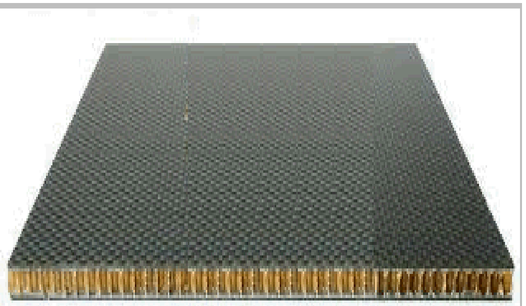
SAND2014-2106C

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Photos placed in horizontal position with even amount of white space between photos and header



Computed Tomography and 3D Rendering of Composite Materials

Burke L. Kernen and David G. Moore
Sandia National Laboratories
Structural Dynamics and X-ray/NDE
blkerne@sandia.gov
505-284-9096

Sandia National Laboratories

Exceptional service in the national interest

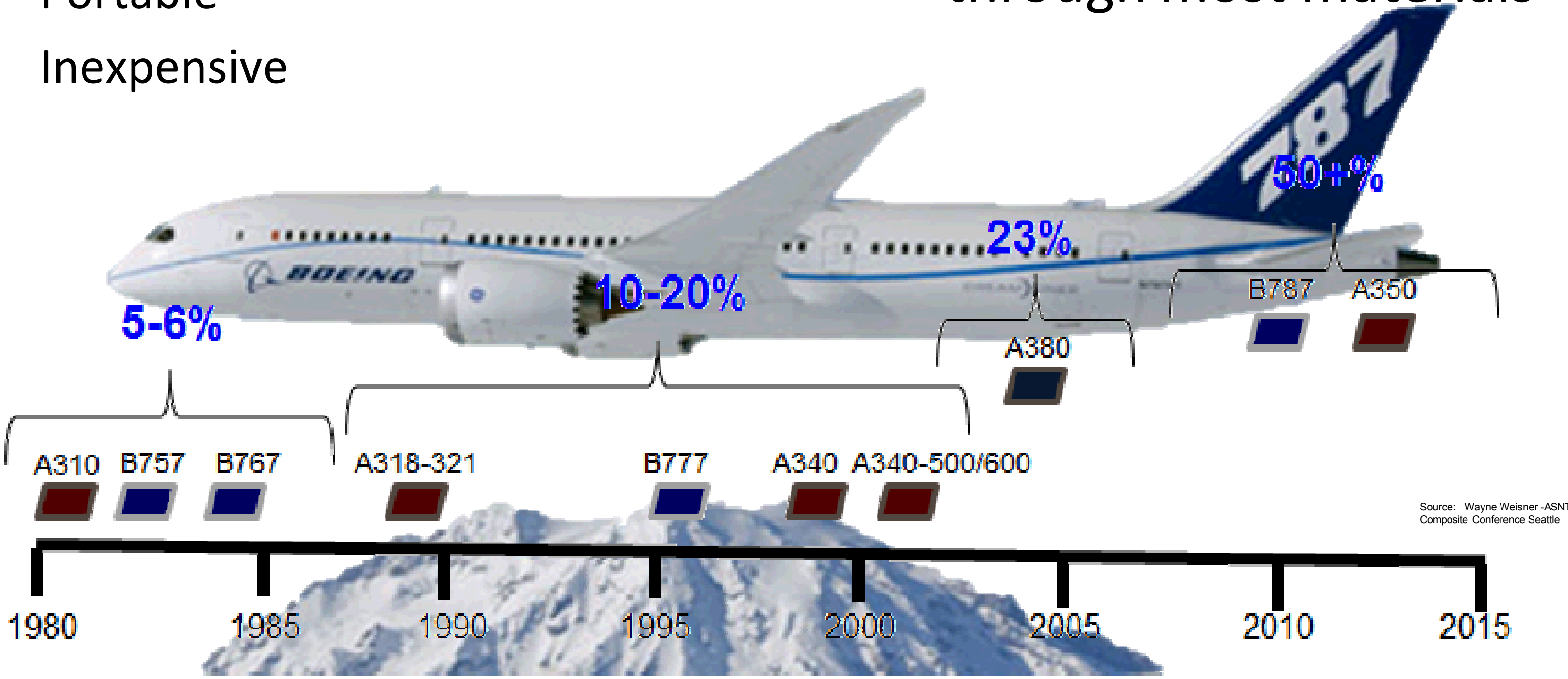
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Computed Tomography and 3D Rendering of Composite Materials

- Background
- Computed Tomography - *overview*
- Technique Development - *3 different sample types*
- Data Analysis - *comparison to other NDT techniques*
- Conclusion

Composite Material NDT

- Aerospace – Lighter Stronger
- High Performance - High consequence failures
- Ultrasonic Testing – Common
  - Portable
  - Inexpensive
- Computed Tomography - Validation and Research Tool
  - High resolution
  - Better penetration through most materials

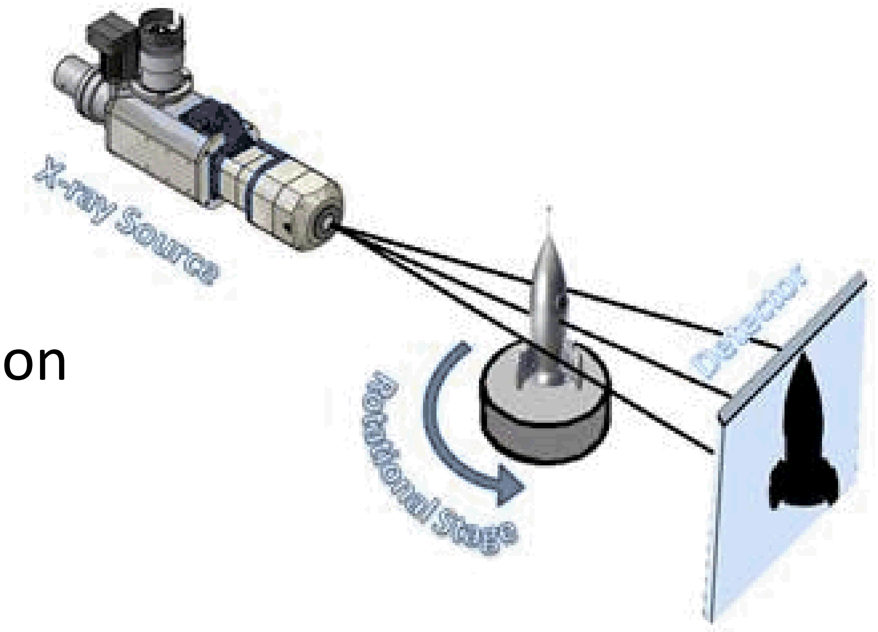


Computed Tomography and 3D Rendering of Composite Materials

- Background
- Computed Tomography - *overview*
- Technique Development - *3 different sample types*
- Data Analysis - *comparison to other NDT techniques*
- Conclusion

X-Ray Computed Tomography (CT) Setup

- Penetrating radiation (X-Ray) attenuated by composite material
- Digital sampling of the radiation
- Multiple images taken at different angles
- Images mapped into a three dimensional data set
- Data shown as single "slice" or rendered

