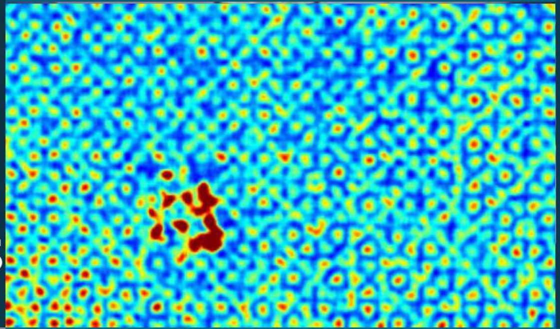
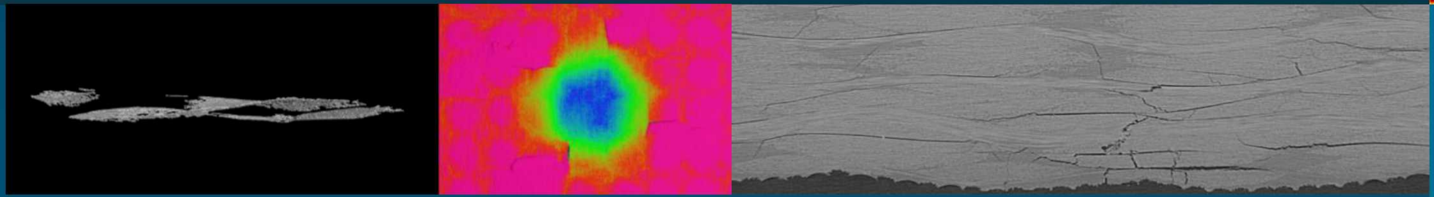
Sandia National Laboratories

SAND2019-7871C

Nanofocus X-ray Computed Tomography and Ultrasonic Inspection of Barely Visible Impact Damage in Carbon Fiber Reinforced Polymers





PRESENTED BY

Elliott Jost—*July 17, 2019—QNDE 2019*

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U.S. DEPARTMENT OF ENERGY NNSA

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Introduction

Carbon Fiber Reinforced Polymers (CFRP)

- Laminated composites are used in aerospace, defense, and automotive and are susceptible to impact damage

Composites Impacts

- Studying impacts reveals damage mechanisms and helps improve damage resistance of materials
- BVID (Also called low-velocity impact damage)
  - Difficult or impossible to visibly identify
  - Defined as 1-10m/s impacts by some, but dependent on other factors (total energy input, layup, etc.)

Composites Inspection Techniques

- Ultrasonics (UT)
- Thermography
- Computed Tomography (CT)

Ultrasonics is most often used due to its **portability** and ability to **image entire structures**

Literature Review/Prior Work

CFRP Impact Damage

- Richardson and Wisheart (1996) identified several damage modes (next slide) observed in composite impacts.

Computed Tomography

- McCombe et al. (2012) used CT to characterize CFRP impact damage on a ply-by-ply basis. Not BVID.
- Léonard et al. (2017) compared CT to UT inspections of CFRP impact damage. Their study addressed the curvature induced by the indentation of the damage to more accurately quantify ply-by-ply damage. Not BVID.
- Bull et al. (2013) used Synchrotron Laminography (SRCL) to identify damage in CFRPs. Crack-length and delamination area were determined on a per-ply-interface basis.
- Böhm et al. (2015) performed in-situ CT testing of CFRP tensile samples to observe deformation.

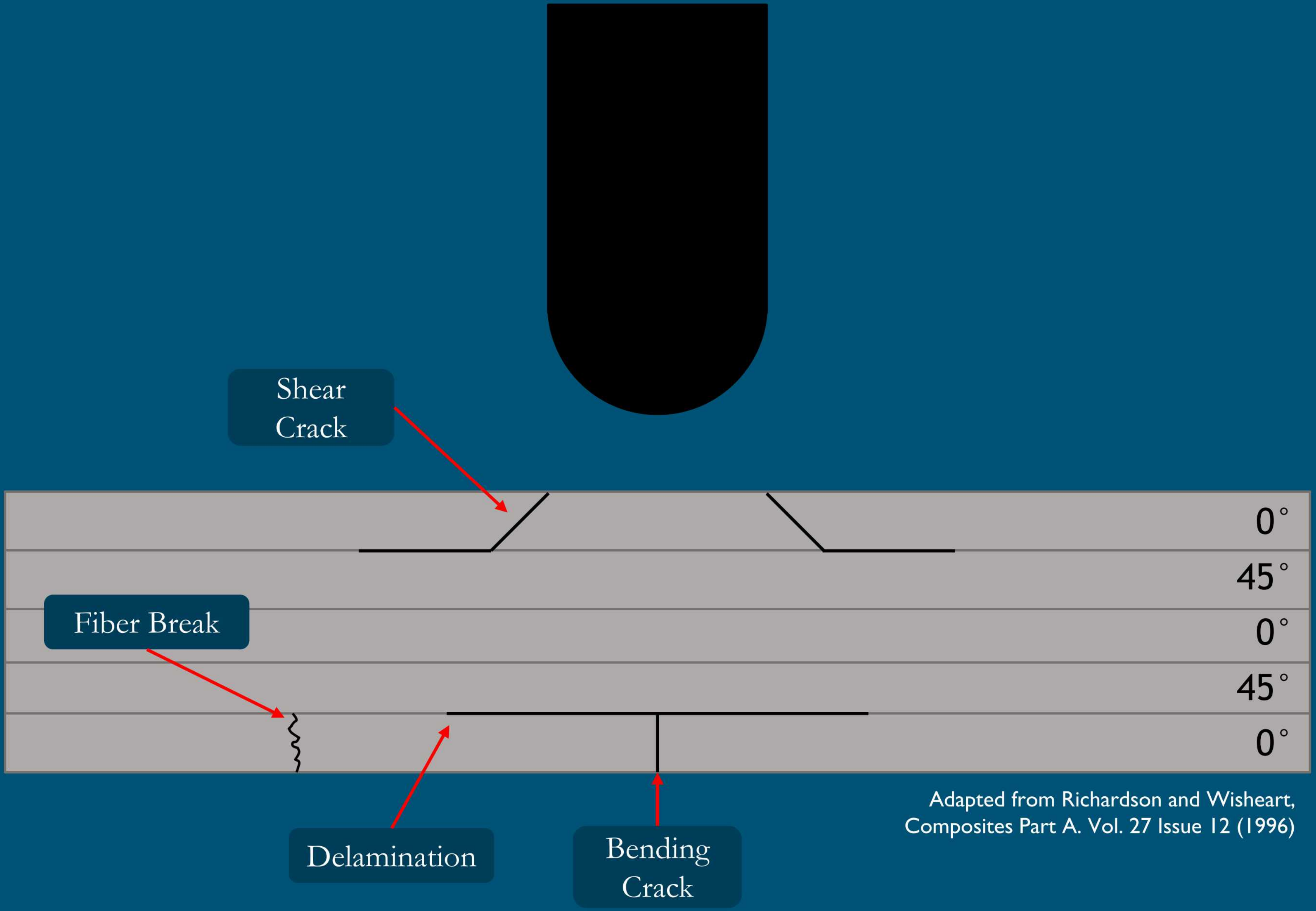
Through pre- and post-impact UT and nanofocus CT inspection, this study seeks to characterize barely visible impact damage in CFRP’s and the detection thresholds for these methods.

Composites Damage Modes

Impact Energy Increase

1. Matrix Cracking:
   - Shear Cracking:
     - Caused by high transverse shear forces upon impact
   - Bending Cracking:
     - Caused by high tensile bending forces on back side of composite
2. Delamination:
   - Cracking due by high interlaminar stresses
   - Occurs between plies of different fiber orientation
3. Fiber Breakage:
   - Fibers cracking under impactor due to indentation effects

~~4. Penetration~~

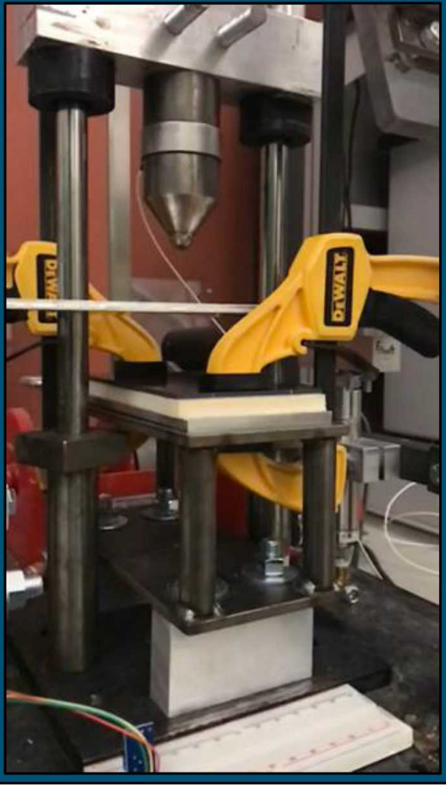


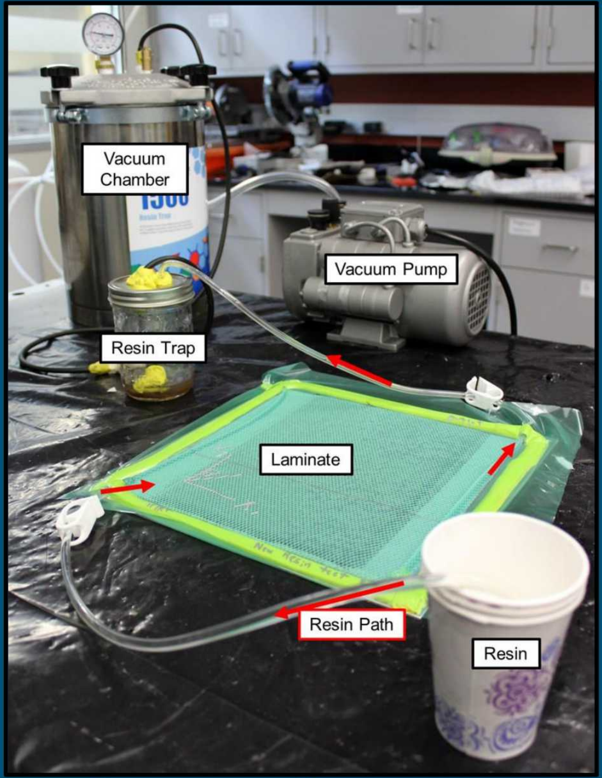
Adapted from Richardson and Wisheart, Composites Part A. Vol. 27 Issue 12 (1996)

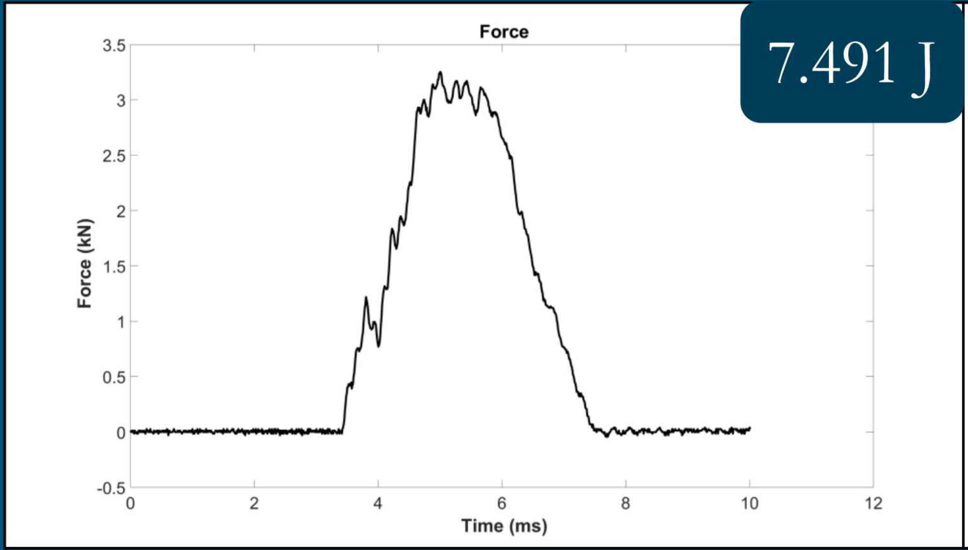
Samples Manufacture/Impact

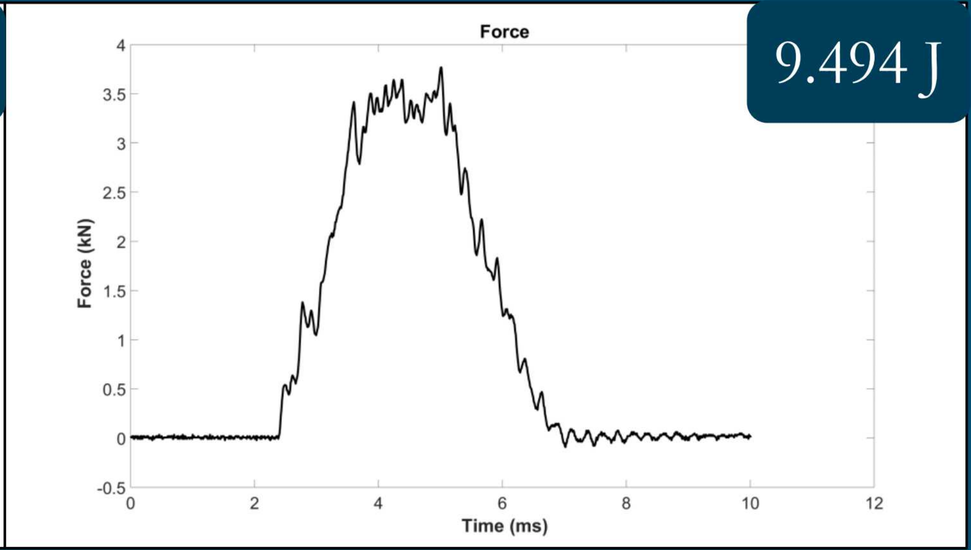
Manufacture
- Two 3K tow, 18-ply $[(0/45)_4/0]_s$ samples manufactured
- Vacuum-assisted resin transfer method (VARTM) used

