate Proficiency Specimen 1C



Inverted Image to Match Front

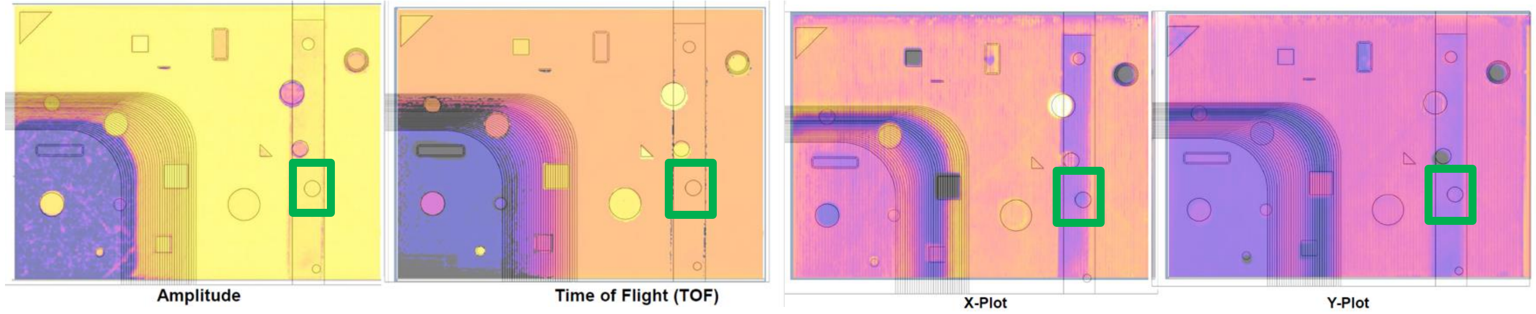


ITEM #	FLAW TYPE	SIZE	PLY LAYER
1	IMPACT	Ø1.50	SEE SECTION B-B
2	CARBOSPHERES	Ø2.00	BTN PLIES 16 & 17 (50%)
3	PILLOW INSERT	Ø1.50	BTN PLIES 8 & 9 (25%)
4	PILLOW INSERT	Ø0.75	BTN PLY 32 & ADHESIVE
5	PILLOW INSERT	Ø1.00	BTN PLY 16 & 17 OF SUBSTR
6	PILLOW INSERT	1.00 X 1.00	BTN PLY 10 & 11 OF TAPER
7	PILLOW INSERT	1.00 X 1.00	BTN PLY 24 & 25 (75%)
8	PILLOW INSERT	Ø1.50	BTN PLY 4 & 5 OF TAPER
9	PILLOW INSERT	Ø0.75	BTN PLY 26 & 27 OF TAPER
10	PILLOW INSERT	1.50 X 1.50	BTN PLY 24 & 25 (75%)
11	GREASE	Ø1.00	BTN PLY 1 & 2 OF TAPER
12	GRAFOIL	Ø1.00	BTN PLIES 16 & 17 (50%)
13	FLAT BOTTOMED HOLE	Ø1.50	0.120" ↧ (BTN PLIES 16 & 17)
14	FLAT BOTTOMED HOLE	Ø0.50	0.360" ↧ (BTN PLIES 48 & 49)
15	FLAT BOTTOMED HOLE	Ø0.50	0.060" ↧ (BTN PLIES 24 & 25)
16	PREPREG BACKING	0.75 X 0.75	BTN PLIES 8 & 9 (25%)
17	PREPREG BACKING	2.00 X 2.00	BTN PLIES 24 & 25 (75%)
18	ADHESIVE BACKING	2.00 X 1.50	BTN ADHESIVE & PLY 1 OF SUBSTR
19	SEALANT BLOB	2.00 X 1.00	32 PLY BACKSIDE
20	SEALANT BLOB	3.00 X 0.75	64 PLY BACKSIDE
21	GRIND DISK GROOVE	0.10 x 0.75	APPROX. 0.070" ↧

FLAWS Detected

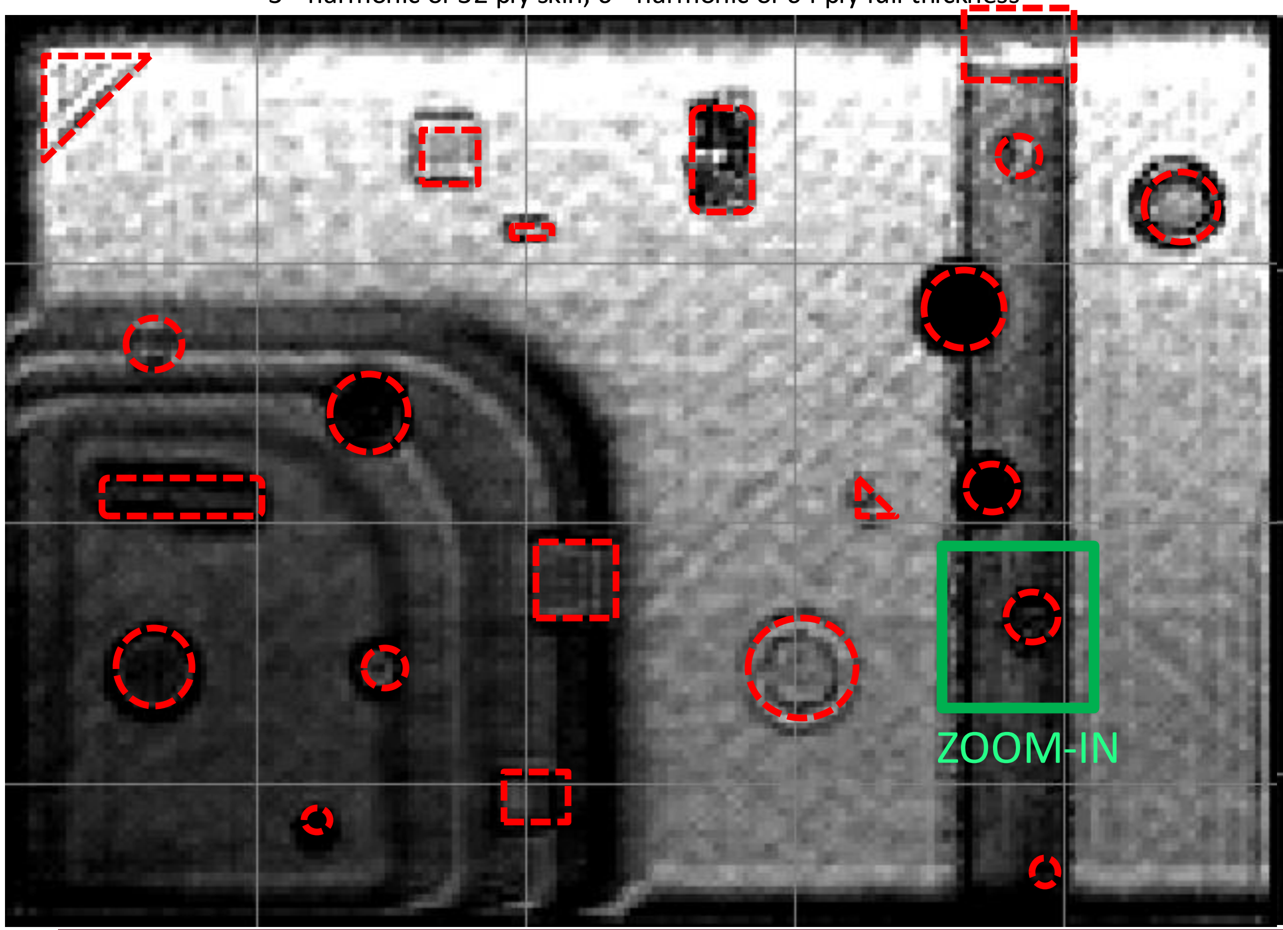
Traditional Methods	18/21	86%
UltraSpec Method	21/21	100%