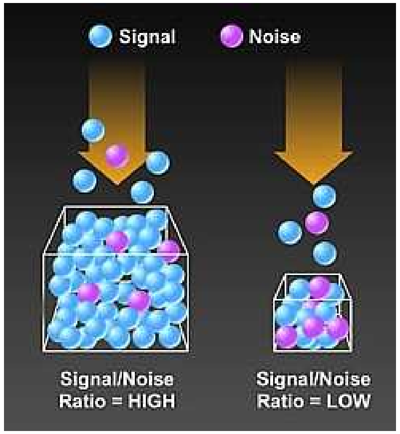


Computed Tomography and 3D Rendering of Composite Materials

- Background
- Computed Tomography - *overview*
- Technique Development - *3 different sample types*
- Data Analysis - *comparison to other NDT techniques*
- Conclusion

Technique Design

- Higher Signal to Noise Ratio through Artifact Reduction
  - Beam Hardening and Under Sampling
  - Cone Beam
  - Unsharpness
  - Motion and Centering
  - Ring



Source: nikonian.com

- Higher Resolution through Smaller Detector Pixels
  - More pixels per sample area = higher resolution images
  - Less sensor area = increased sampling times
  - Smaller focal spot sizes = less x-ray power

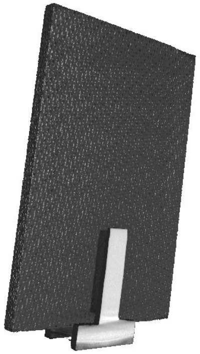
Composite Specimen Types

- Honeycomb Composite
  - Nomex™ honeycomb sandwiched between two laminates with defined engineered flaws

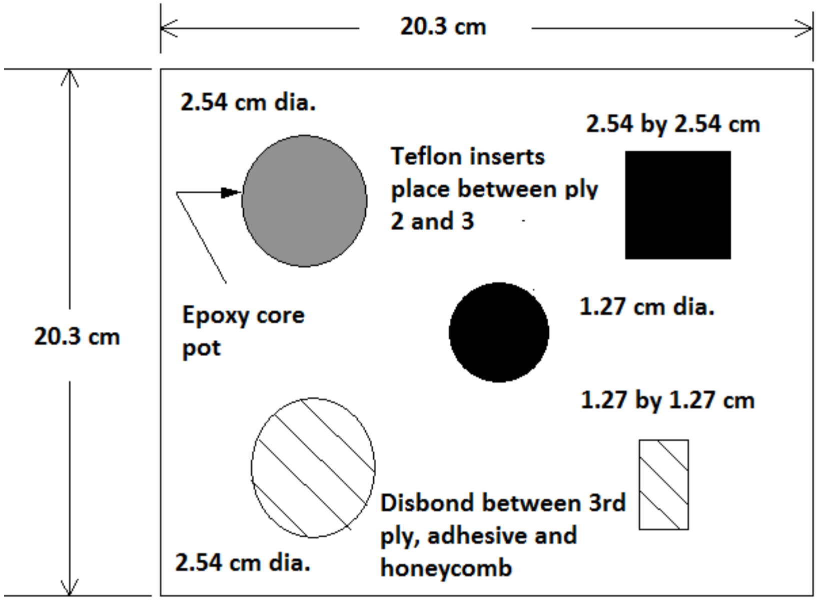
- Wind Turbine Blade
  - Fiber Glass Composite with varied porosity and resin concentration

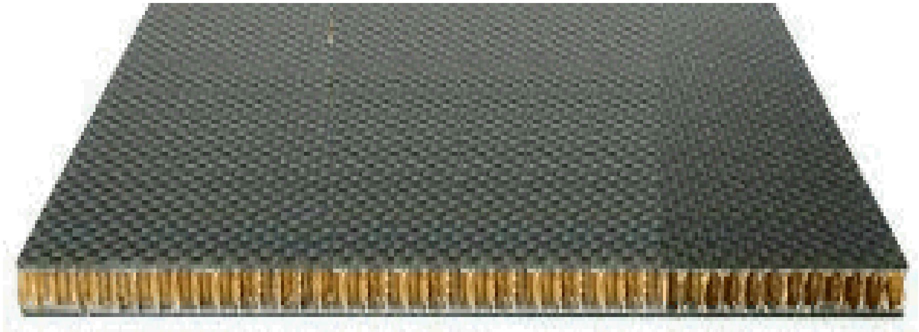
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

- Carbon Fiber Weave
  - Carbon Fiber Composites with varied porosity from curing conditions



Honeycomb Sample Preparation





Simulated Flaws

1) **2.54 cm square Teflon shim (located between plies 2 and 3)**
2) **12.7 mm diameter Teflon shim (located between plies 2 and 3)**
3) **1.27 cm square disbond (located at adhesive bond line)**
4) **2.54 cm diameter disbond (located at adhesive bond line)**
5) **2.54 cm diameter epoxy potted honeycomb core (full thickness)**
6) ***Core damage location 1 (in center of core)***
7) ***Core damage location 2 (in center of core)***

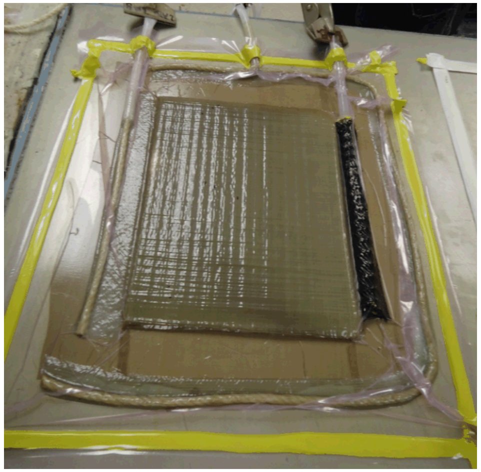
Honeycomb CT Technique

- Optimized for Signal to Noise
  - Higher x-ray photon density (increased flux)
  - Beam filtering to narrow x-ray spectrum
  - Source to object distance maximized
  - Increased frame averaging
  - Increased number of Projections
  - Multipoint detector calibration
  - ~20:1 SNR achieved with this technique
- Techniques used:

Sample	***Honeycomb***		
Energy	***90 KeV***	**Projections**	***1999***
Target Power	***1KW***	**Effective Pixel Size**	***200um (native resolution of detector)***
Magnification	***1.2x***	**Detector Type**	***Perkin Elmer XRD 1621 AN3-ES***
Filter	***1mm Al***	**X-ray Head Type**	***Comet MXR 451 HP/11***
Frame Average	***32***		

Fiberglass Sample Preparation

- Specimens are fiber glass filled with resin
  - Each specimen filled with resin under vacuum
  - Air was introduced in various quantities to create different porosities
    - One method used clamped tubes vented to atmosphere
    - The second method used injection ports at various locations
  - The specimens were then allowed to cure