Impact
- Samples were damaged using hemispherical impactor
- 7.5 and 9.5 J impacts induced.
- Impact monitored using PCB 200C50 force sensor at **100 kHz**
- Impact tests in accordance with ASTM D7136-15

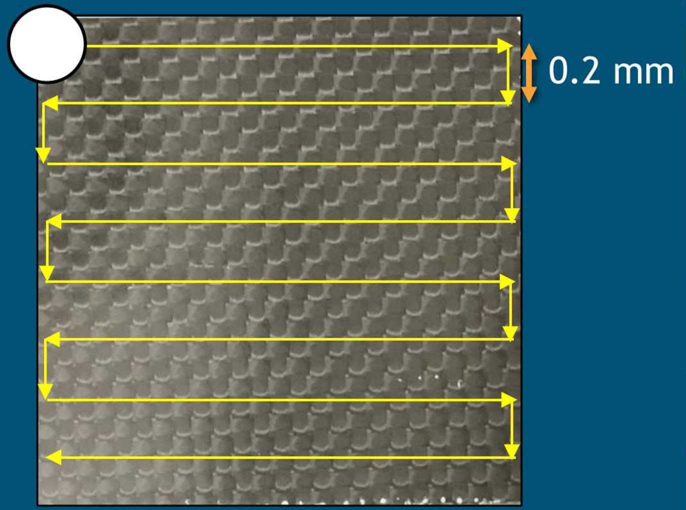








Ultrasonic Inspection



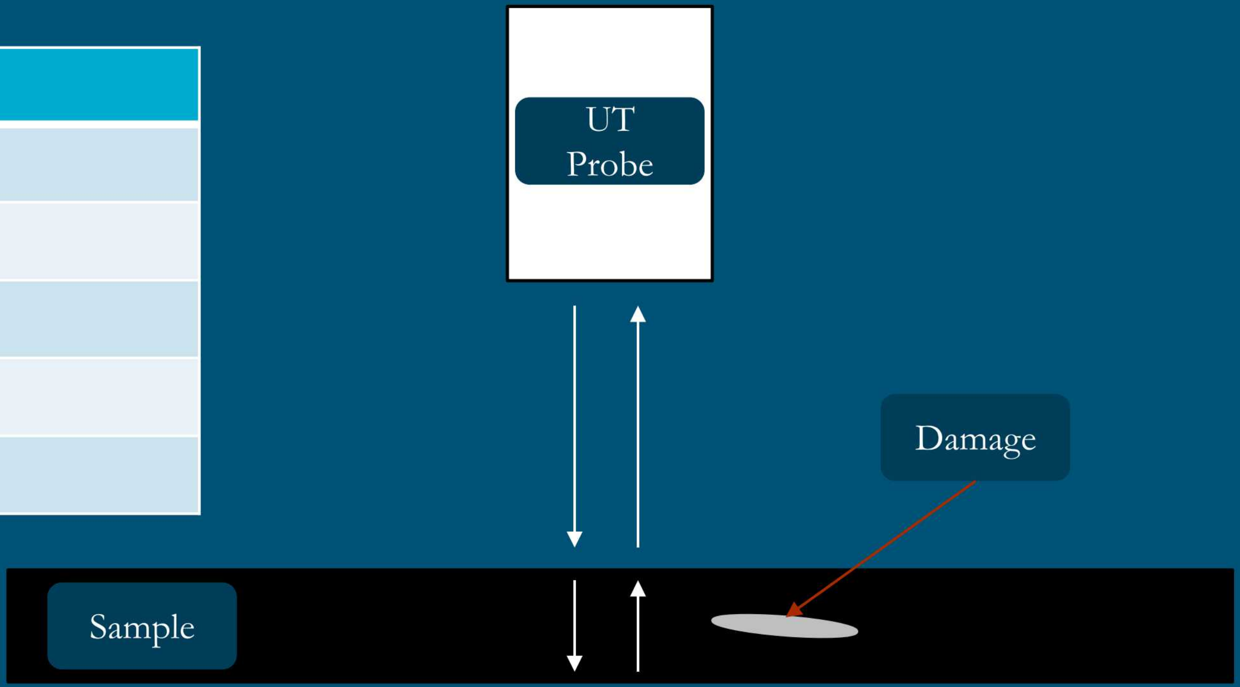
Pre- and post-impact C-Scan ultrasonic inspections were performed on each sample

Inspections conducted over 75x50 mm area containing impact region

Based on 15 MHz frequency and 2700 m/s wave speed:

- Minimum detectable feature is ~90 μm

Inspection Parameter	Value
Transducer Frequency	15 MHz
Focal Length	38.1 mm
Spatial Resolution (X-Y)	0.2 mm/A-scan
Sampling Frequency	160 MHz
Scan Time	2.5 hr (25 min/in^2)

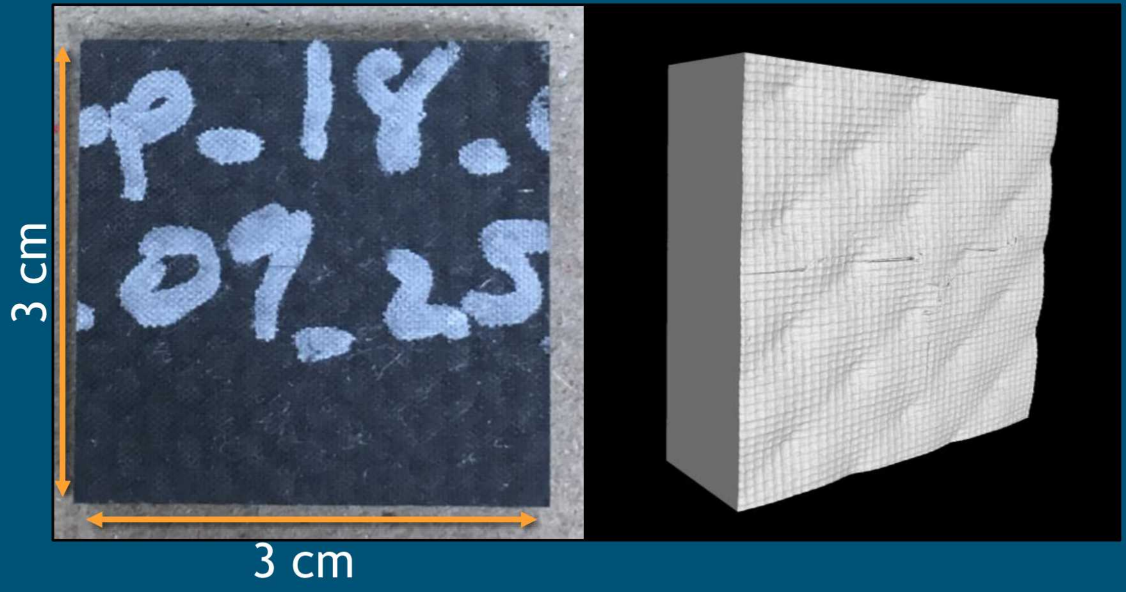


Computed Tomography Inspections

Samples were cut down to 3x3 cm with low-speed saw for CT inspection

Samples were inspected on both a standard microfocus CT system and a nanofocus CT system to understand damage type detectability

CT analysis was performed using Volume Graphics VGSTUDIO MAX 3.2



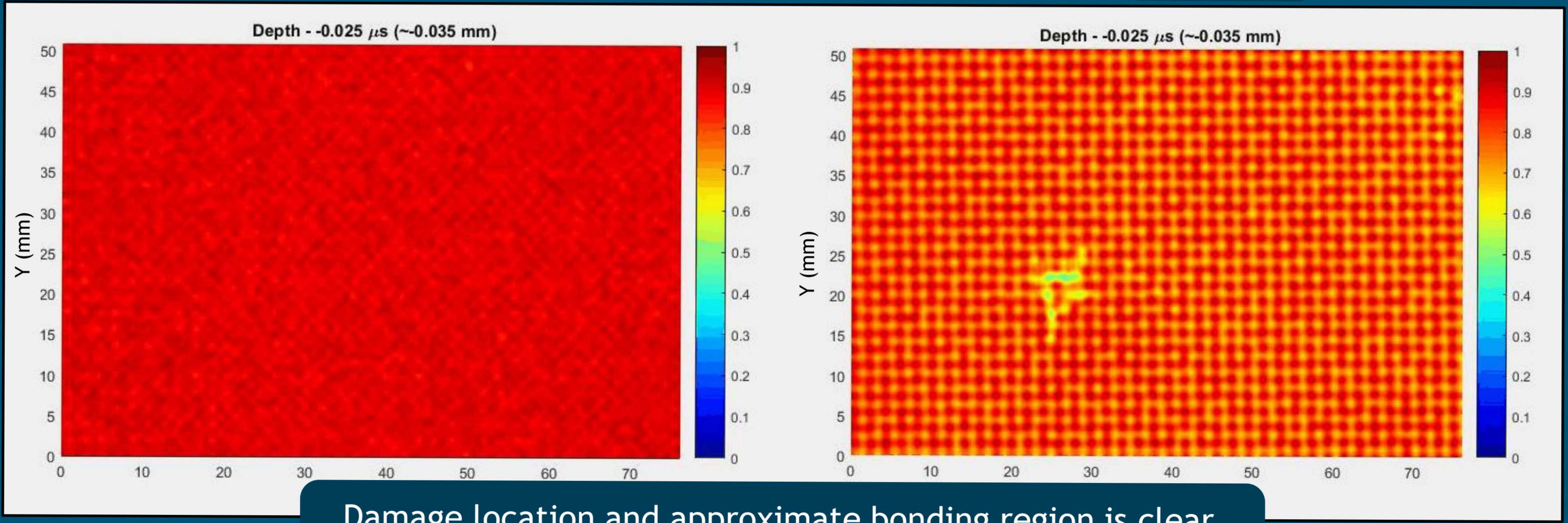
Inspection Parameter	Microfocus CT	Nanofocus CT
CT System	North Star Custom System	Zeiss Xradia 520 Versa
Number of Projections	2500	3200
Accel. Voltage	220 kV	80 kV
Voxel Side Length	**23.6 µm**	**4.37 µm**
Inspected Area (2D)	**30 x 30 mm**	**10 x 10 mm**
Scan Time	**1.25 hr**	**10.75 hr**