1C Panel: PEUT vs UltraSpec™ Results

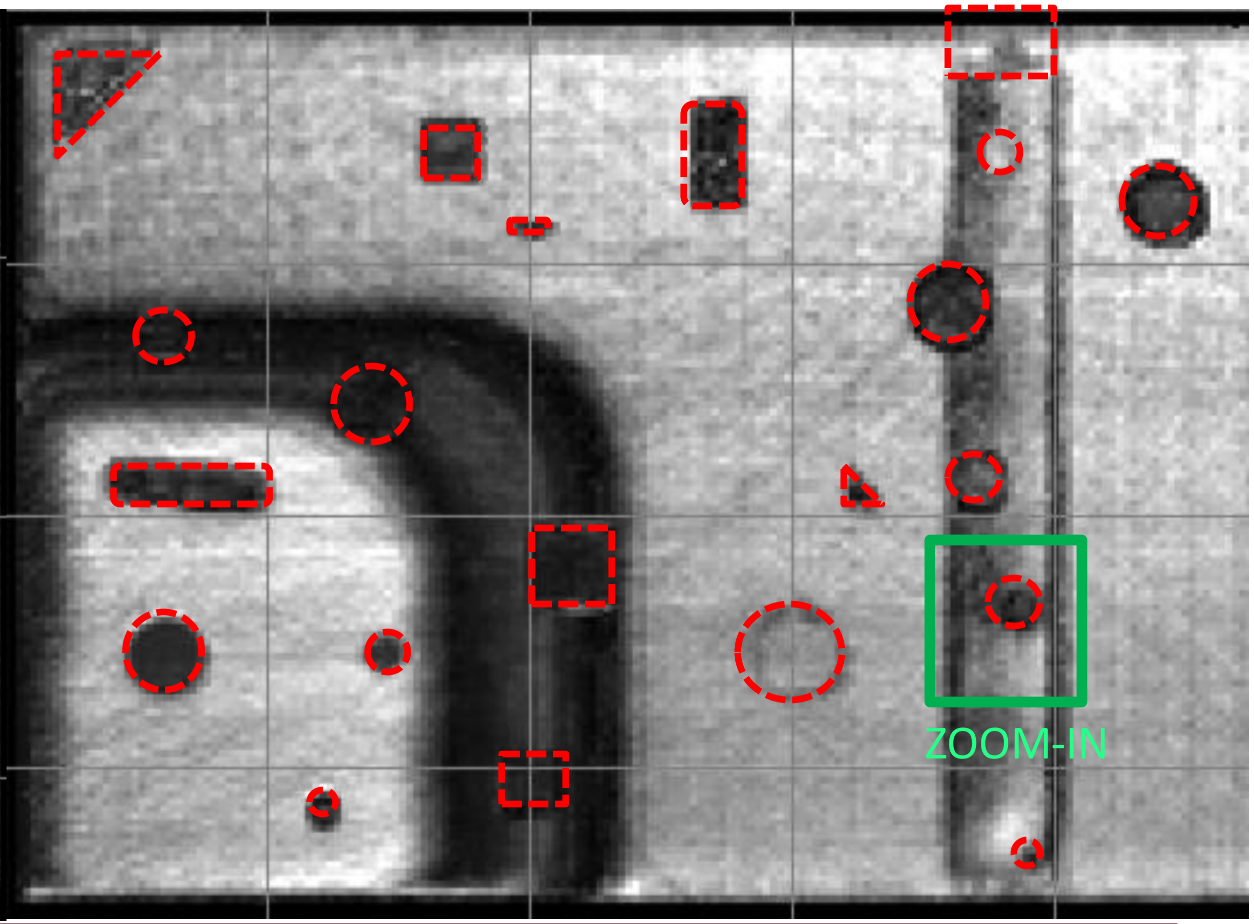


Spectral Amplitude ~720kHz*

*3rd harmonic of 32 ply skin, 6th harmonic of 64 ply full thickness



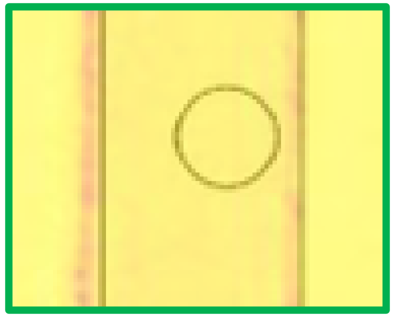
Time Amplitude near 64 ply backwall



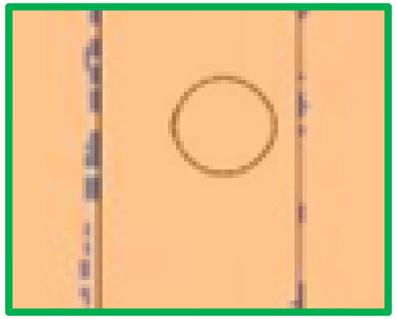
1C Panel (Flaw #5): PEUT vs UltraSpec™ Results

Traditional UT Misses with Flaw Outline Overlay

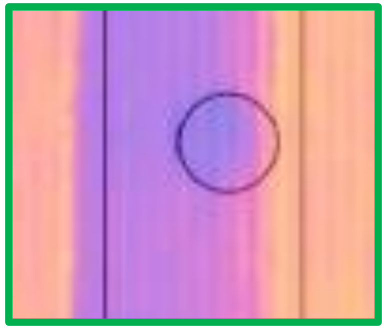
PE 5 MHz Amplitude

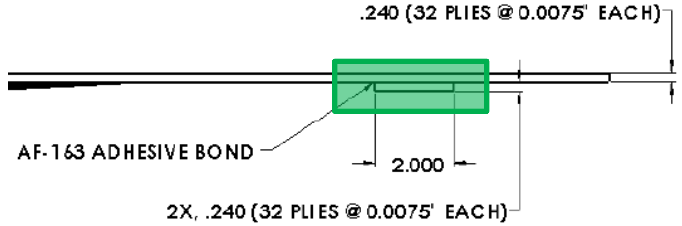


PE 5 MHz TOF

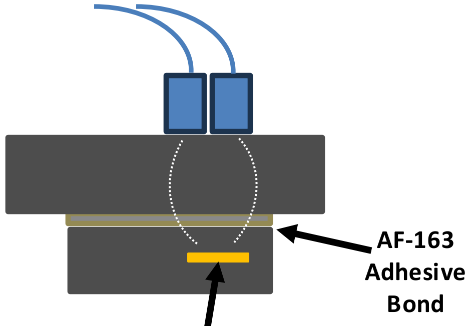


PE Resonance X Scale





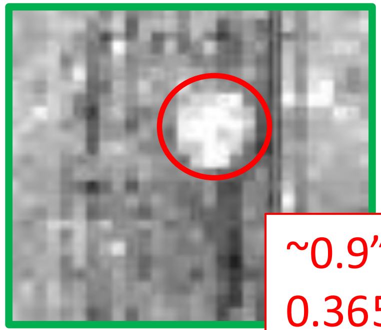
5	PILLOW INSERT	Ø1.00	BTN PLY 16 & 17 OF SUBSTR