Fiberglass CT Technique

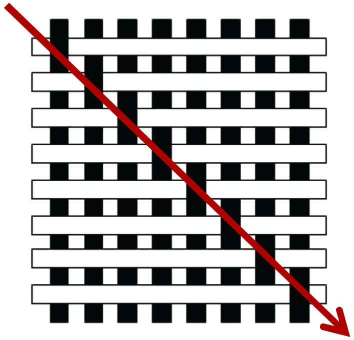
- Optimized for Signal to Noise
  - Higher x-ray photon density (increased flux)
  - Beam filtering to narrow x-ray spectrum
  - Source to object distance maximized
  - Energy increased for edge penetration
  - Increased frame averaging
  - Increased number of Projections
  - Multipoint detector calibration
  - ~15:1 SNR achieved with this technique

- Techniques used:

Sample	*Fiberglass Resin*		
Energy	*350 KeV*	**Projections**	*1999*
Target Power	*1.5KW*	**Effective Pixel Size**	*200um (native resolution of detector)*
Magnification	*1.2x*	**Detector Type**	*Perkin Elmer XRD 1621 AN3-ES*
Filter	*1mm Cu*	**X-ray Head Type**	*Comet MXR 451 HP/11*
Frame Average	*32*		

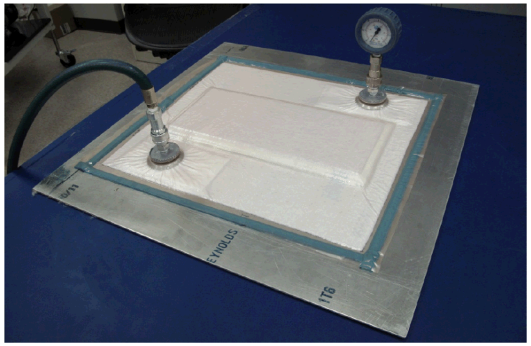
Carbon Fiber Sample Preparation

- Specimens are carbon fiber reinforced plastic (CFRP)
  - constructed of [0/90] prepreg; 8 harness-satin weave with UF3352 TCR™ Resin
  - 150 X 100 X 4.6 mm (12 plies)



- Each sample was cured in an autoclave under different total pressures
  - Total = Bag Pressure + Autoclave Pressure

Sample	1	2	3	4	5	6
psi	0	15	25	35	45	60



Source: Andrew Siever Master Candidate
University of California Los Angles, 2014

Carbon Fiber CT Technique

- Optimized for Resolution
  - Smaller native pixel size (127um VS 200um)
  - Higher resolution (93um VS 168um)
  - Source to detector distance shortened (flux)
  - Reduced frame averaging (time)
  - Same number of projections (Nyquist)
  - Multipoint detector calibration (non-linear detector response)

- Technique used:

Sample	*Carbon Fiber*		
Energy	*225 KeV*	**Projections**	*1799*
Target Power	*54W*	**Effective Pixel Size**	*93um*
Magnification	*1.4x*	**Detector Type**	*Varian 2520 -14bit*
Filter	*1mm Cu*	**X-ray Head Type**	*Yxlon 225 micro focus*
Frame Average	*16*		

Computed Tomography and 3D Rendering of Composite Materials

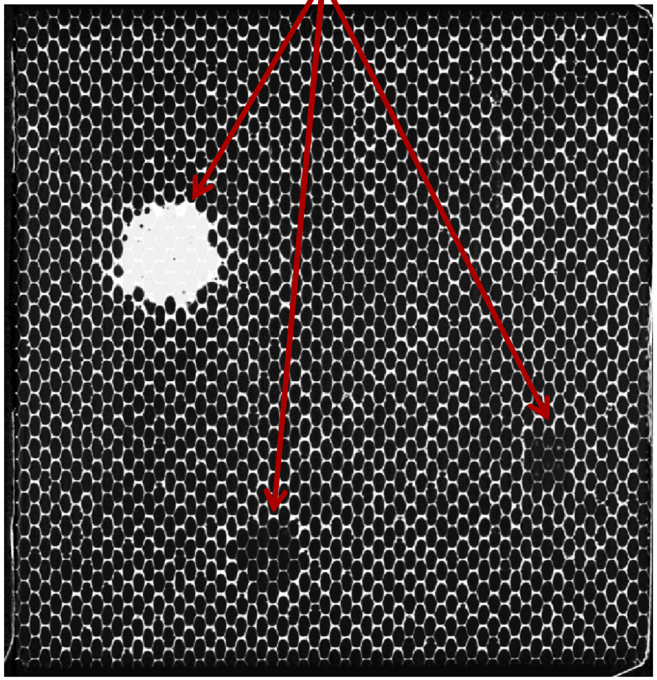
- Background
- Computed Tomography - *overview*
- Technique Development - *3 different sample types*
- Data Analysis - *comparison to other NDT techniques*
- Conclusion

Honeycomb Flaw Detection

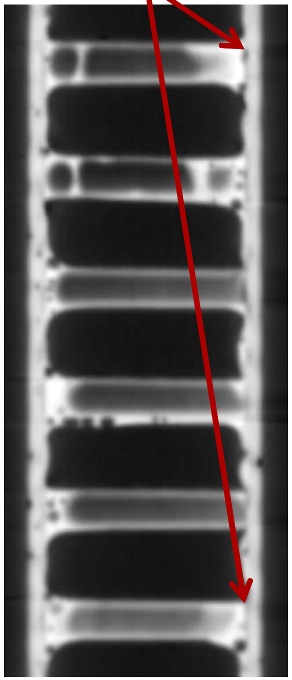
Inter-ply layer 2-3 (delaminations detected)

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Laminate and adhesive bond line (disbonds and epoxy fill detected)