Results & Discussion

Ultrasonics Results: C-Scan

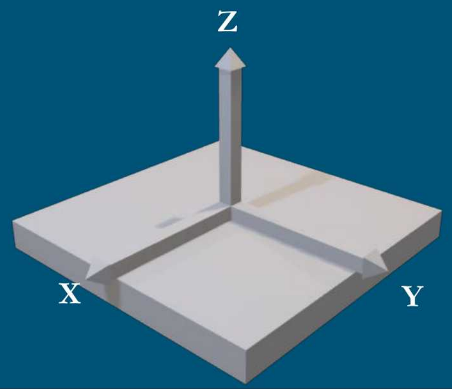
7.5J

9.5J



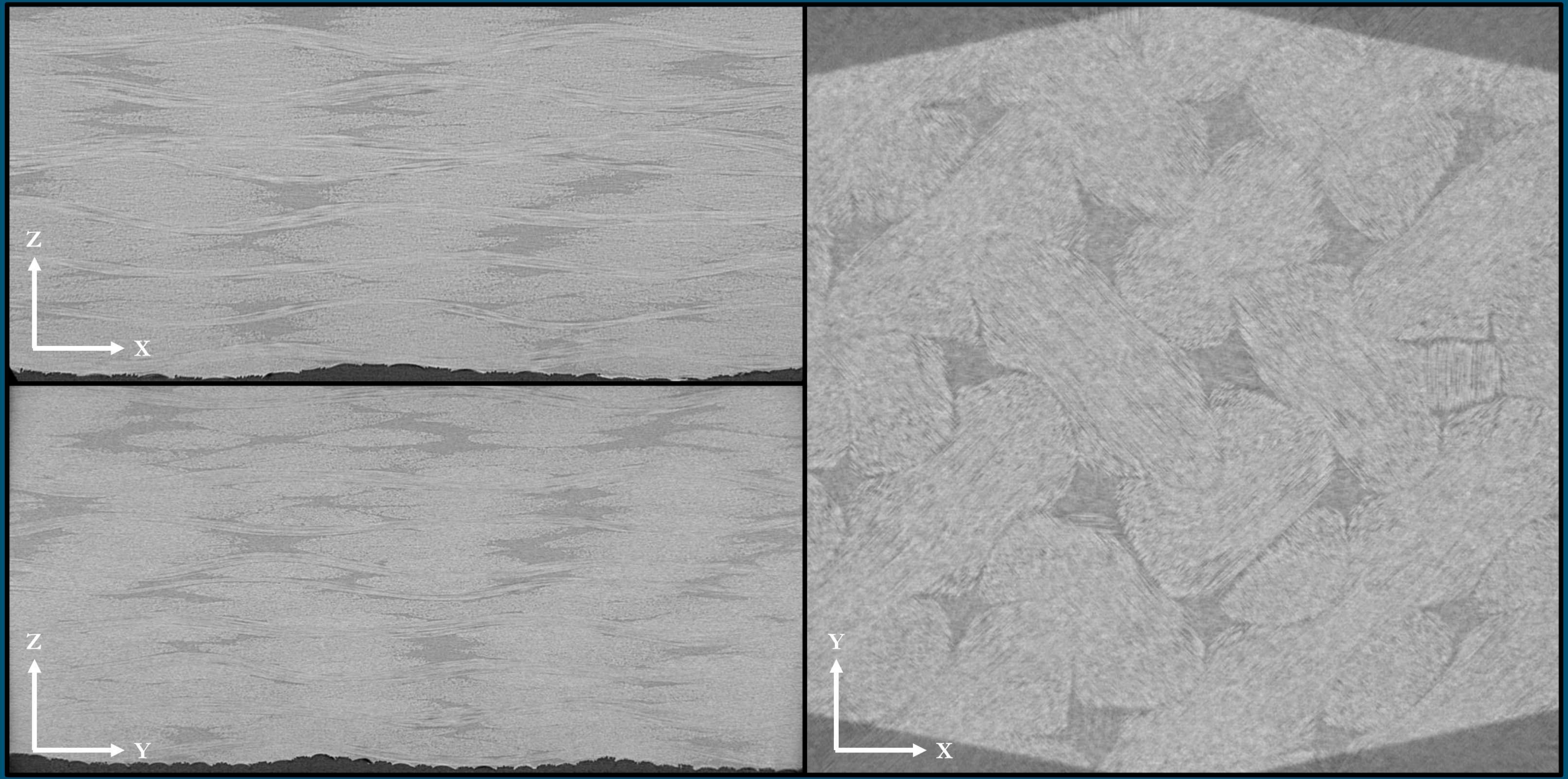
Damage location and approximate bonding region is clear, but ***extent and type of damage is unclear.***

Nanofocus CT Results: Undamaged Sample



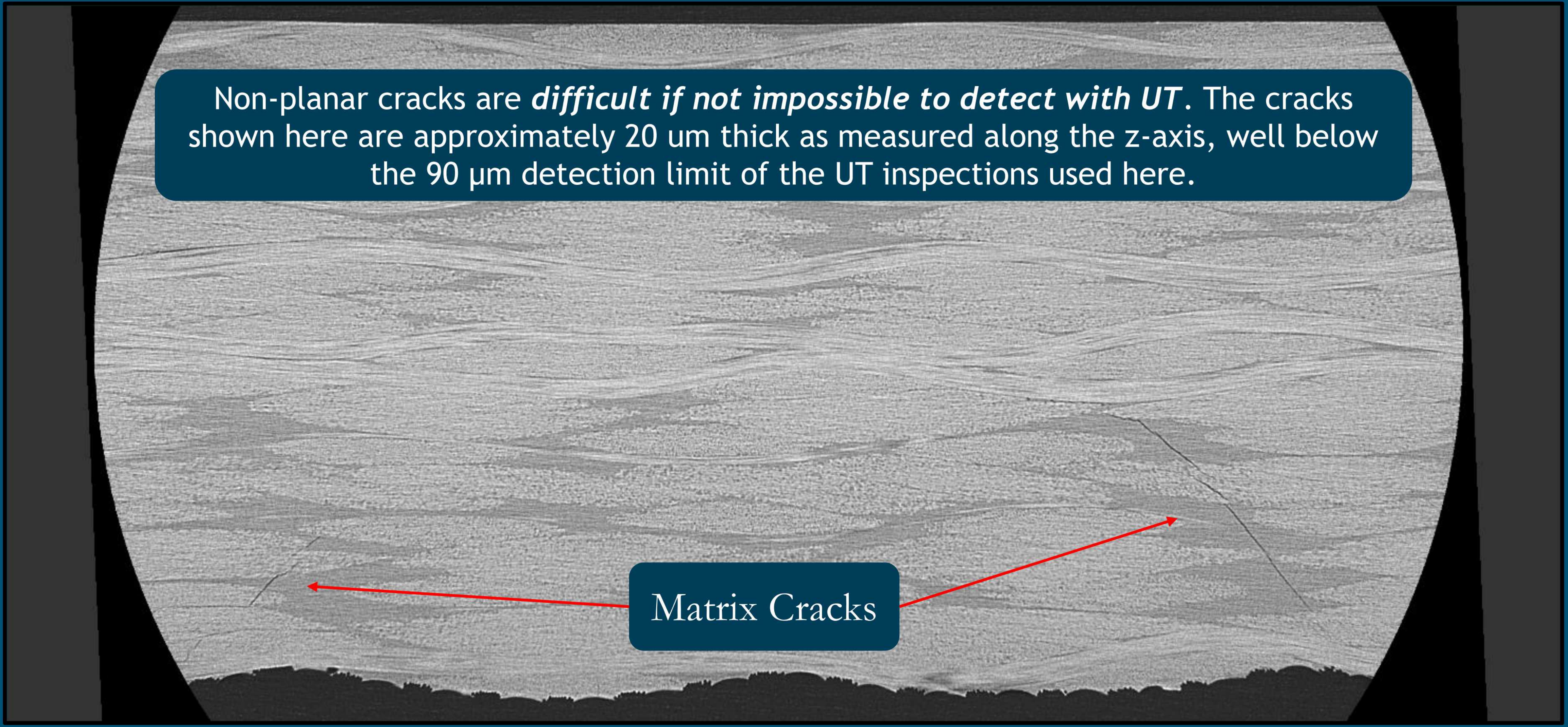
Undamaged CFRP was inspected to create a control inspection.

No delamination or other damage was observed.

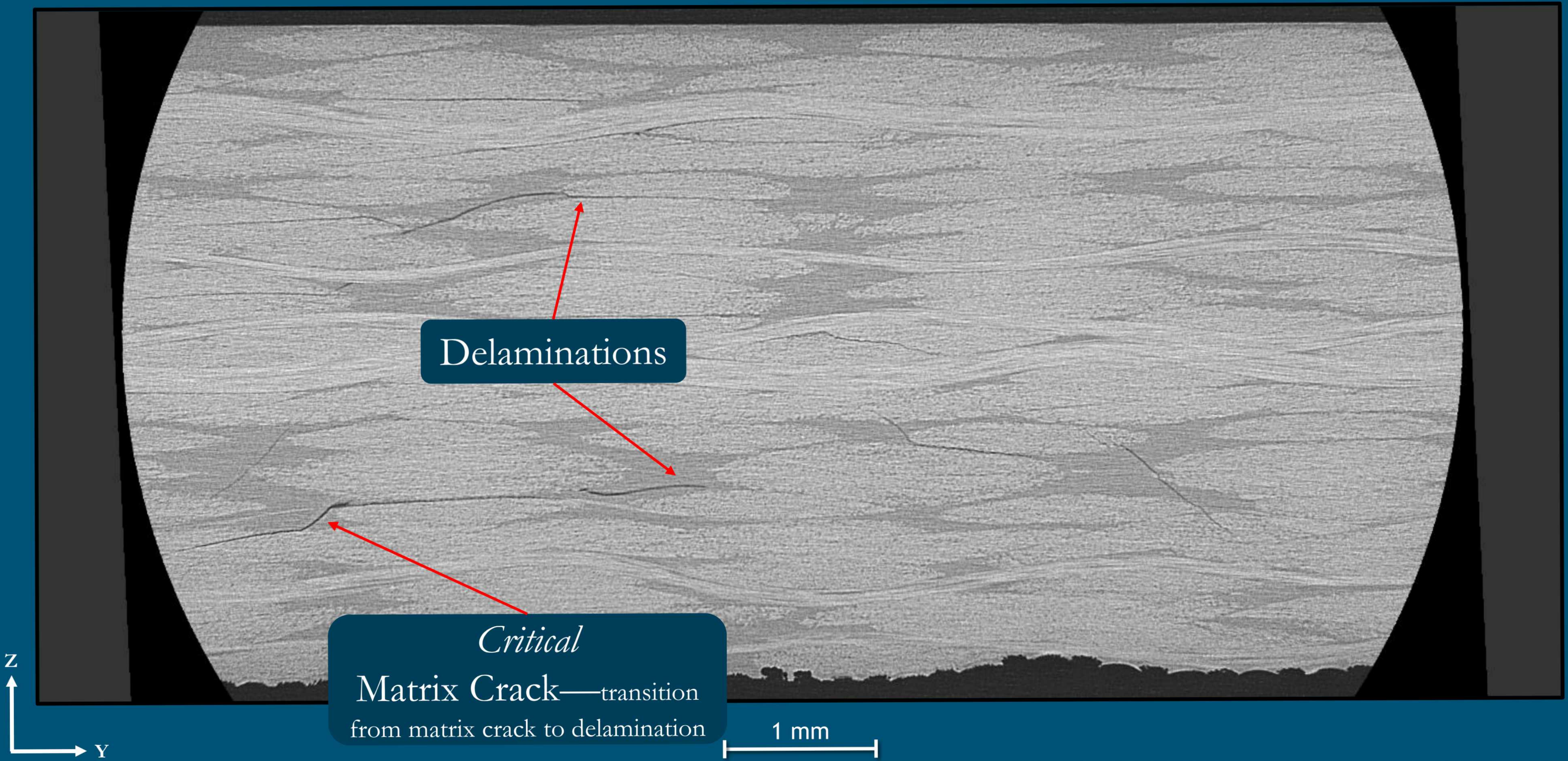


7.5J Impact

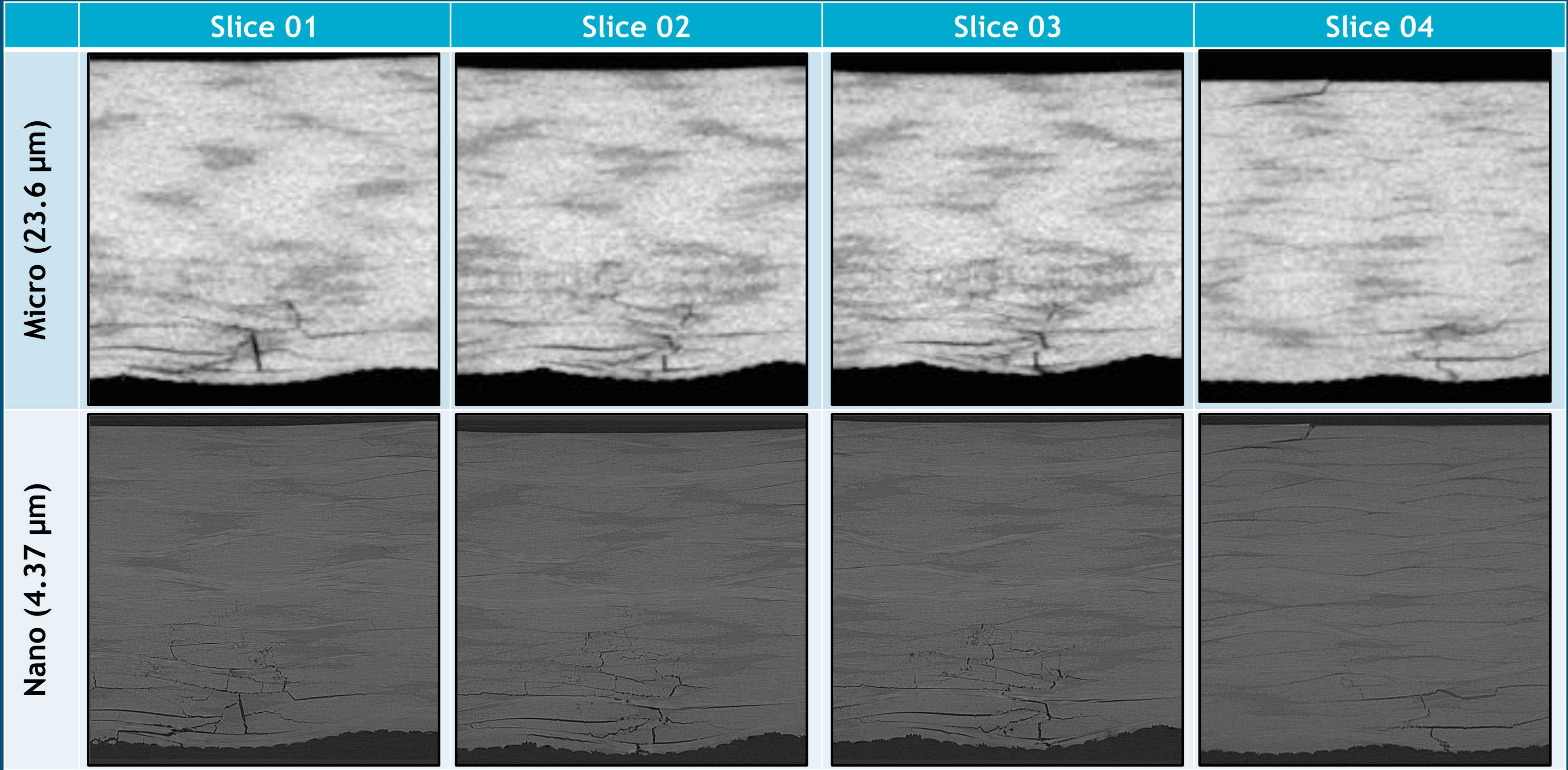
Non-planar cracks are ***difficult if not impossible to detect with UT***. The cracks shown here are approximately 20 um thick as measured along the z-axis, well below the 90 μm detection limit of the UT inspections used here.