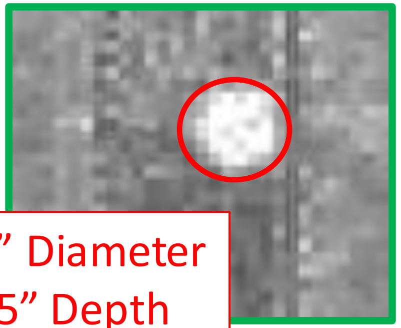
Pillow Insert

Pillow insert
*Delamination

Resonance Spacing Amplitude 160 kHz
(DELAMINATION F_R)
WHITE: DELAM

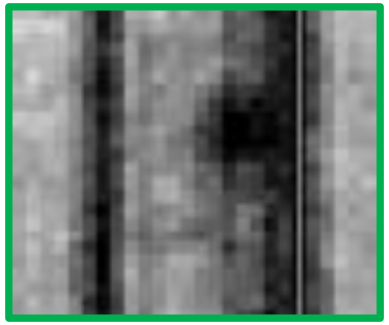


PC Time Amplitude
9.7µs
(DELAM Reflection)
WHITE: DELAM

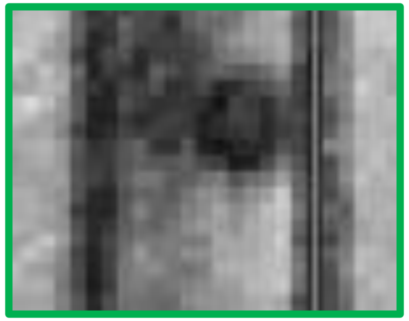


~0.9" Diameter
0.365" Depth

Resonance Spacing Amplitude 121 kHz
(Substr Resonance)
DARK: DELAM

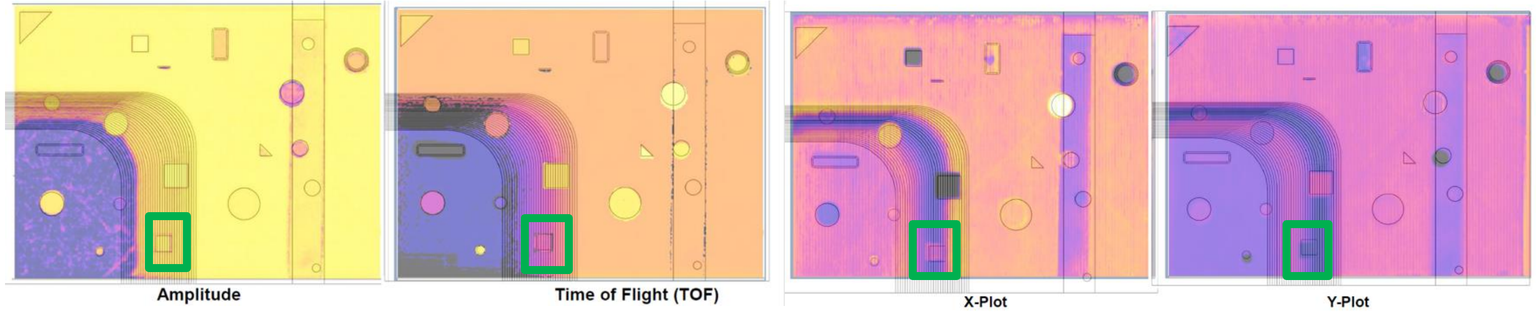


PC Time Amplitude
11.2µs
(near BW)
DARK: DELAM



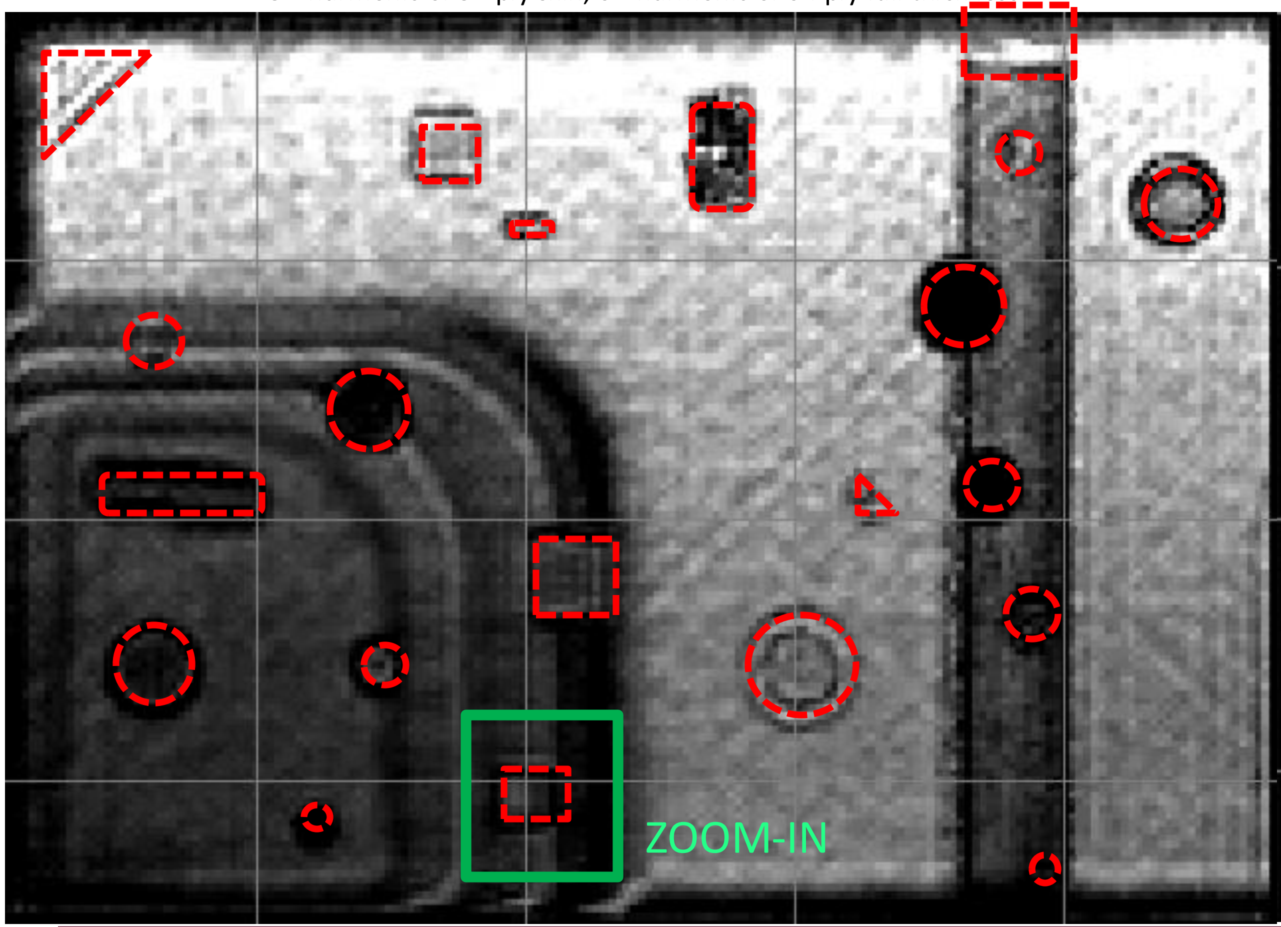
Description	Layup	Depth (in)	Velocity (in/µs)	F_R (kHz)	PC BW (µs)
Skin	32 plies 0.0075ea	0.24	0.117	244	7
Skin+Adh+Substrate	32 plies+ADH+32 plies	0.485	0.117	121	11.2
DELAMINATION	32 plies+ADH+16 plies	0.365	0.1166	160	9.7