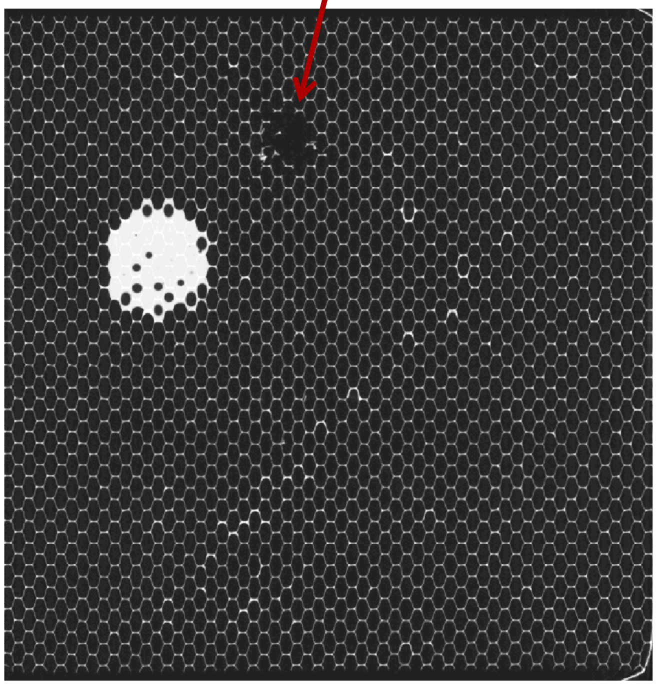


Side view showing disbond

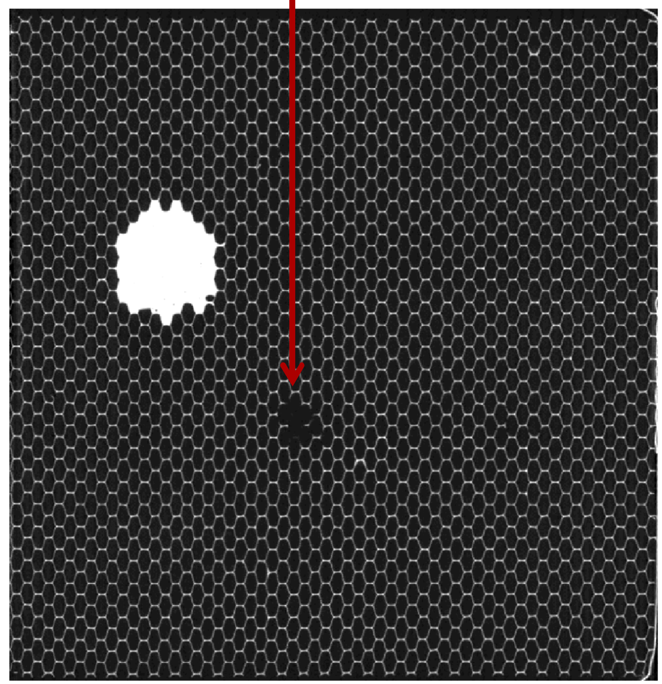


Manufacturing Anomalies in Honeycomb

Damaged core site near middle of sample



Another damaged core site near middle of sample



Side view showing core damage

Measurements – Disbond/Delamination

Simulated Flaw Measurement

1) **Teflon Shim #1: 28mmX26mm**
2) **Teflon Shim #2: 12mm Dia.**
3) **Disbond #1: 20mmx16mm**
4) **Disbond #2: 27mm**

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Measurements – Epoxy Fill

- Simulated Flaw Measurement
  5) Potted epoxy fill: 27mm/10,000mm^3
- Ideal cells filled = 39
- Ideal volume = 10,920mm^3
- Missing 920mm^3 of epoxy fill

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Measurements – Core Damage

- Flaw Measurement
  6) Core damage affected area #1: 840 mm2
  7) Core damage affected area #2: 335 mm2

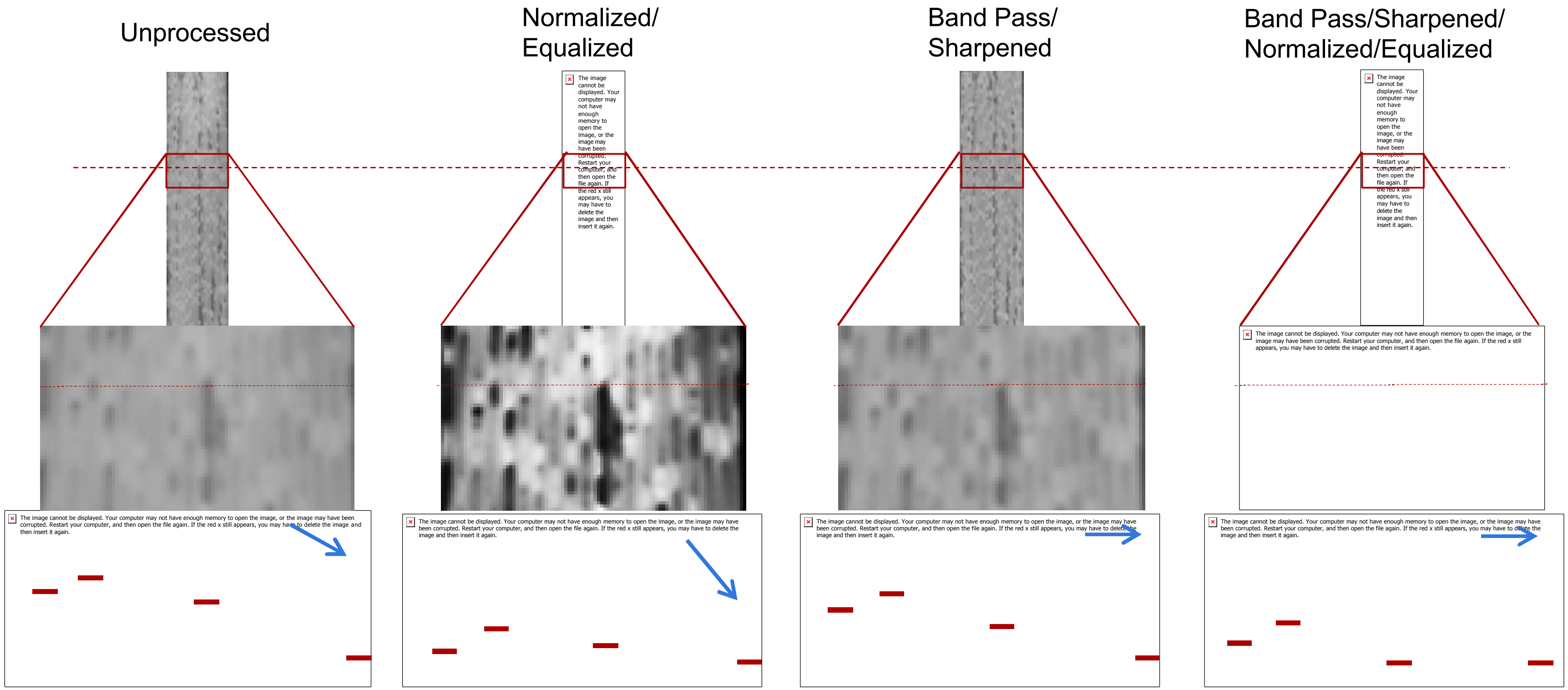
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Fiberglass Post CT Processing

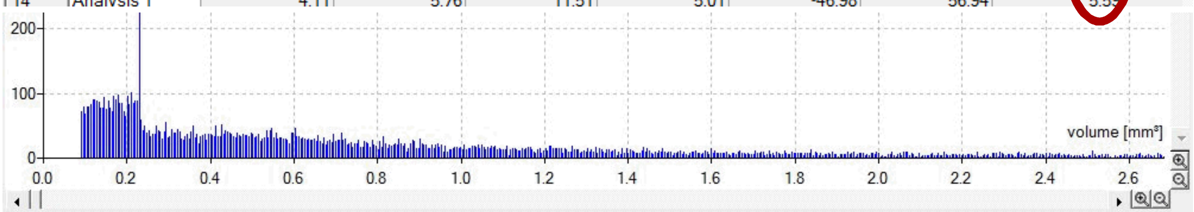
- Accentuation and homogenization of select greyscale values with edge enhancement for porosity segmentation
  - Filter data using band pass technique
  - Find threshold value using the Maximum Entropy method
  - Segmentation of data volumetrically



Fiberglass Porosity Analysis

- Segmentation and measurement of pores
  - Pore propagation dominant along the long fibers and in the upper half of the sample
  - Overall pore volume is 4.31%
  - Correlates with visual observation and expected results