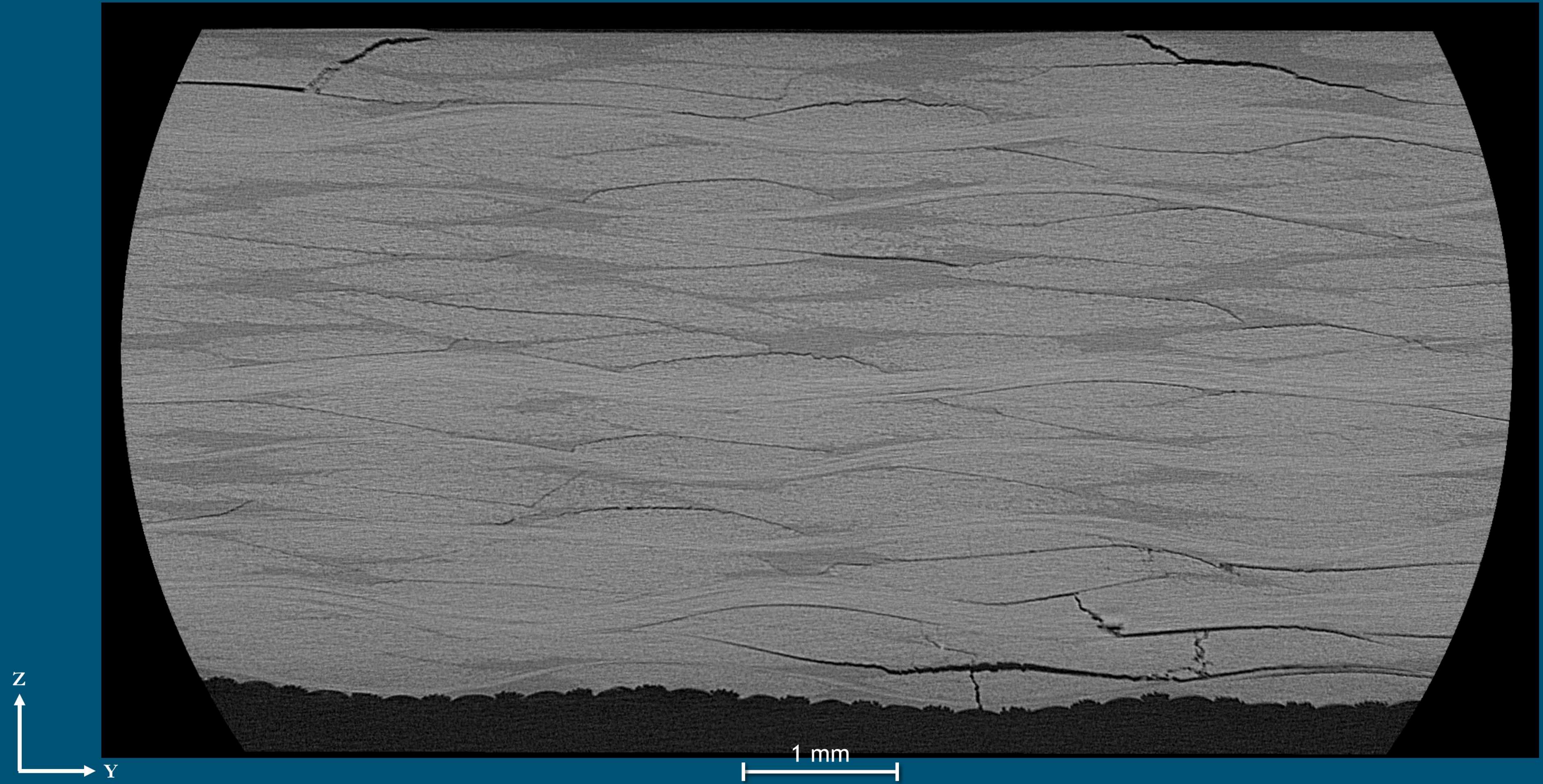
7.5J Impact


Delaminations
Critical
Matrix Crack—transition from matrix crack to delamination
1 mm
Z
Y

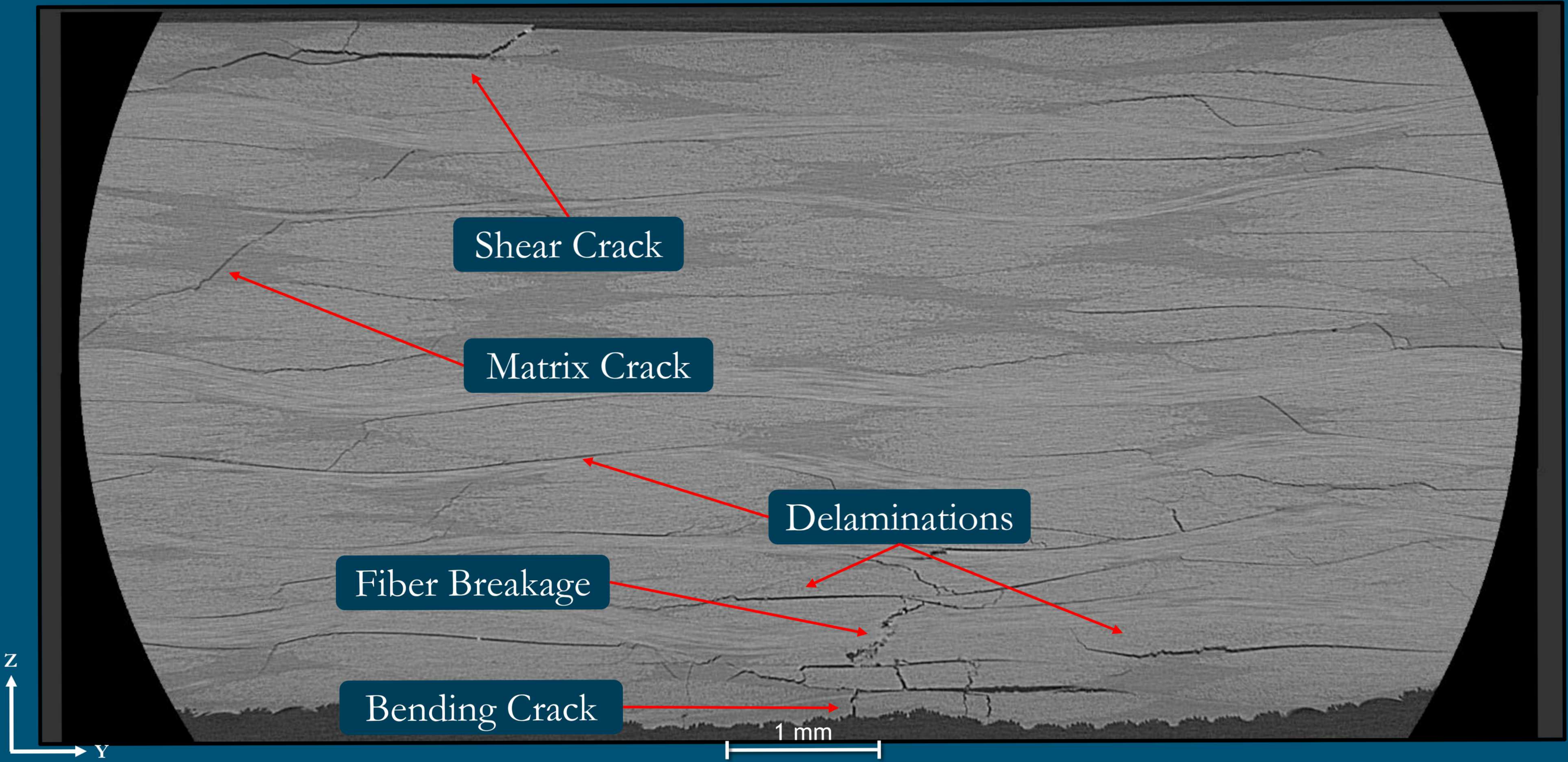
9.5J Impact: Nano/Microfocus Comparison Side View