1C Panel: PEUT vs UltraSpec^{TM} Results

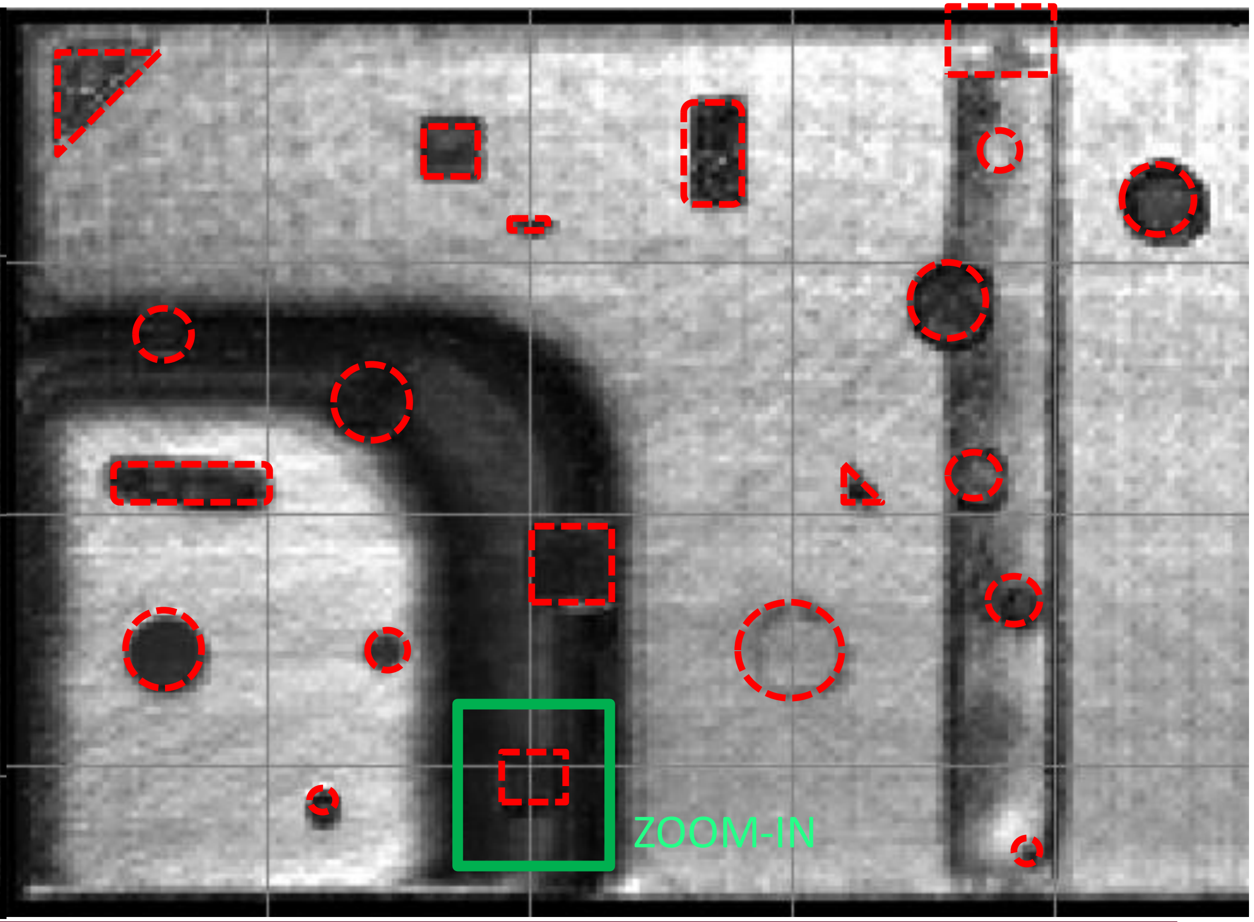


Spectral Amplitude ~720kHz*

*3rd harmonic of 32 ply skin, 6th harmonic of 64 ply full thickness



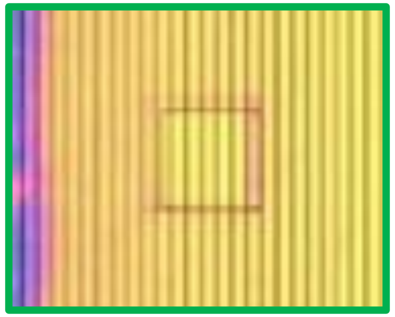
Time Amplitude near 64 ply backwall



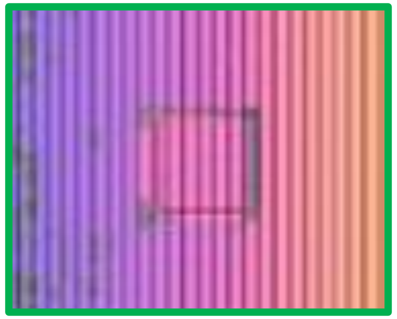
1C Panel (Flaw #6): PEUT vs UltraSpec™ Results

Traditional UT Misses with Flaw Outline Overlay

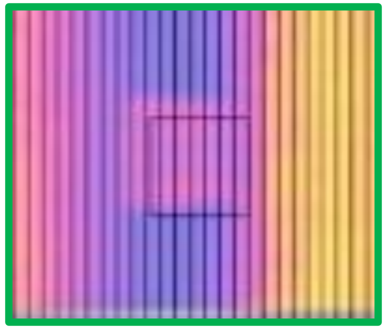
PE 5 MHz Amplitude

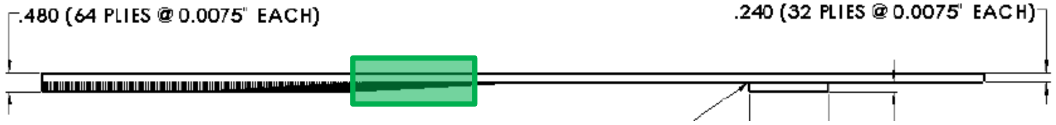


PE 5 MHz TOF

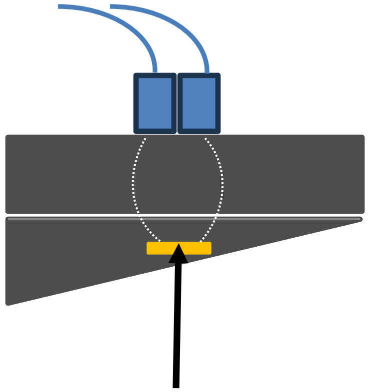


PE Resonance X Scale





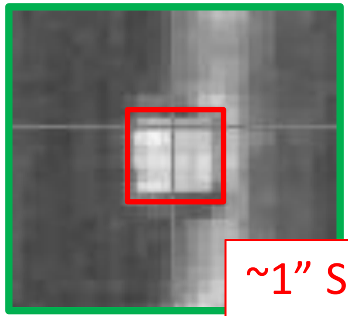
6	PILLOW INSERT	1.00 X 1.00	BTN PLY 10 & 11 OF TAPER