	Analysis	Probability	Radius [mm]	Diameter [mm]	Center X [mm]	Center Y [mm]	Center Z [mm]	Volume [mm³]	Voxel
1	Analysis 1	5.38	2.15	4.29	3.70	47.15	-94.57	3.30	
2	Analysis 1	5.08	2.23	4.46	2.50	6.06	-95.47	3.83	
3	Analysis 1	4.94	0.94	1.89	3.42	8.37	-59.13	0.88	
4	Analysis 1	4.69	1.70	3.41	1.84	-54.91	-66.19	1.89	
5	Analysis 1	4.67	0.92	1.85	3.84	-54.28	-103.86	0.62	
6	Analysis 1	4.60	1.54	3.07	3.26	41.69	-80.57	1.47	
7	Analysis 1	4.60	1.60	3.21	4.88	-41.83	-29.43	2.14	
8	Analysis 1	4.60	2.18	4.36	3.12	-24.22	72.91	2.83	
9	Analysis 1	4.51	14.66	29.32	2.78	15.36	-102.90	26.30	
10	Analysis 1	4.41	1.42	2.85	2.52	-45.25	-82.64	1.60	
11	Analysis 1	4.37	1.18	2.36	-0.55	20.85	-103.70	0.68	
12	Analysis 1	4.24	1.18	2.35	3.84	-54.11	-92.76	1.45	
13	Analysis 1	4.16	2.35	4.70	3.48	-17.39	-84.54	3.55	
14	Analysis 1	4.11	5.76	11.51	5.01	-46.98	56.94	5.59	



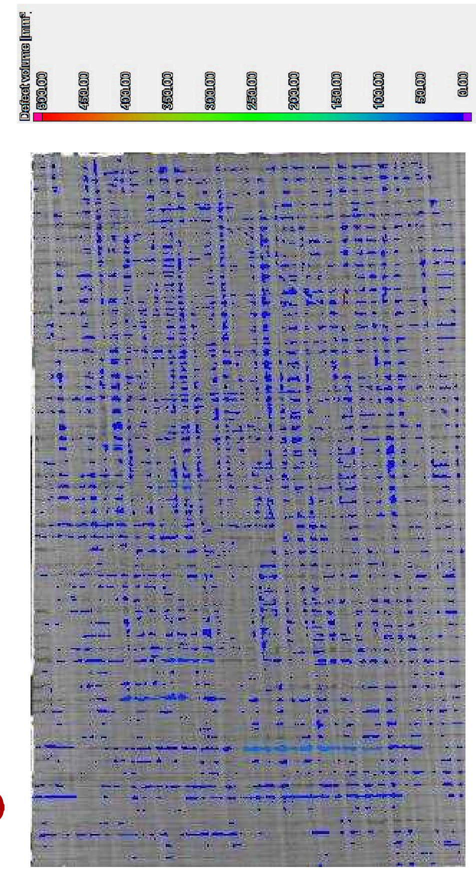
Options

Binning: Off | Scale X: Linear | Scale Y: Linear

Voids			
∑ Voxel	3829658	∑ PX	34482.66 mm²
∑ Volume	17640.45 mm³	∑ PY	10586.40 mm²
∑ Surface	174291.66 mm	∑ PZ	34208.38 mm²

Inclusions			
∑ Voxel	n/a	∑ PX	n/a
∑ Volume	n/a	∑ PY	n/a
∑ Surface	n/a	∑ PZ	n/a

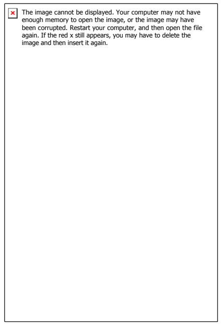
Material			
Iso value	using surface determination	Volume	392042.78 mm
Voids	17640.45 mm³	Voids	4.31 %
Inclusions	n/a	Inclusions	n/a



Carbon Fiber Porosity Analysis

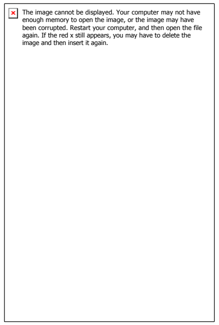
- Calculation of pore sizes and distribution prior to damage