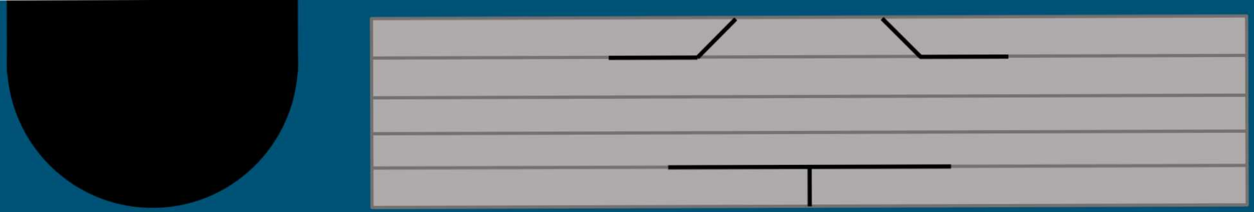
9.5J Impact Video

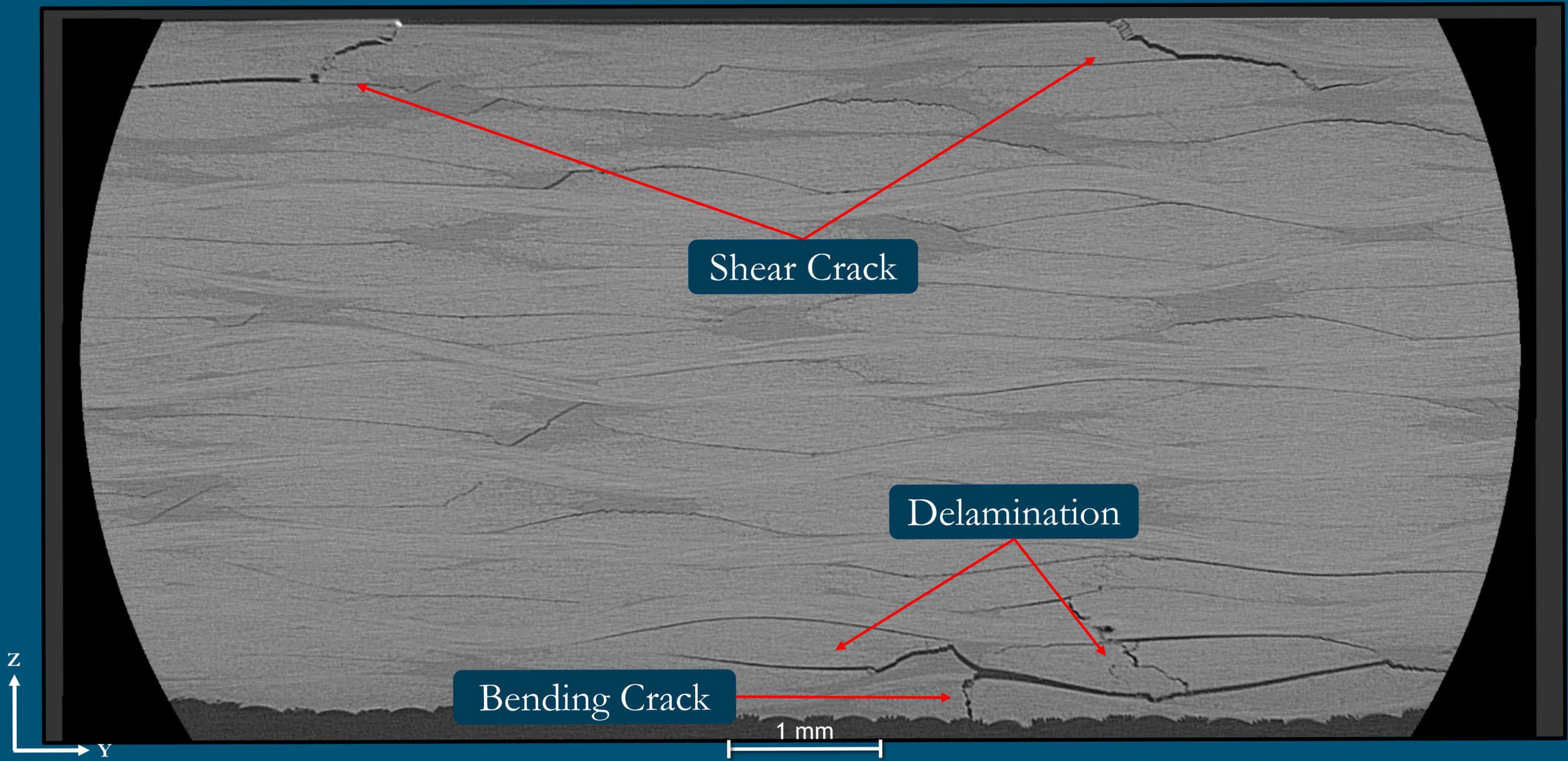


9.5J Impact


Shear Crack
Matrix Crack
Delaminations
Fiber Breakage
Bending Crack
1 mm
Z
Y

9.5J Impact

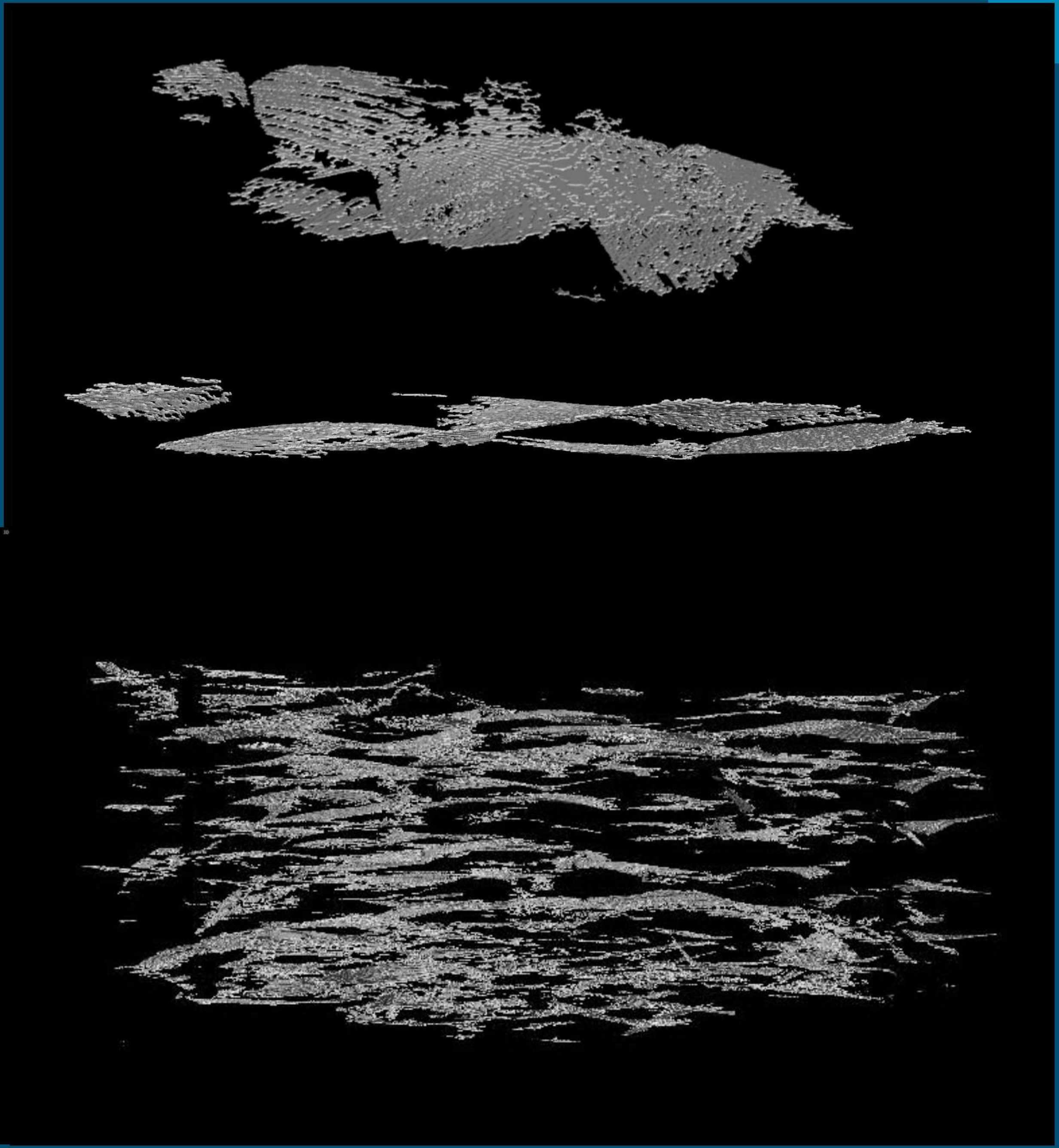


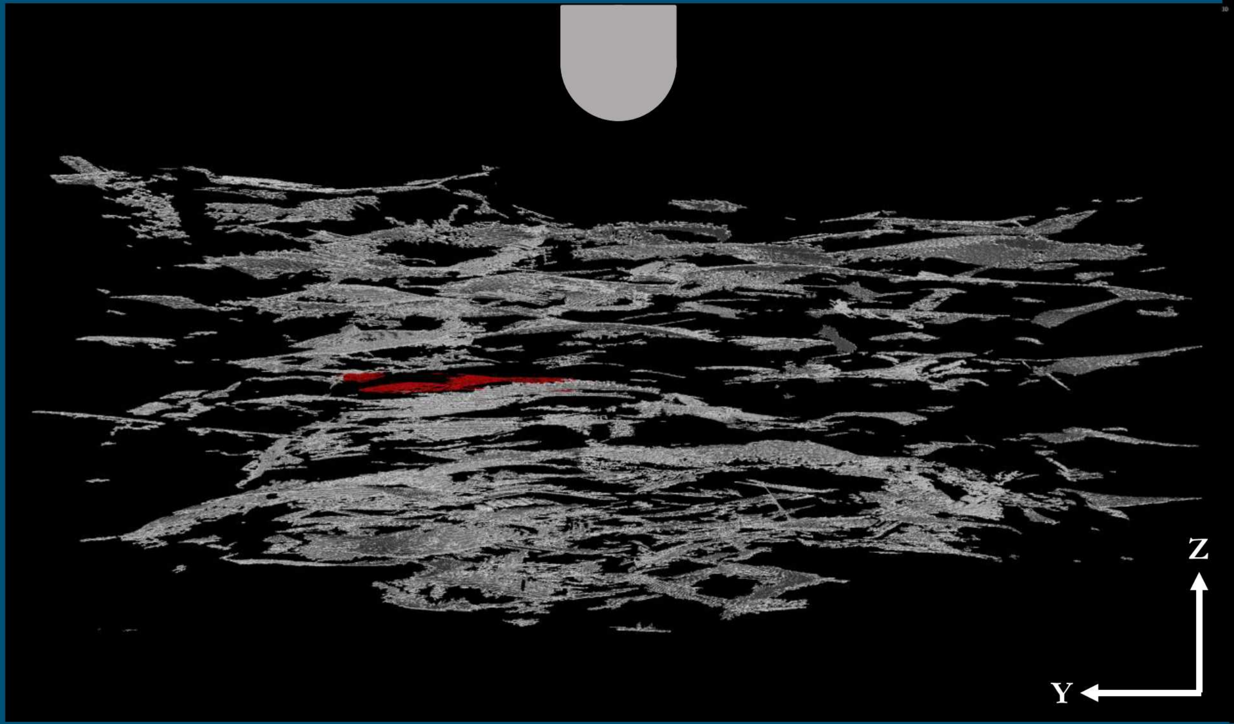


9.5J Impact: 3D Damage Visualization

Delaminations are easily identified in 3D damage visualization.

Microcracks may not be captured in this visualization, as they appear as noise during segmentation.





Damage Per Depth—9.5J Impact

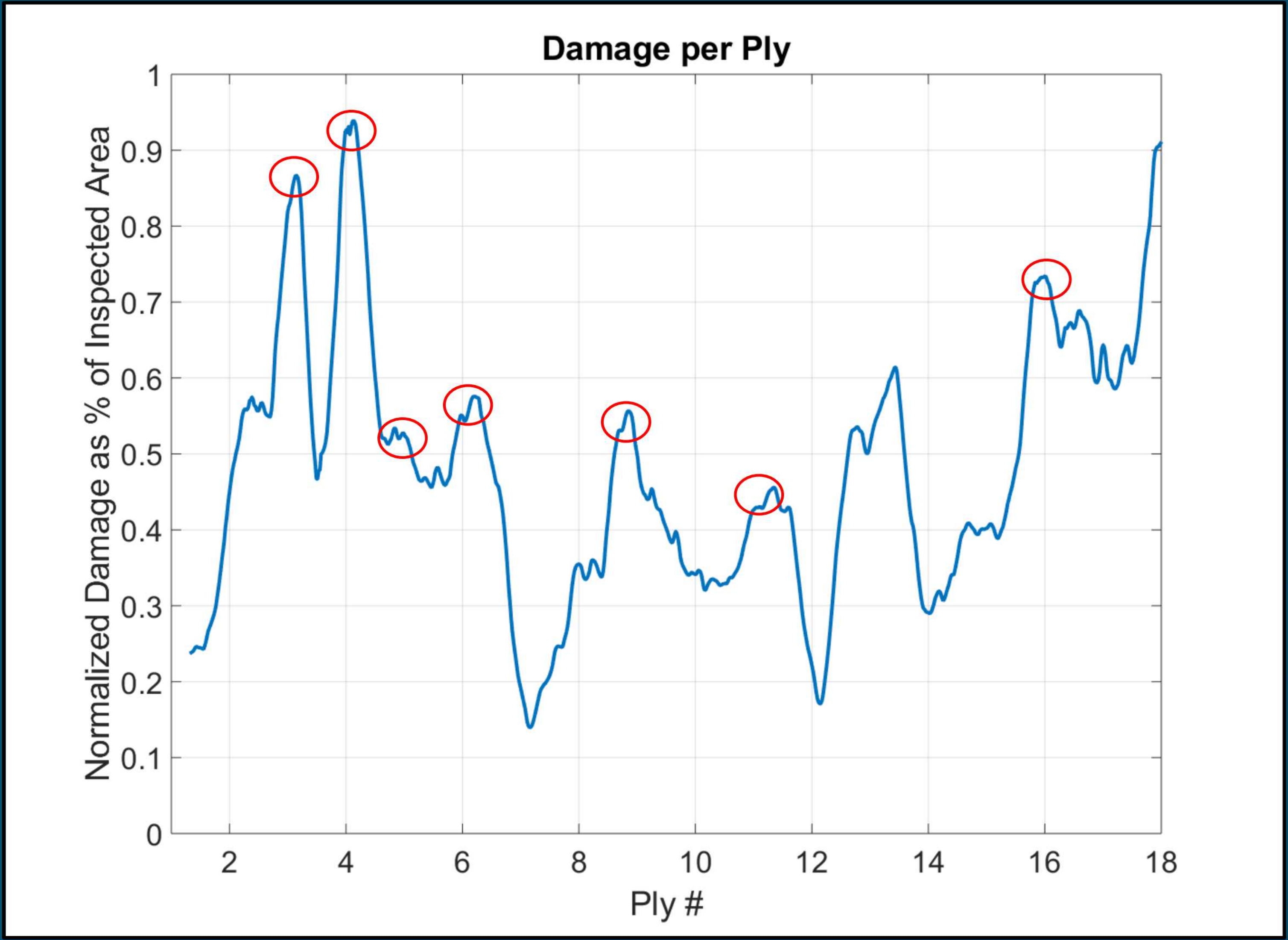
Damage was plotted as a function of depth and mapped to ply based 51 CT slices per ply.

- Curvature of impact was not accounted for in these calculations

Damage approximated by summing detected damage for each CT slice and calculating a % Area of damage.

- Tradeoff between resolution and size of scan/encompassing entirety of damaged area

Most damage (shown by local maxima) occurs between plies as delaminations.