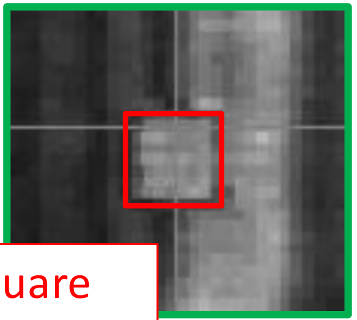
Pillow Insert

Pillow insert
*Delamination

Resonance Spacing Amplitude 185 kHz (DELAMINATION F_R) WHITE: DELAM

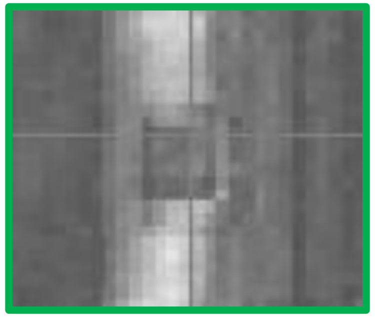


PC Time Amplitude 8.5µs (DELAM reflection) WHITE: DELAM

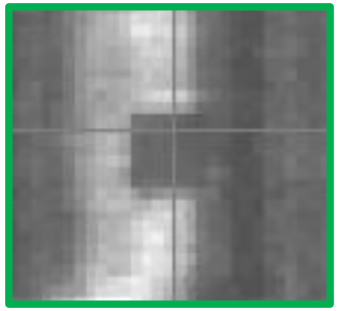


~1” Square
0.315” Depth

Resonance Spacing Amplitude 162 kHz (~Taper Resonance) DARK: DELAM



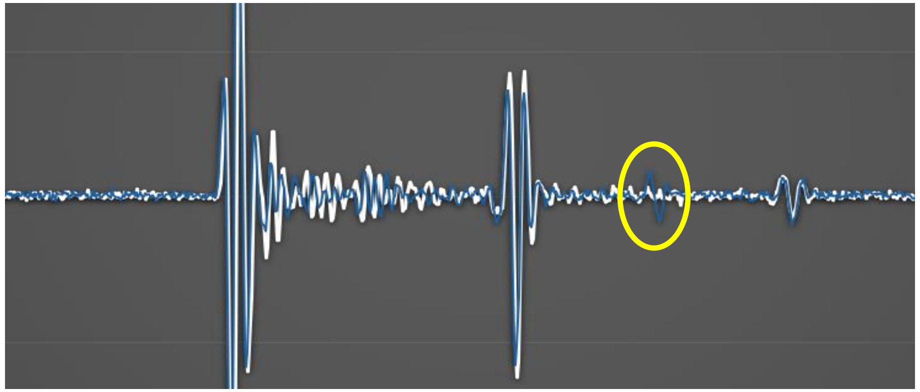
PC Time Amplitude 9.5µs (~Taper BW) DARK: DELAM



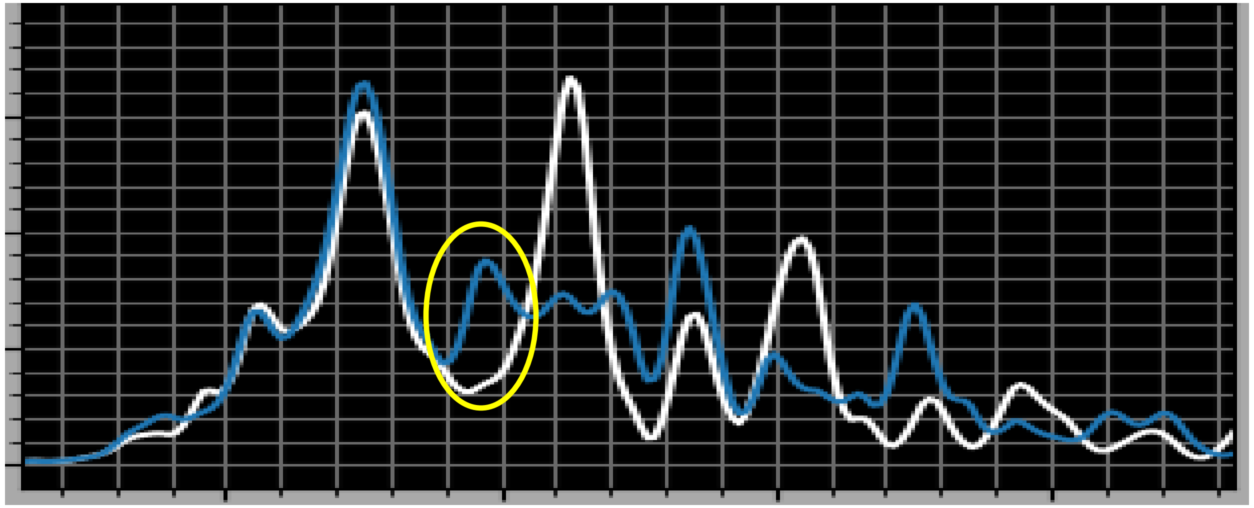
Description	Layup	Depth (in)	Velocity (in/µs)	F_R (kHz)	PC BW (µs)
Skin	32 plies 0.0075ea	0.24	0.117	244	7
Skin+Center of Taper	32 plies+16 plies	0.36	0.1166	162	9.5
DELAMINATION	32 plies + 10 plies	0.315	0.1166	185	8.5

1C Panel (Flaw #5): PEUT vs UltraSpec™ Results

Traditional A-Scan (Flaw #5)



UltraSpecTM Pulse Compression (Flaw #5)

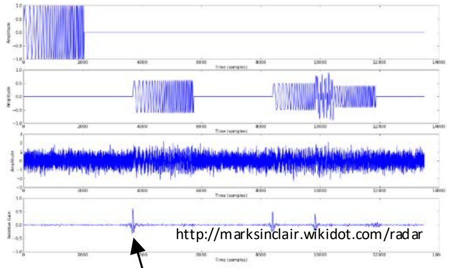


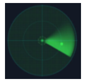
Processed Time Domain: More Robust

PEAKS represent where full sweep aligns in time.

See things that might not otherwise be found in traditional A-Scans.

