Characterization of Low-Velocity Impact Damage in Thermoplastic Laminated Composites

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Objectives

- Conduct impact testing to create a range of damage levels in thermoplastic materials
  - Investigate the effect of material system on damage
  - Investigate the effect of high-rate processing on damage
- Create detailed damage maps
  - Ultrasonic testing (UT)
    - Front- and back-surface scans to obtain delamination outlines
    - Time-of-flight (B-scan) data used to approximate depth of individual interfaces
  - X-ray computed tomography (CT)
    - Images used to document matrix cracking and fiber fractures
    - Provided partial images of delaminations (tightly closed delaminations were not visible)
  - UT and CT data combined to create layer-by-layer images of matrix cracks, delaminations, and fiber fractures
    - Create database to evaluate the accuracy of models to predict the impact performance of thermoplastics
- Compare the impact damage response of two thermoplastic materials
- Evaluate significance of low levels of crystallinity on the impact damage response

Specimens

Two Thermoplastic Materials

- Carbon-fiber-reinforced, semi-crystalline materials
- 24-ply quasi-isotropic layup

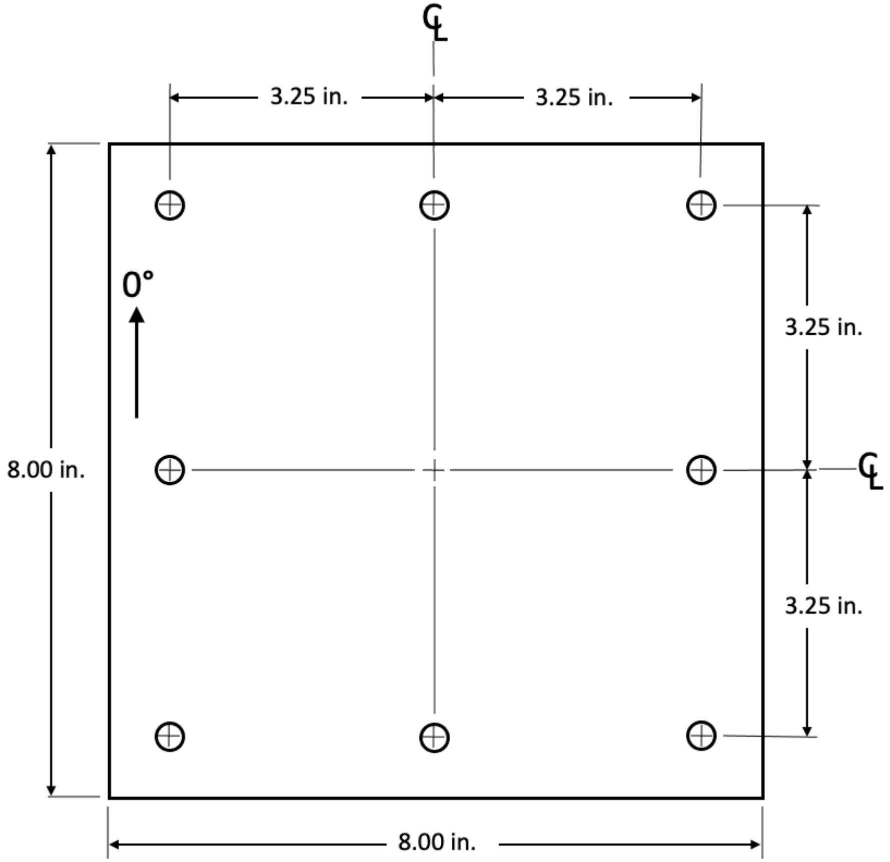
Material 1: PEKK (APC AS4D/PEKK-FC from Solvay#)

- $[-45/0/+45/90]_{3S}$ layup
- Thickness: 0.1359 inch

Material 2: PAEK (TC1225 T700/LMPAEK from Toray#)

- $[+45/0/-45/90]_{3S}$ layup
- **Baseline PAEK**
  - Thickness: 0.1283 inch
  - Typical degree of crystallinity (DOC) ranges from 20% to 30%
- **Low-Crystallinity PAEK**
  - Thickness: 0.1315 inch
  - Post-processed at NASA Glenn Research Center
  - Clamped between steel plates and held in an oven above melt temperature for 150 minutes
  - The assembly was then quenched in an ice bath and annealed between the glass transition temperature and melt temperature
  - DOC measurements ranged from 13% to 15%