CFRP Inspection: UT vs. CT Comparison

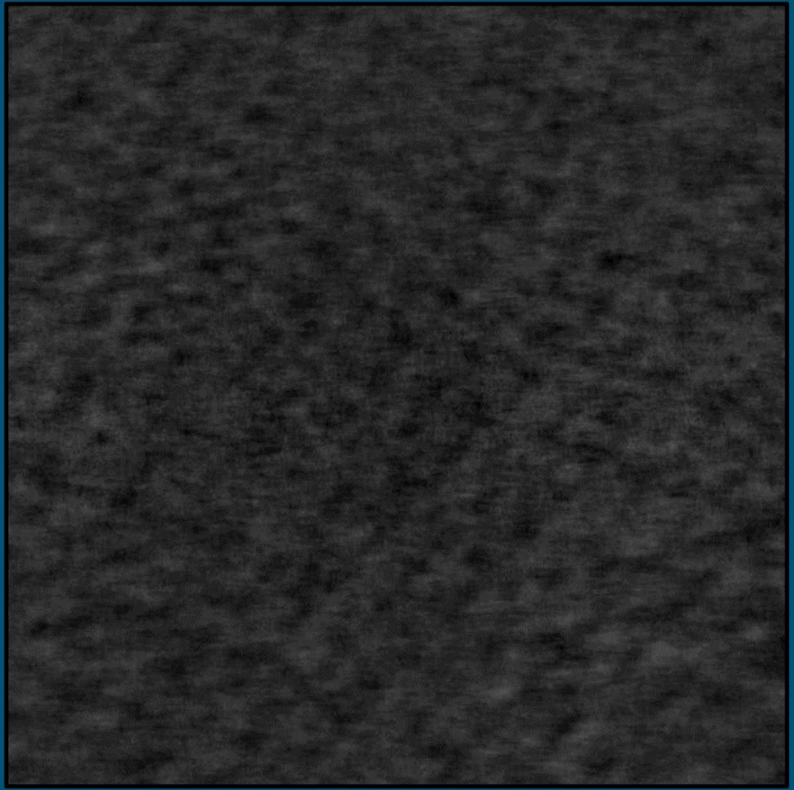
	Ultrasonic Inspection	CT Inspection
Advantages	• Portable • Relatively fast • Cost-effective • Capable of inspecting large areas	• High-fidelity, high-resolution data • 3D visualization • Able to detect microcracking
Disadvantages	• Frequency-dependent resolution • Difficult/impossible to identify vertical cracks • Over-assesses damage area • Difficulty quantifying damage	• Field inspections not possible • Expensive • Difficult/time-consuming to analyze data • Difficulty inspecting large areas

Fiberglass Impacts

Fiberglass Impacts

Fiberglass composite was impacted at 10J with hemispherical impactor.

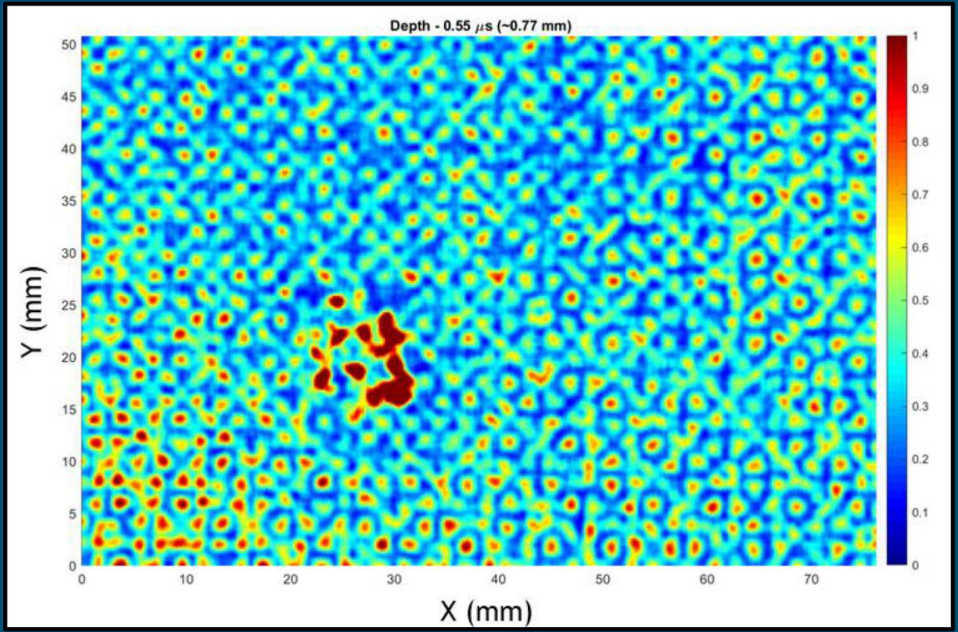
Damage can easily be seen with naked eye

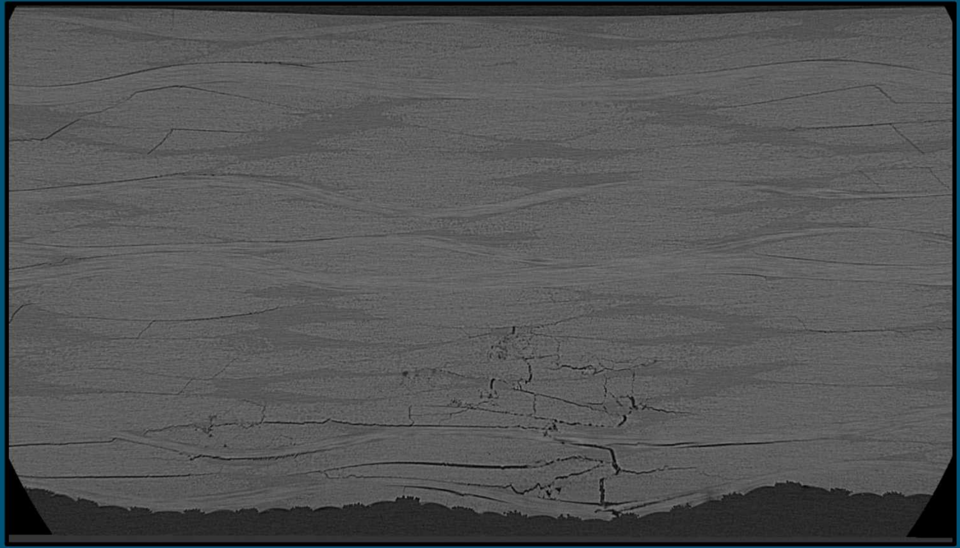


Conclusions

1. UT cannot fully account for or characterize damage in CFRP samples
   - Significant amounts of damage remains unseen by UT alone.
2. CT can be used to refine damage models and better understanding composite impact damage modes.
3. High-resolution CT data can be used to improve UT inspections of laminated composites.

Questions?

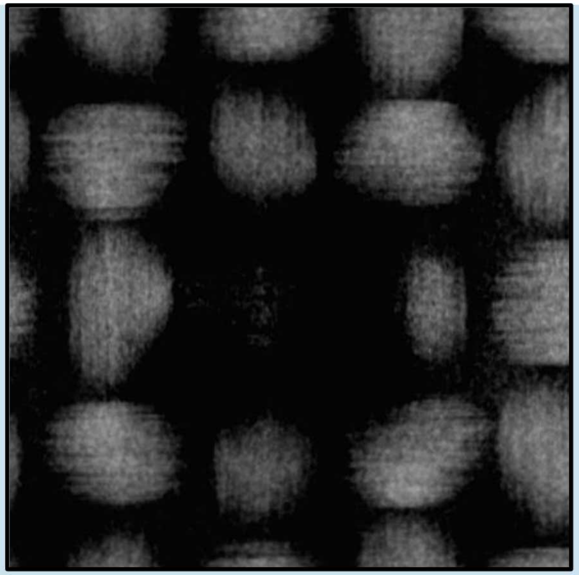
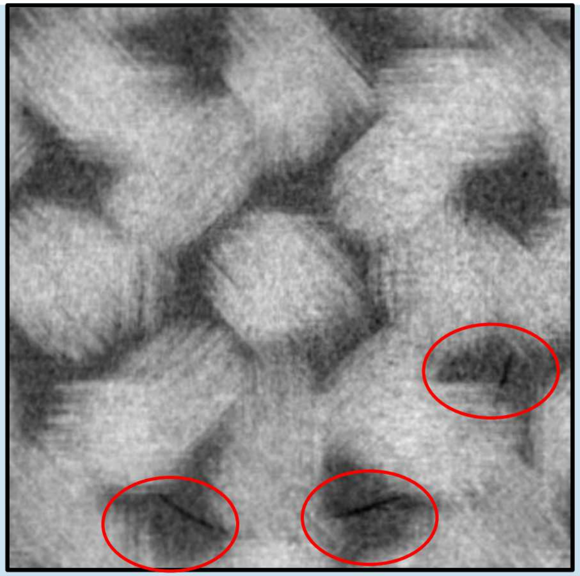
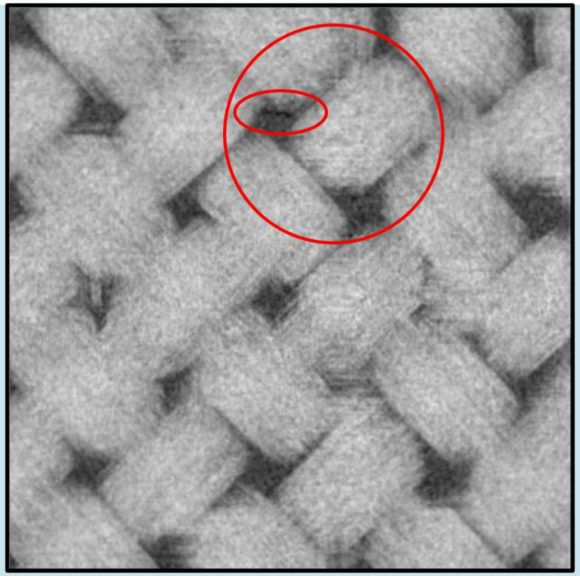
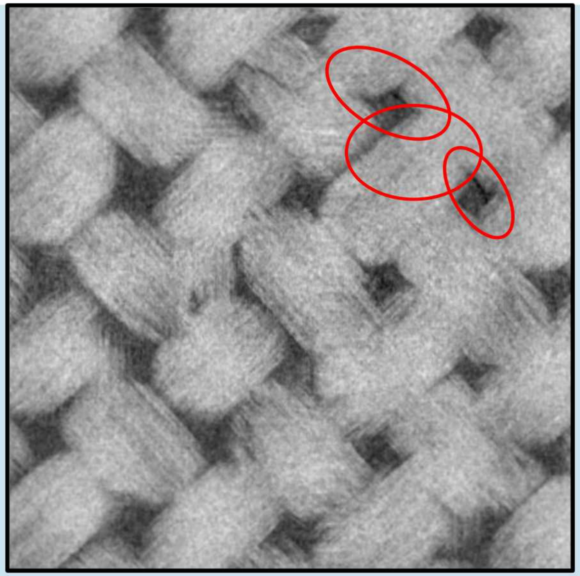
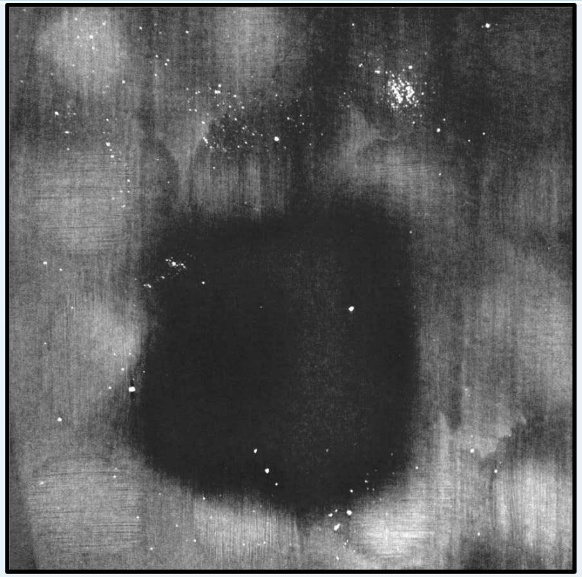
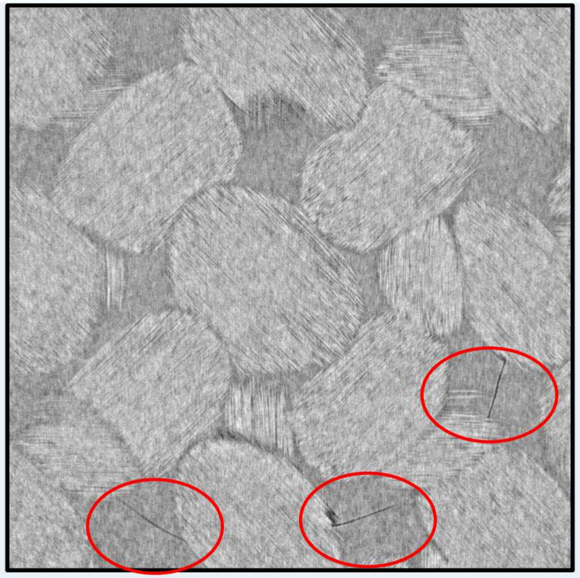
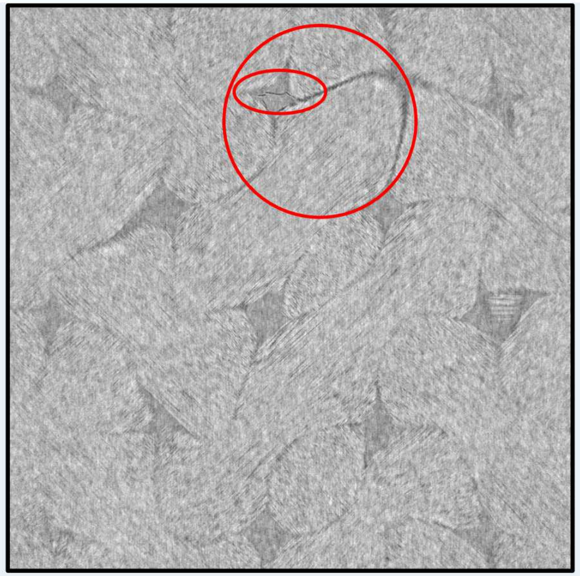
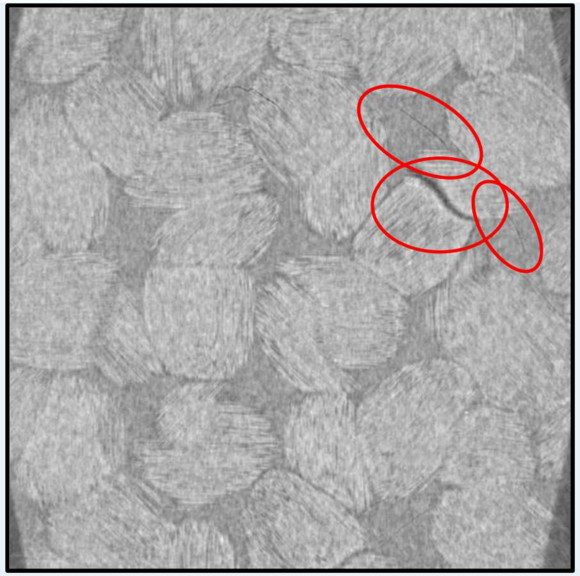