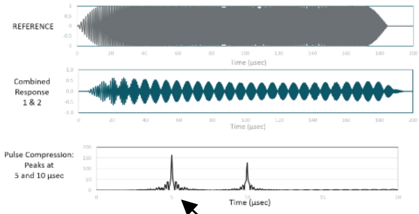
Radar

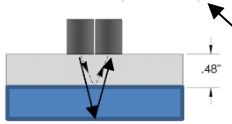




"Blips" on RADAR Screen

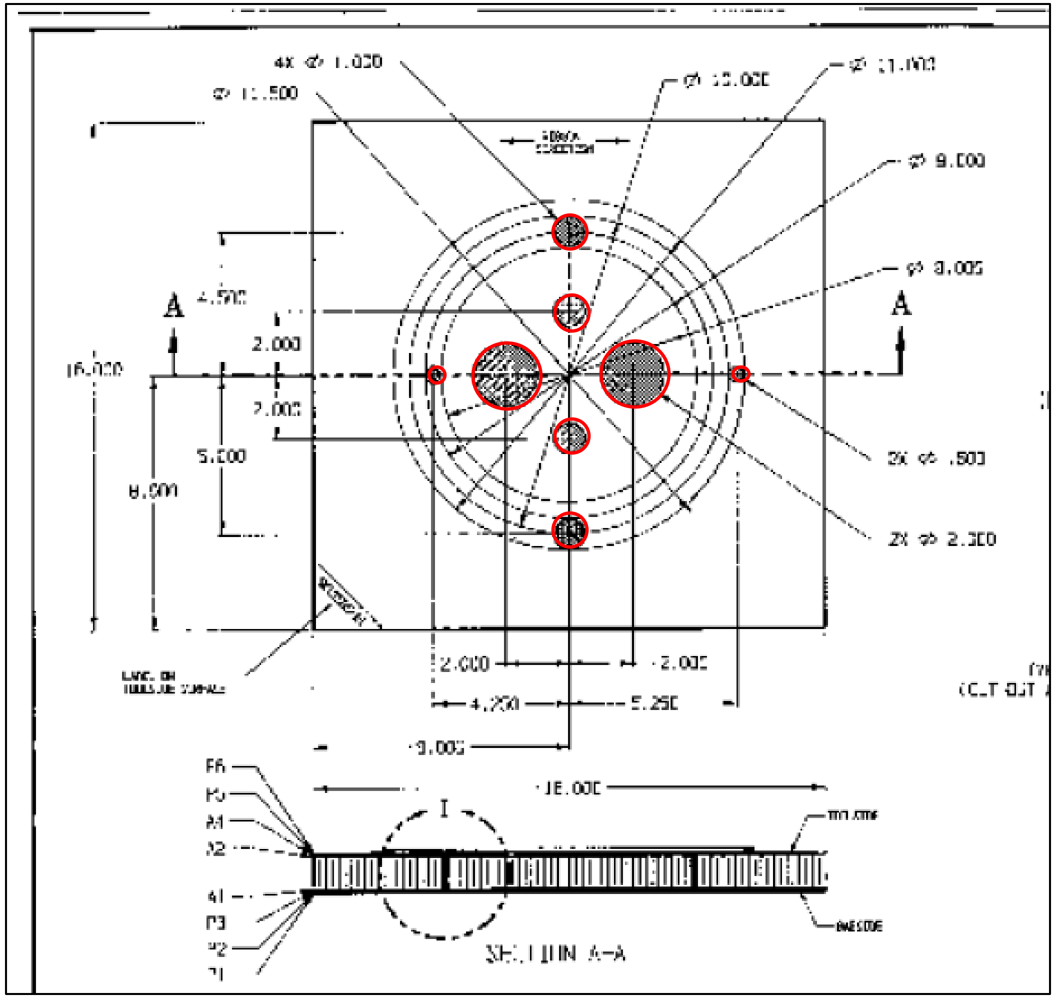
UltraSpec™





Interface reflections in Material Structure

Inspection of Repairs in Honeycomb Composite Structures
Scarf Repair SK 12595-R1



4-ply Repair

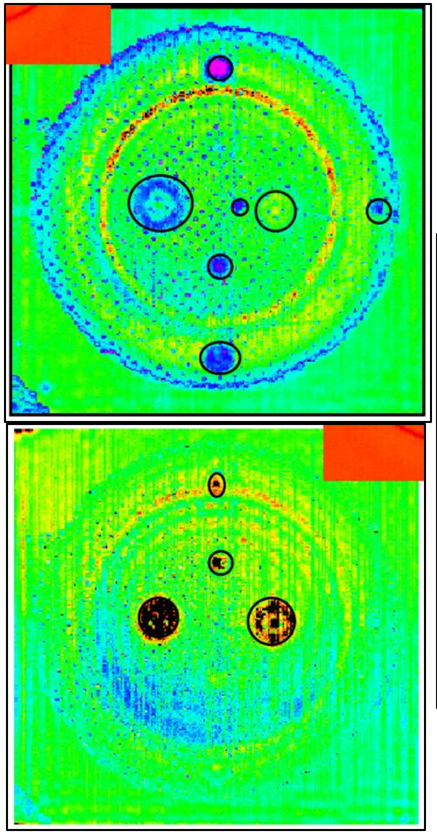
Engineered FLAWS in the Repair

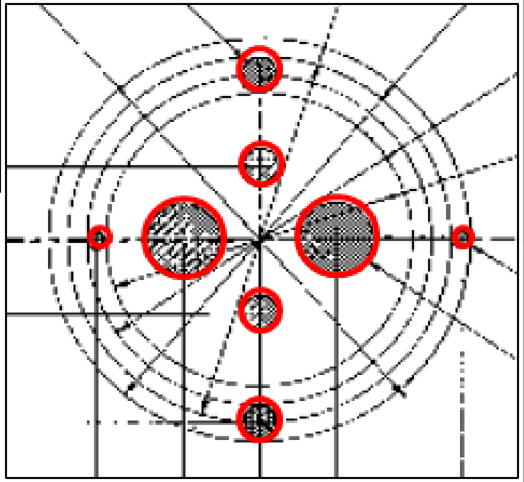
Debonds, Delaminations

FAA-AANC NDI Test Specimen Library Sample

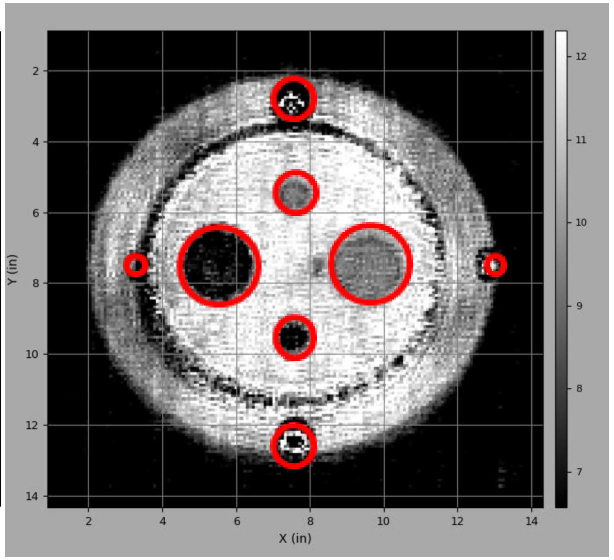
Inspection of Repairs in Honeycomb Composite Structures
Scarf Repair SK 12595-R1