1



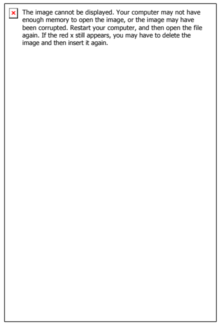
Color Scale 0-5000 mm^3

2



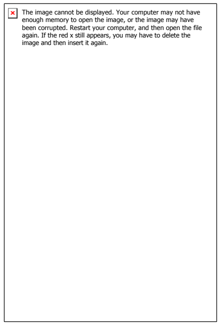
Color Scale 0-500 mm^3

3



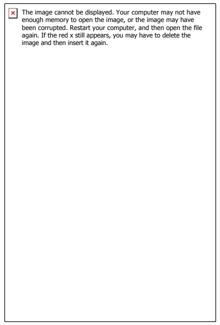
Color Scale 0-500 mm^3

4



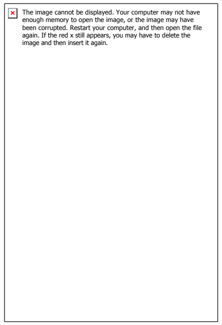
Color Scale 0-500 mm^3

5

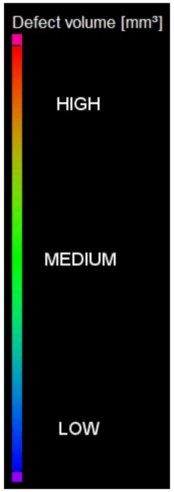


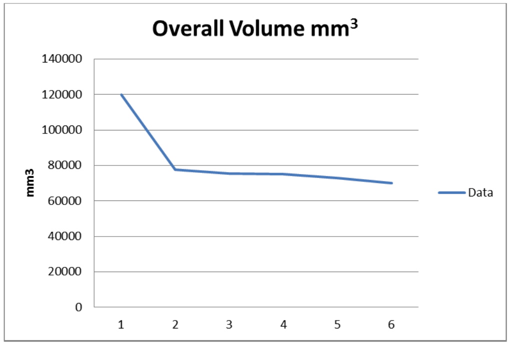
Color Scale 0-500 mm^3

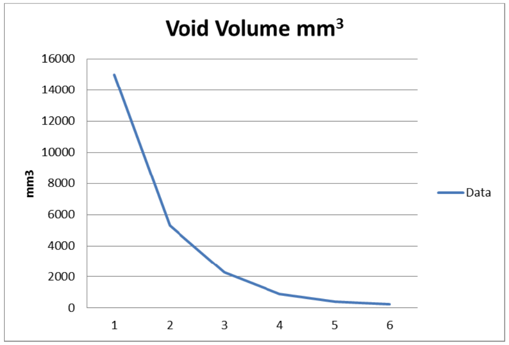
6

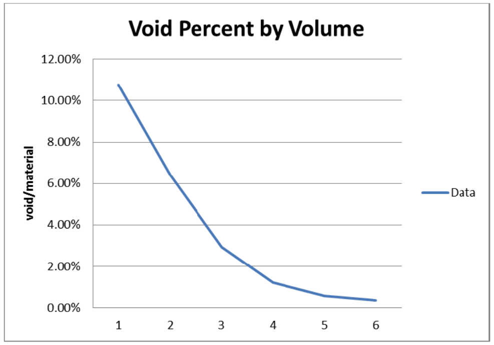


Color Scale 0-1 mm^3



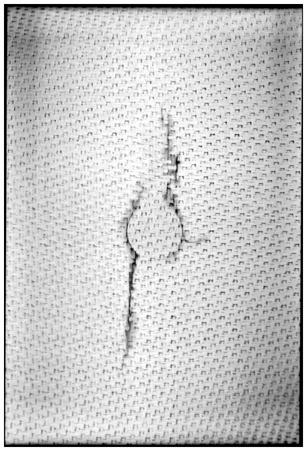




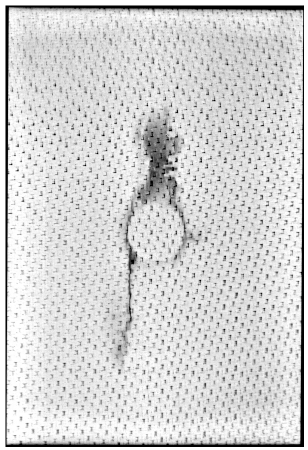


Post Damage CT Images

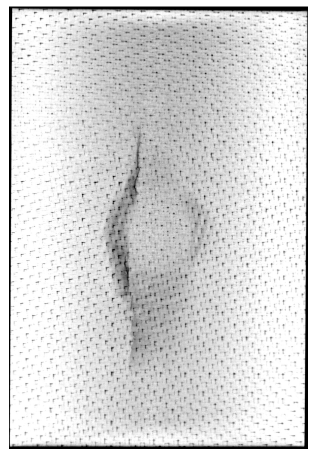
- Example images showing damage at various depths from the impact surface (samples impacted per ASTM D7136)



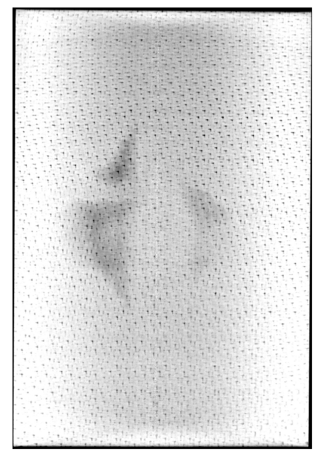
0.75mm depth



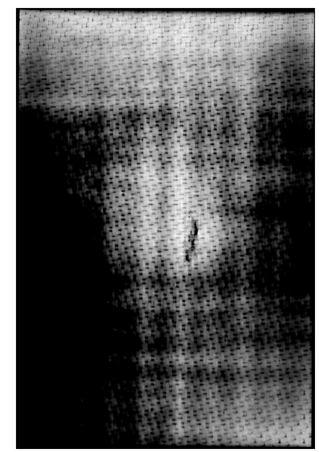
1.2mm depth



2.3mm depth



3.4mm depth



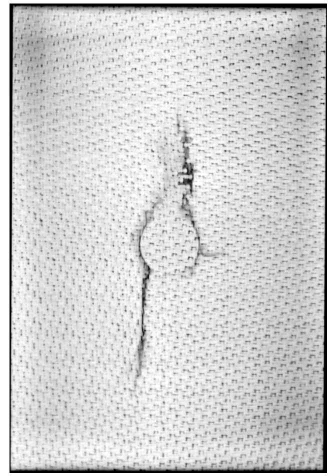
4.9mm depth

Carbon Fiber CT – IR – UT Comparison

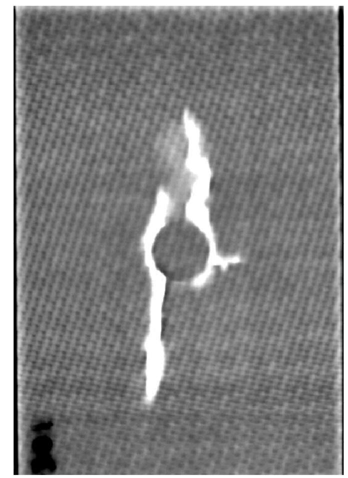
- Samples inspected with CT, IR, UT
- CT data shows good correlation with IR
  - On surface and at shallow depths
  - IR dispersion beyond shallow depths
- UT interrupted by porosity