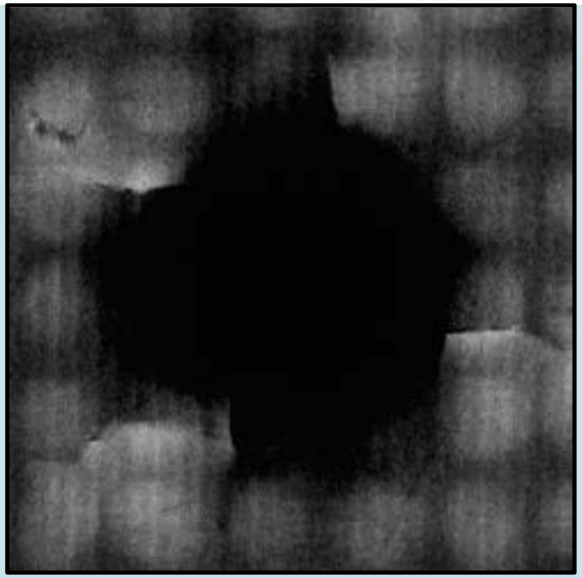
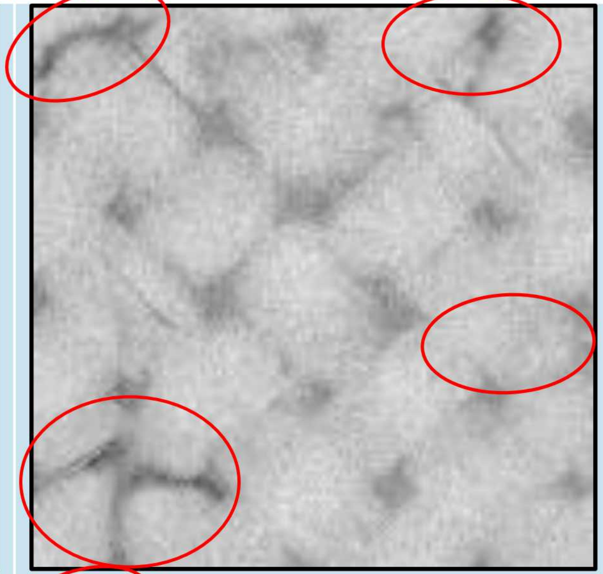
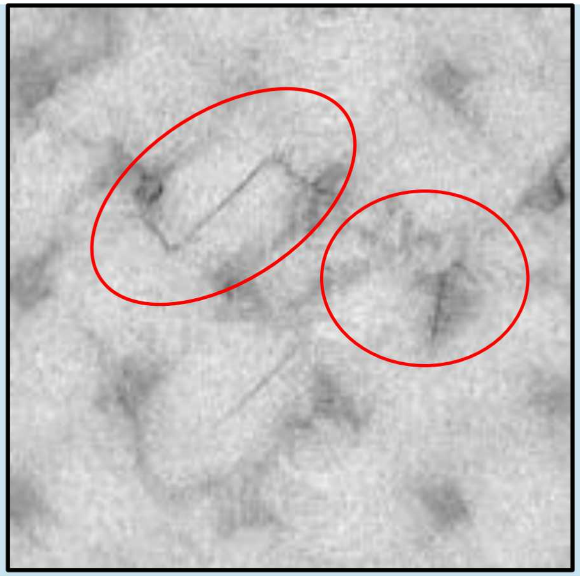
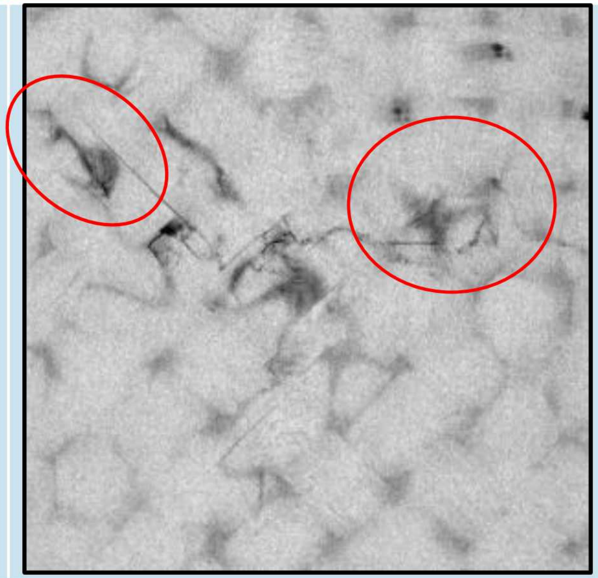
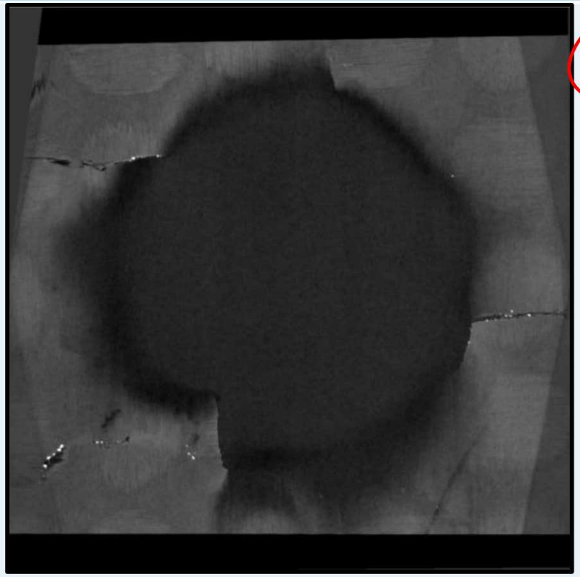
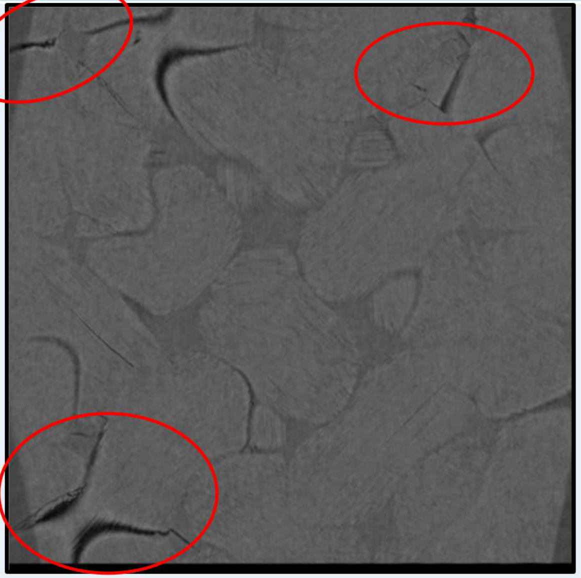
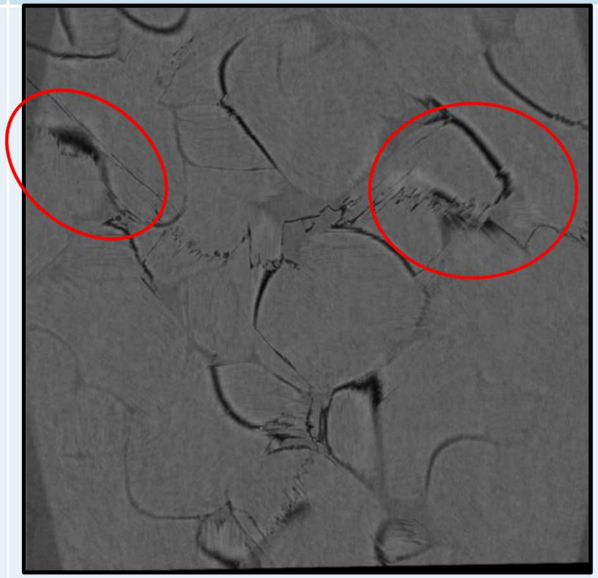
Backup Slides

Damage Mode	7.5 J Impact	9.5 J Impact
Shear Cracking	Yes	Yes
Bending Cracking	Yes	Yes
Delamination	Yes	Yes
Fiber Breakage	No	Yes
Penetration	No	No

7.5J Impact: Nano/Microfocus Comparison

	0 mm	1.385 mm	2.45 mm	2.80 mm
Micro (23.6 µm)				
Nano (4.37 µm)				

9.5J Impact: Nano/Microfocus Comparison Top View

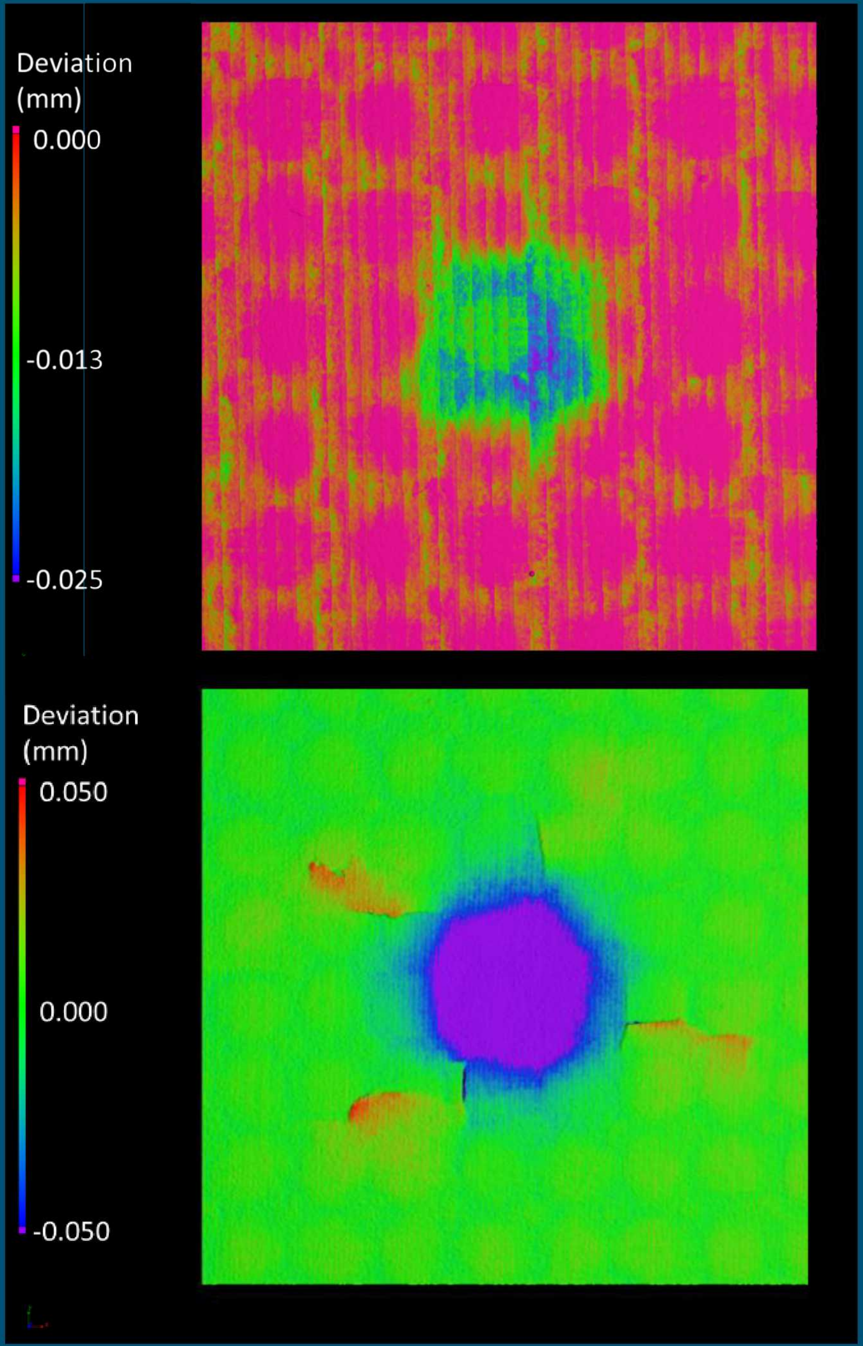
	0 mm	0.25 mm	3.25 mm	3.75 mm
Micro (23.6 µm)				
Nano (4.37 µm)				

Indent Depth

Using microfocus CT, nominal surface was compared to actual CT data and indent map was created.