Traditional NDE Results: MIA

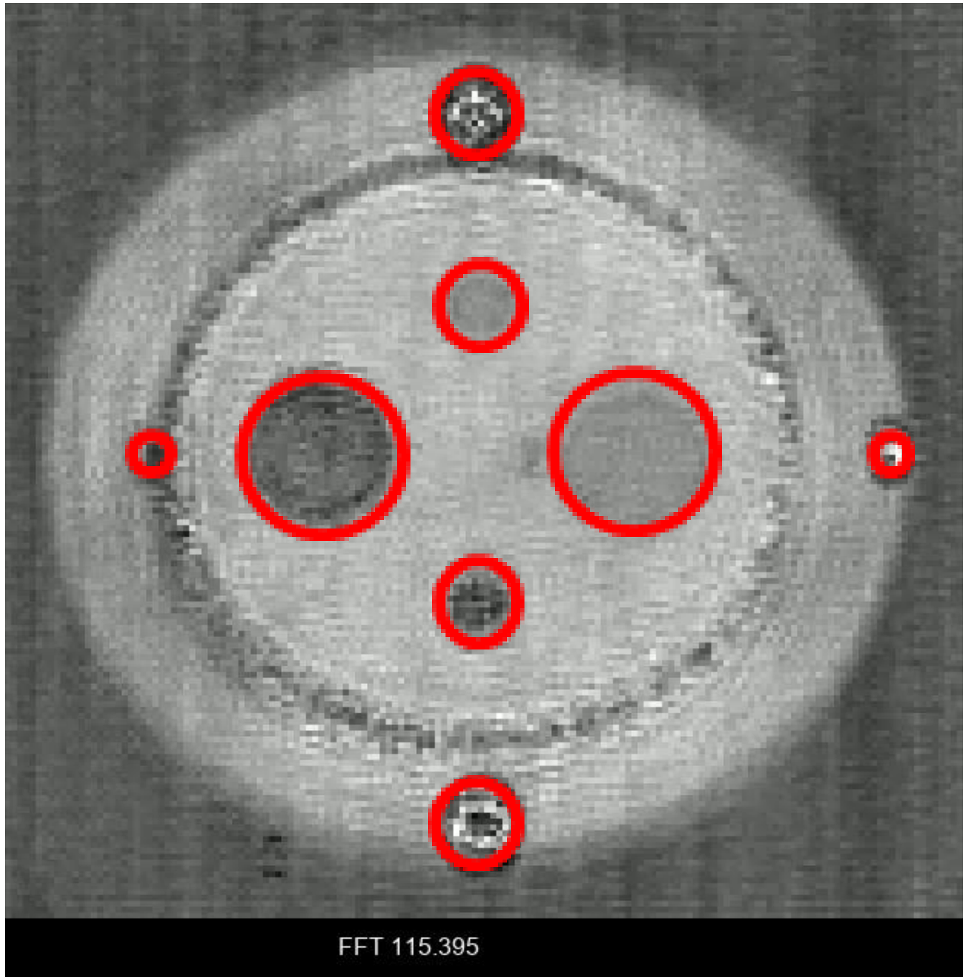




UltraSpec™ Results 116kHz

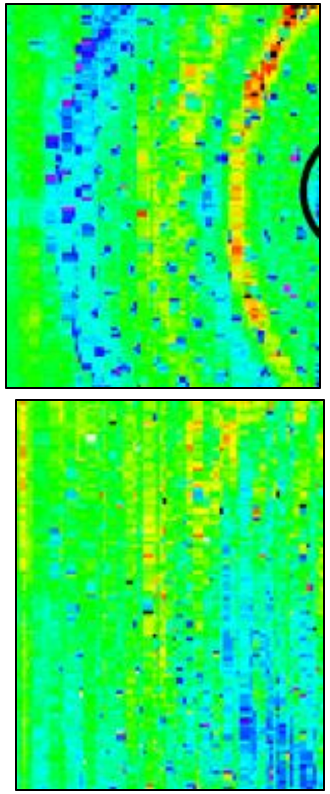


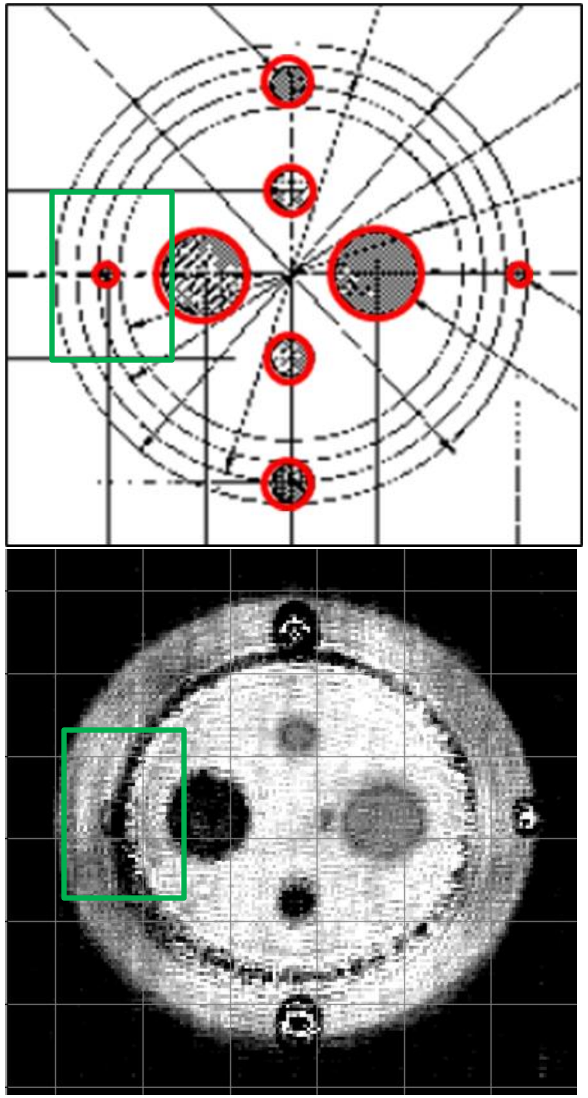
UltraSpec™ Spectral Amplitude Movie

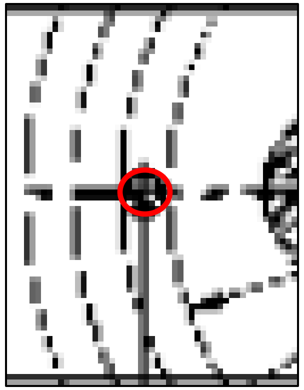


Inspection of Repairs in Honeycomb Composite Structures
Scarf Repair SK 12595-R1

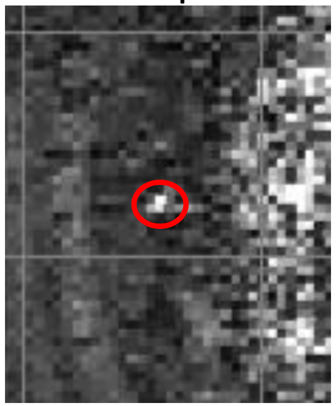
Traditional NDE Results: MIA



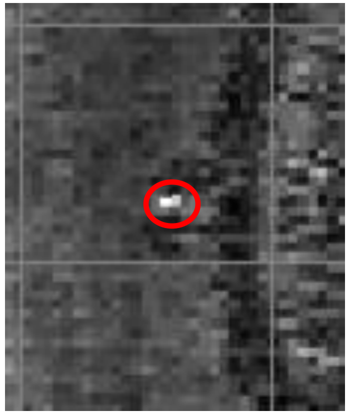




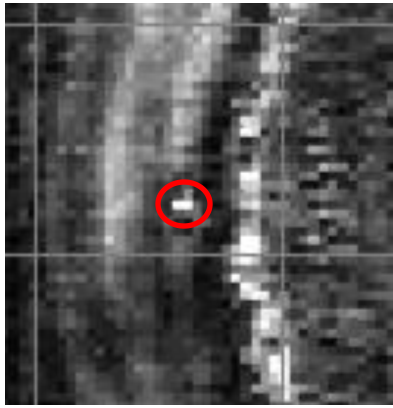
Early Reflection ~14µs



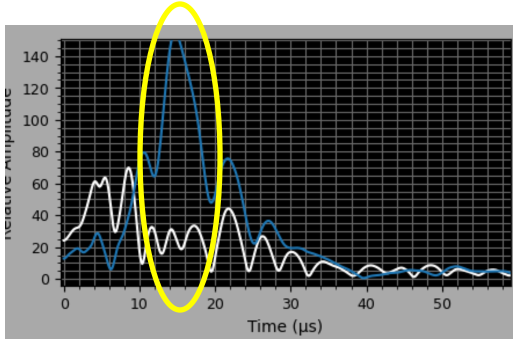
Spectral Amplitude 226 kHz



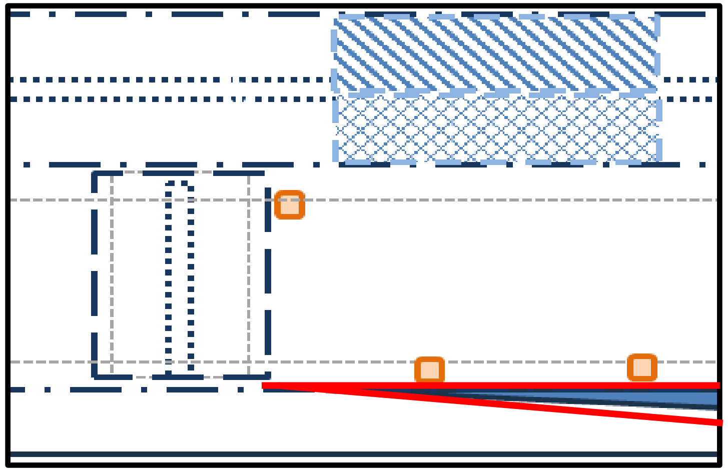
Spectral Amplitude 157 kHz



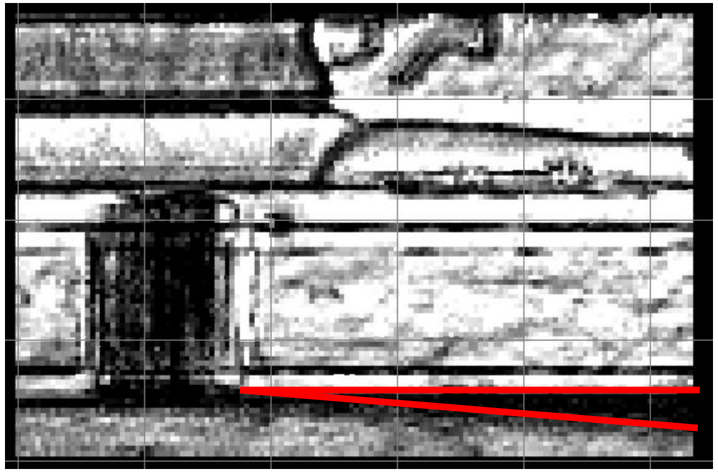
Very small flaw, but visible in multiple frequencies and times (very dramatic change in signal/signature).



FAA Composite Laminate Aircraft Structure Sample



UltraSpec™ Results



- Stringer Delamination/Disbond
- Stringer Delamination/Disbond
- SHM Sensors
- Stringer Partial Disbond

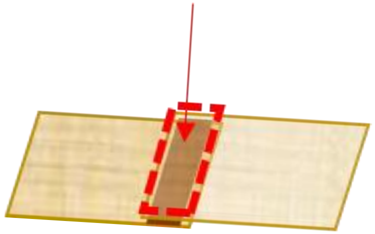
Clearly found partial disbond.