Front surface as seen from impact

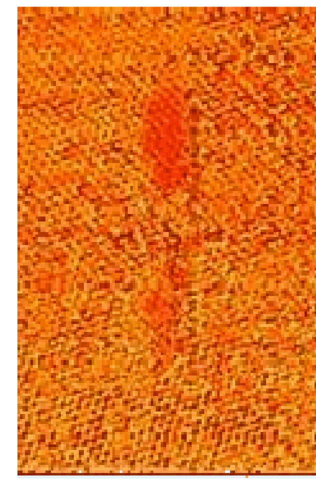
CT



IR

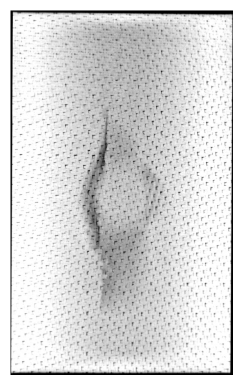


UT

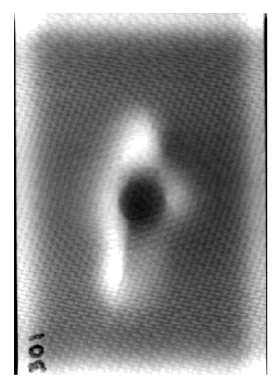


~2.4mm into plate from surface

CT

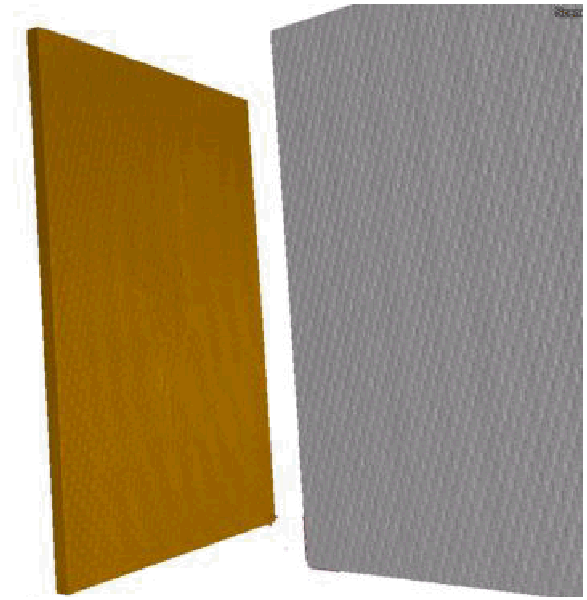


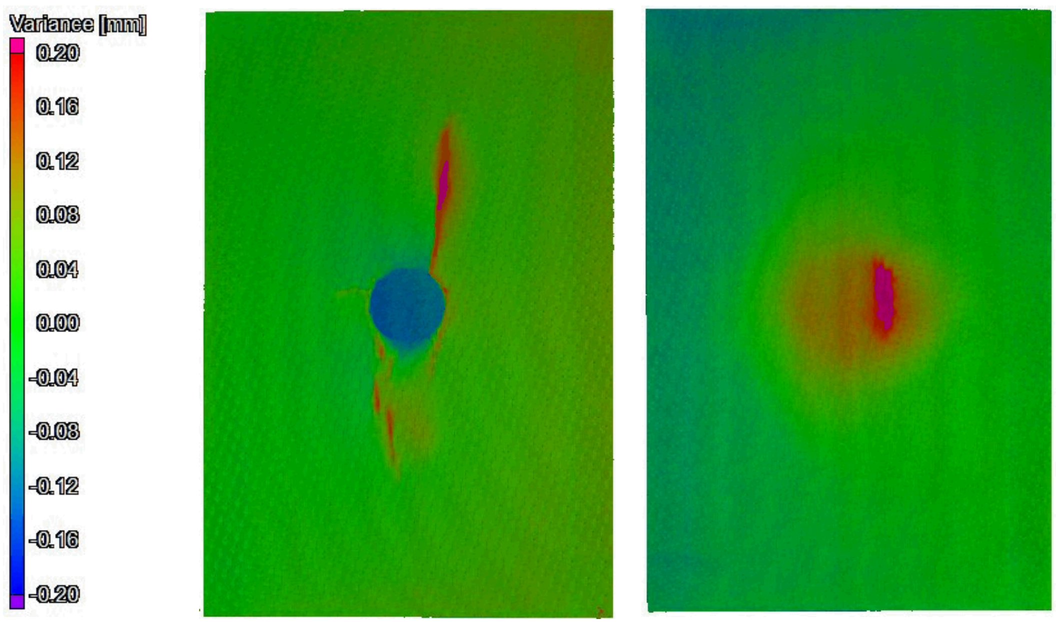
IR

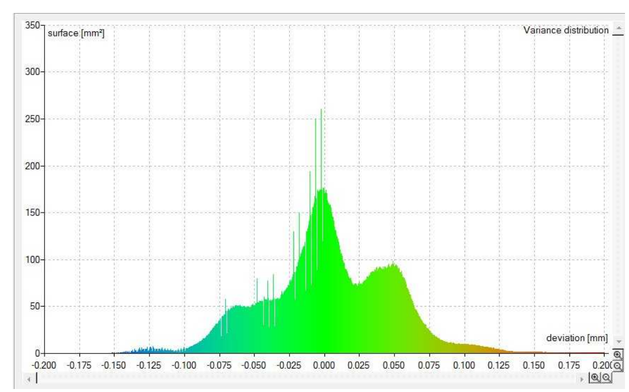


Nominal Actual Comparison

- Compares reference CT or CAD model to another CT
  - Visualization of differences
  - Measurement of variance





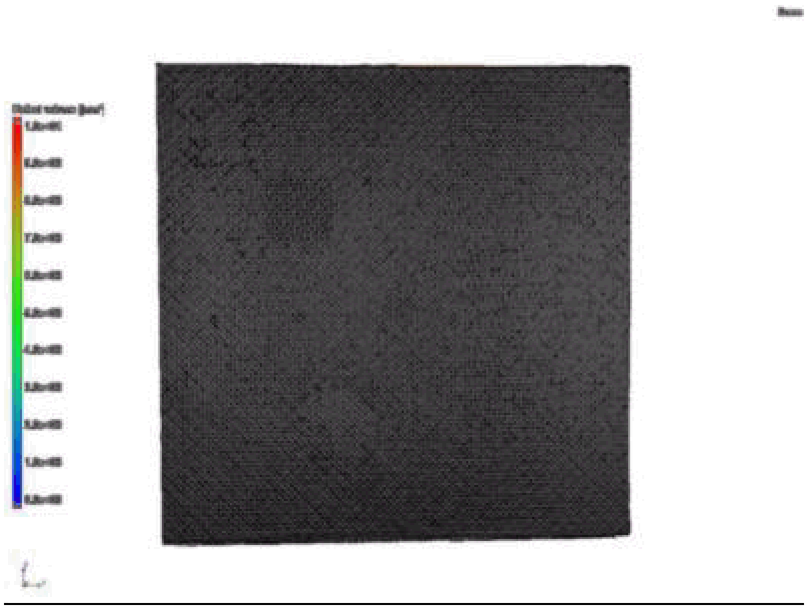


Computed Tomography and 3D Rendering of Composite Materials

- Background
- Computed Tomography - *overview*
- Technique Development - *3 different sample types*
- Data Analysis - *comparison to other NDT techniques*
- Conclusion

Conclusions

- CT is an Excellent Validation and Research Tool
  - Holistic
  - High Resolution
  - 3D Image Visualization
  - Metrology Capable
- CT Constraints
  - Hardware Cost
  - Sample Size



Questions?

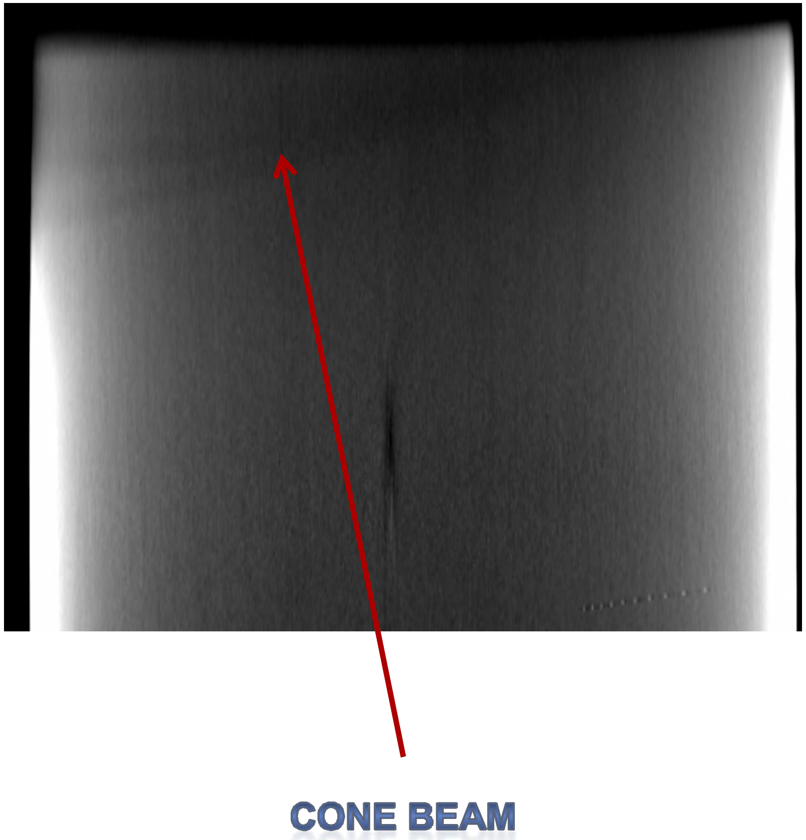
Burke L. Kernen
blkerne@sandia.gov
505-284-9096

Artifact – Beam Hardening and Under Sampling

- Non-Linear Photon Absorption
  - Increase Filtering
  - Collimate Beam
  - Software Correction
- Nyquist Sampling Criteria
  - Increase Sampling