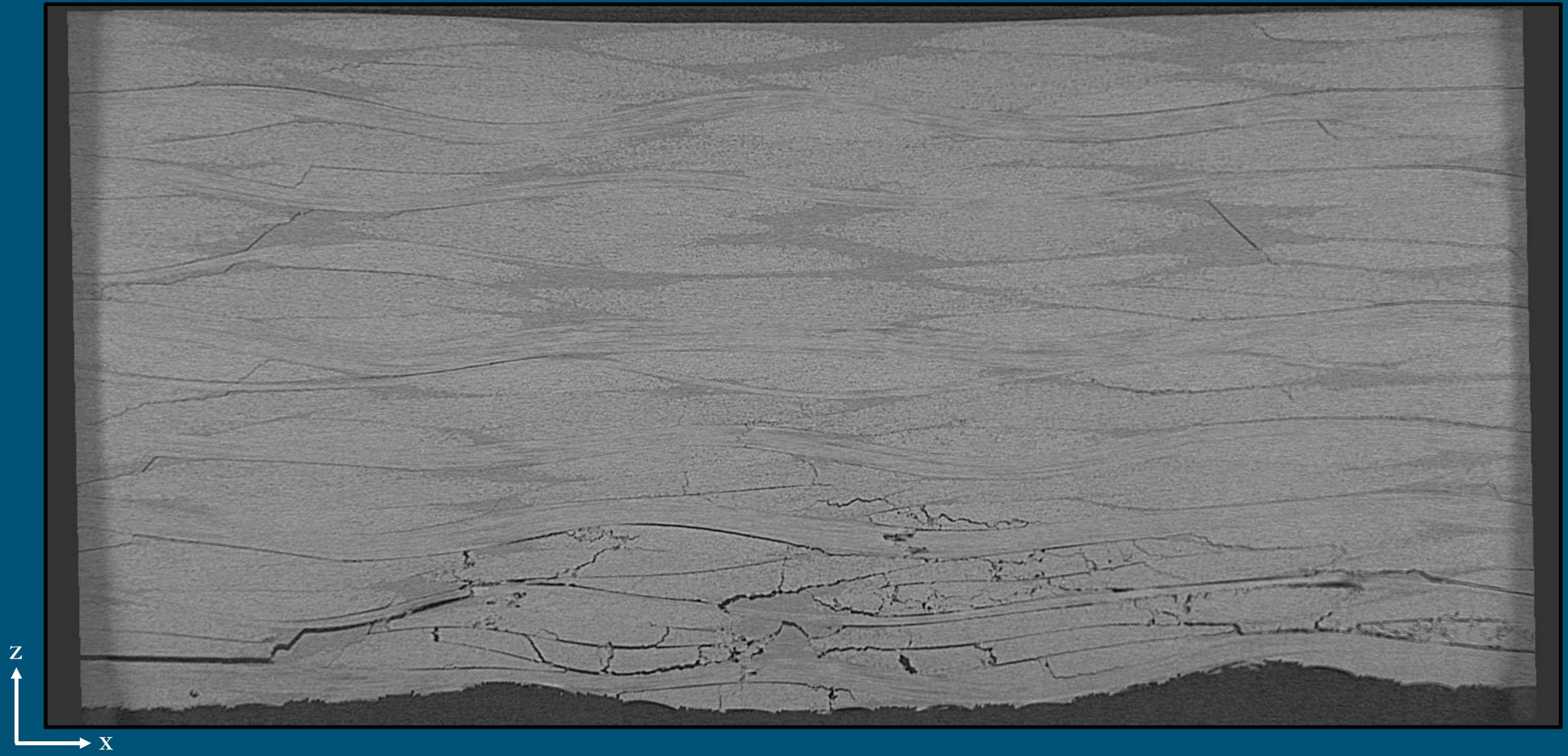
Comparison of indent depth to impact energy provides easy-to-calculate damage metric.

Clear surface cracking observed in 9.5J impact sample

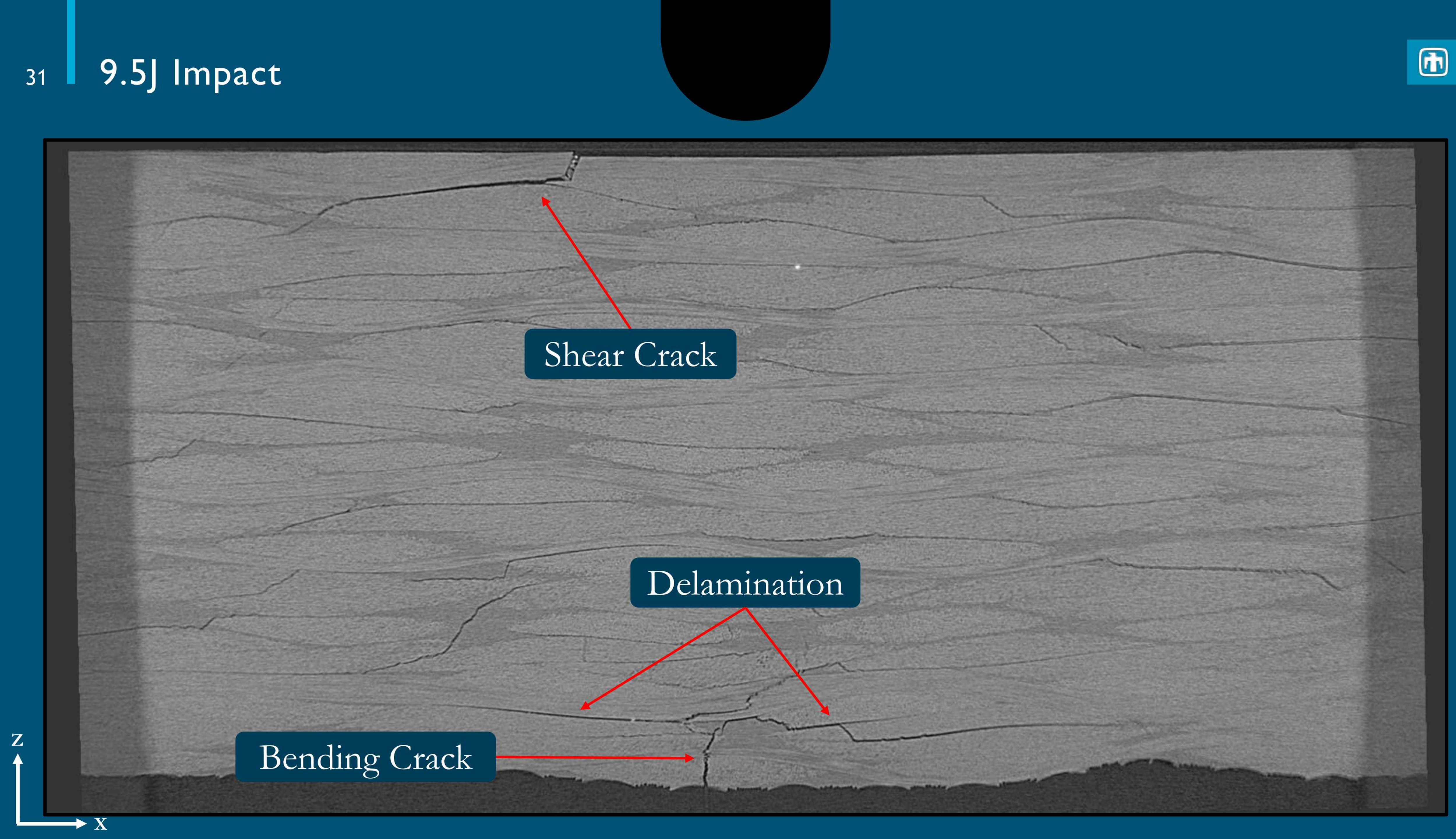


7.5J Impact

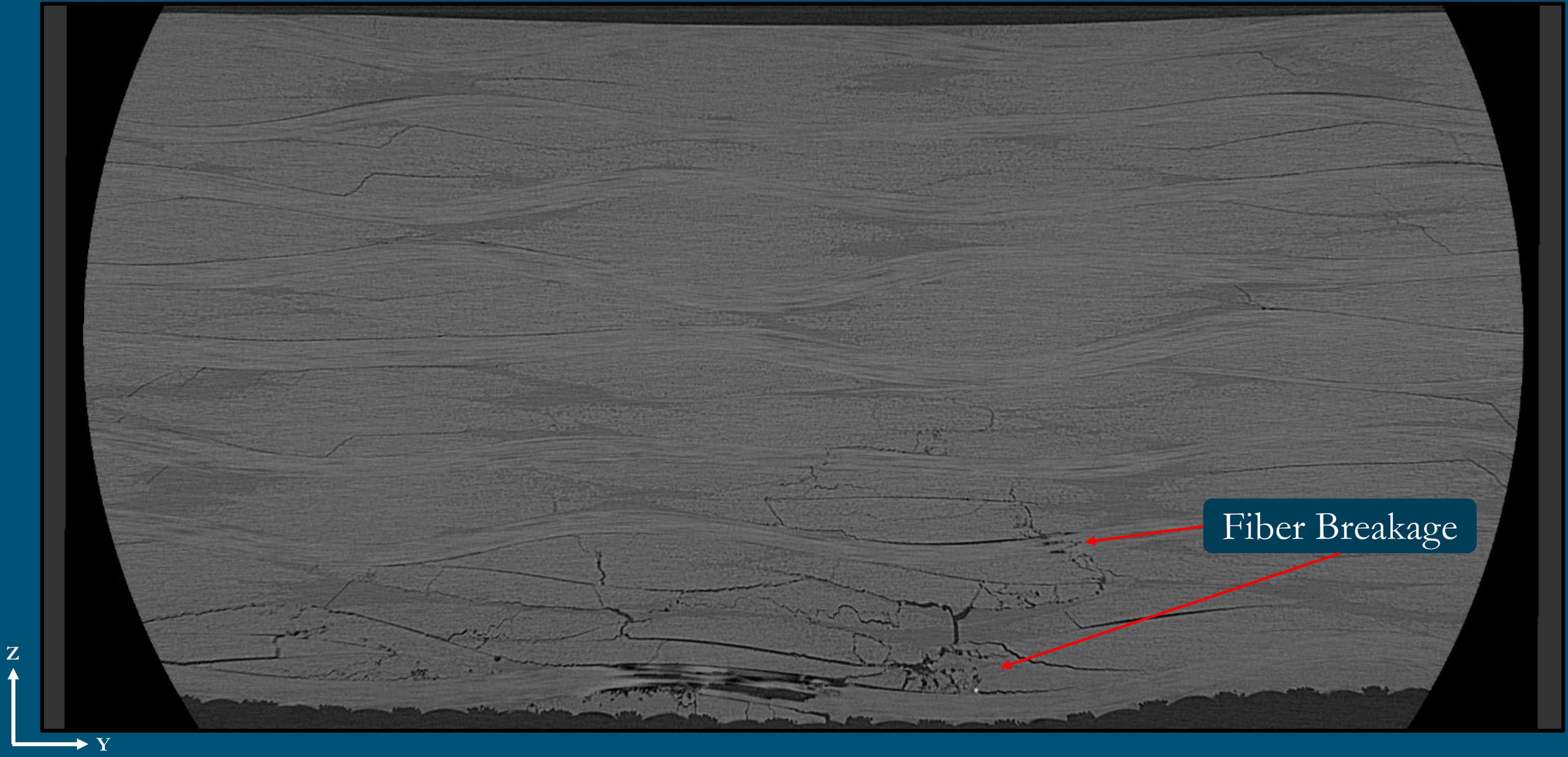
9.5J Impact



9.5J Impact



9.5J Impact—Fiber Breakage



Fiberglass Impacts

Damage perimeter in X-Y CT slices was traced and subsequent images were thresholded.

- Only every 5 slices were considered for simplicity

3D visualization of damage shows cone-like shape.

FGRPs provide significantly less contrast than CRFPs

- More difficult to image damage