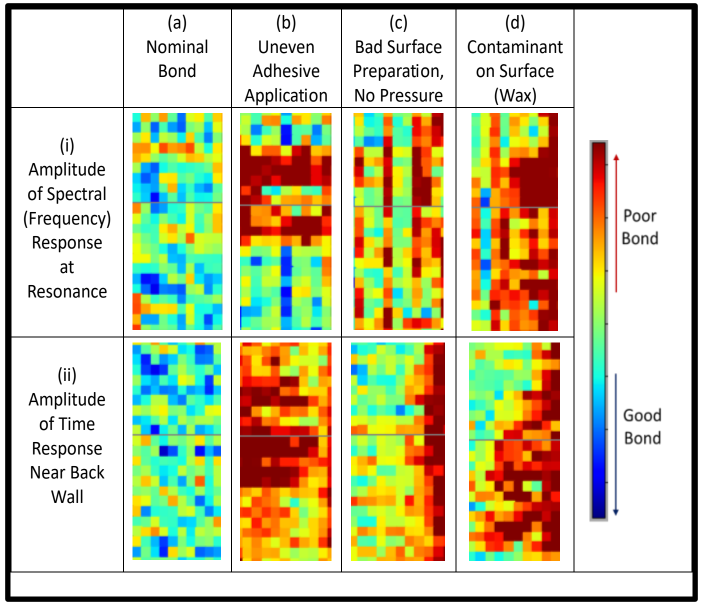
More detail than traditional UT results.

FAA-AANC NDI Test Specimen Library Sample

Future Work

- POD Studies – Laminate Composites
- Bonded Structures (Composite, Metal, Both)
- Weak Bonds (Composite, Metal)
- Characterize material properties (C/C)

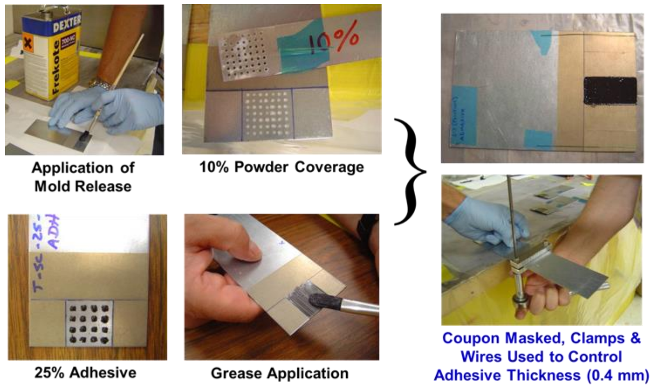




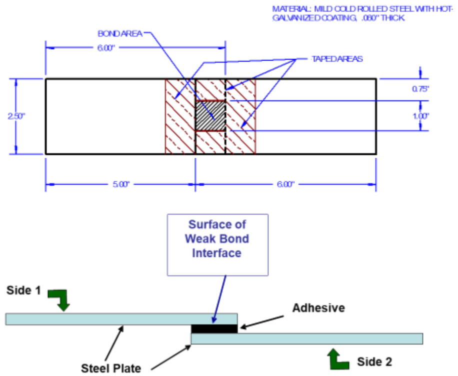
Samples from Composite Repair SME at Redstone Arsenal

Working on Steel/Steel Weak Bond Studies

FAA-AANC NDI Test Specimen Library Samples



Weak Bond Test Specimen



Schematic Showing Position of Weak Bond Surface Relative to Inspection Sides 1 and 2

Acknowledgements

- Kratos TEAM: Tricia Vines, Nathan Davis, Kyra George, AJ Matta, Stephen Ferrell, Jonathan Kinney, Cole Walton
- Dennis Roach, DR Engineering
- FAA AANC NDI Test Specimen Library (Paul Swindell, Danielle Stephens)

Questions?

Can we help you with your inspection challenges?

- Kratos SRE is available for demonstrations
  - TEAMS meetings or in-person
- If you have difficult inspection challenges, send us a sample!
  - We can perform a quick assessment