Artifact – Cone Beam

- Geometry Related
- Reduce Angle from Source to Top/Bottom of Detector

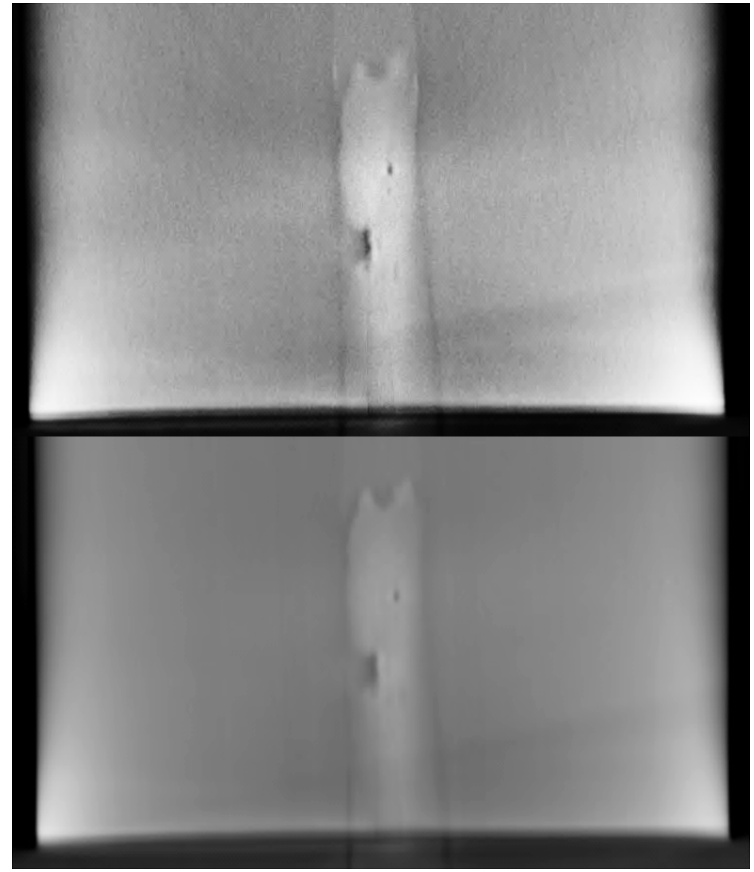


Artifact – Geometric Unsharpness

- Geometry Related
- Reduce Angle from Source to Top & Bottom of Detector

SHARP

UNSHARP



Artifact – Motion and Centering

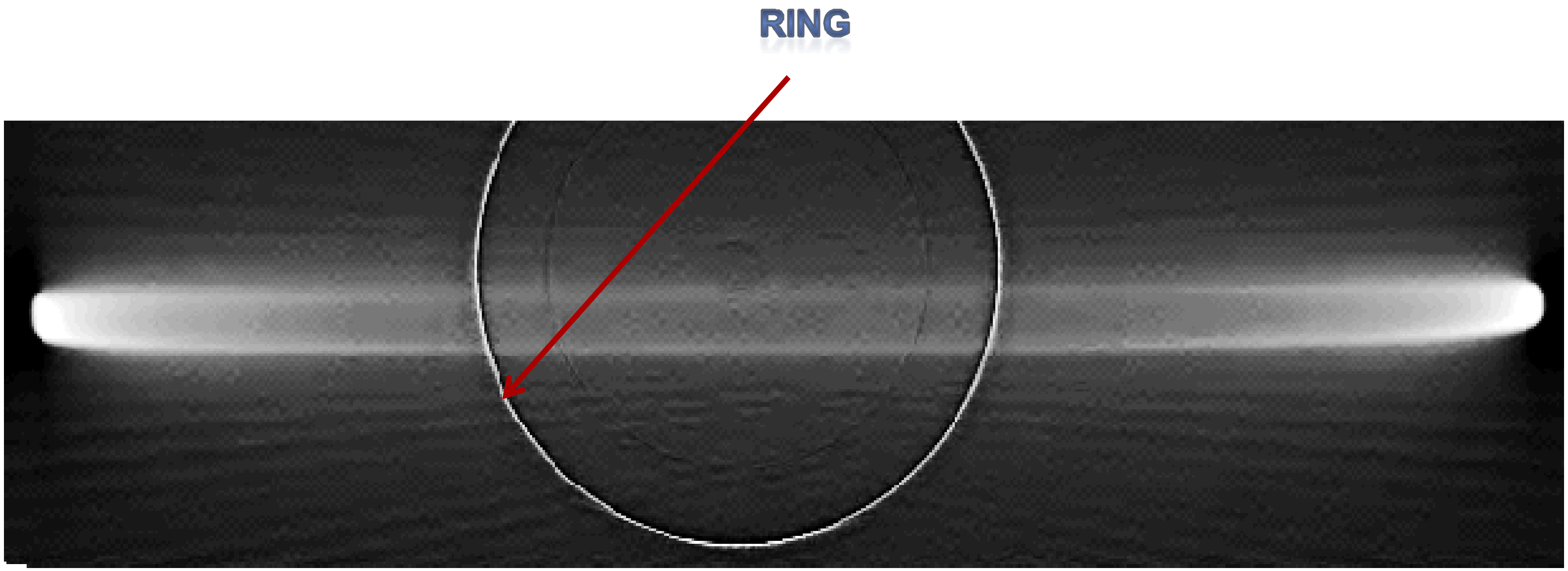
MOTION

CENTERING

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

- Faulty Fixturing
  - Secure Fixturing
- Incorrect Geometry Data
  - Experimentation or Re-Measure

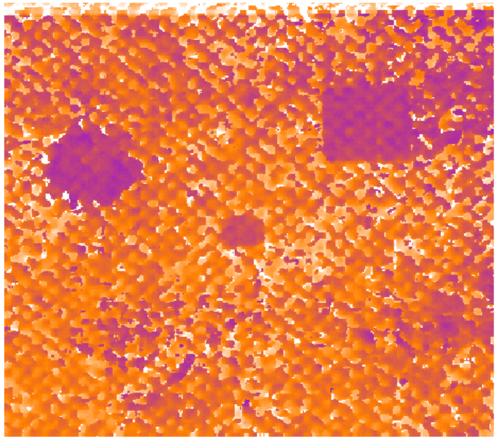
Artifact - Ring



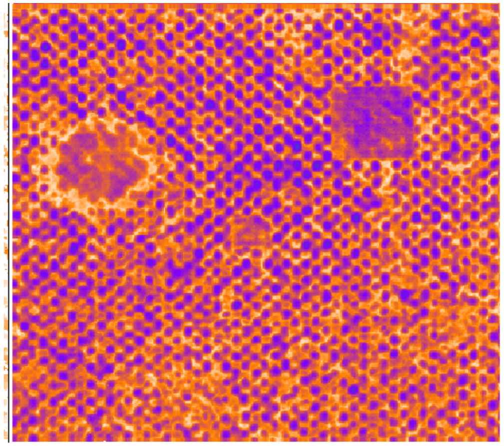
- Bad Detector Pixel
  - Defective Pixel Mask
  - Detector Calibration

Honeycomb CT UT Comparison

- Only the epoxy fill and Teflon delaminations were detected
  - Porosity interference



Amplitude Gate Image



Depth Gate Image

UT Setup

-MAUS V™, (Mobile automated UT scanner) was used to acquire the images
-A 5 MHz probe, 6.35 mm in diameter
-Scanner resolution- 0.5 mm
-The gate was set to monitor the back wall signal from the laminate