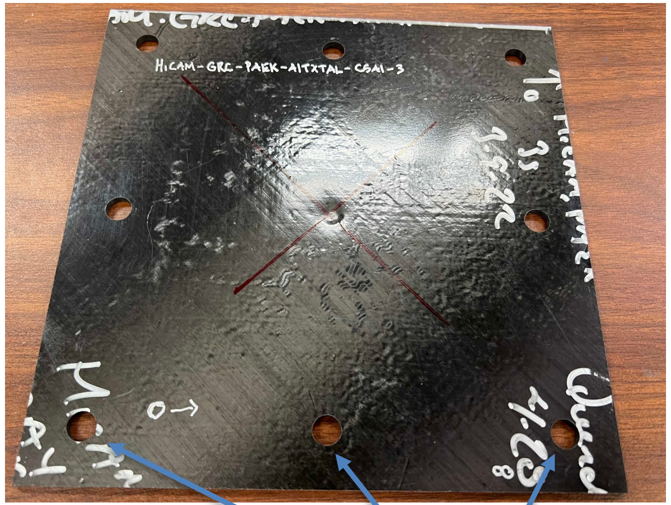
Impact Specimen



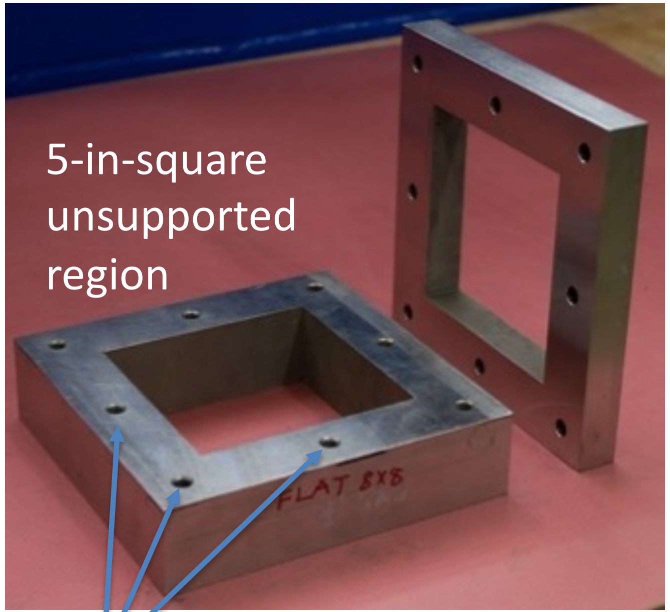
\# Specific manufacturer or product names are explicitly mentioned for informational purposes only. The use of these names does not imply an endorsement by the U.S. Government.

Impact Testing

8-in-Square Specimen

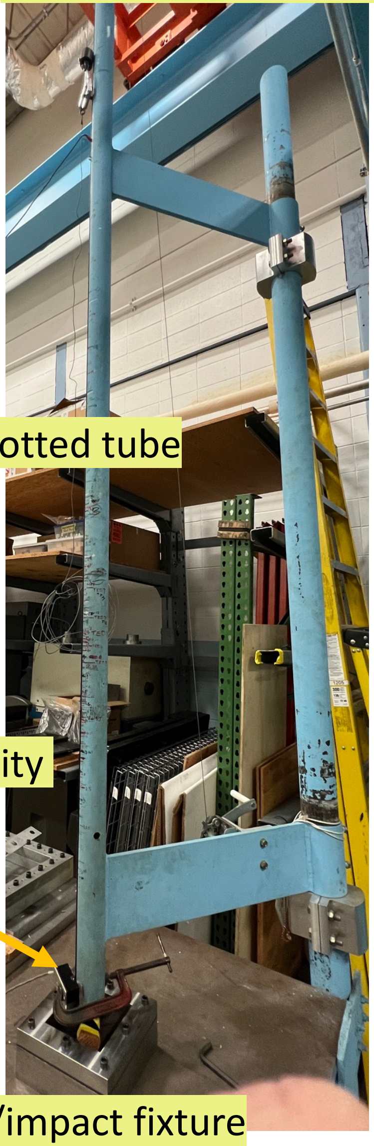


Impact Fixture

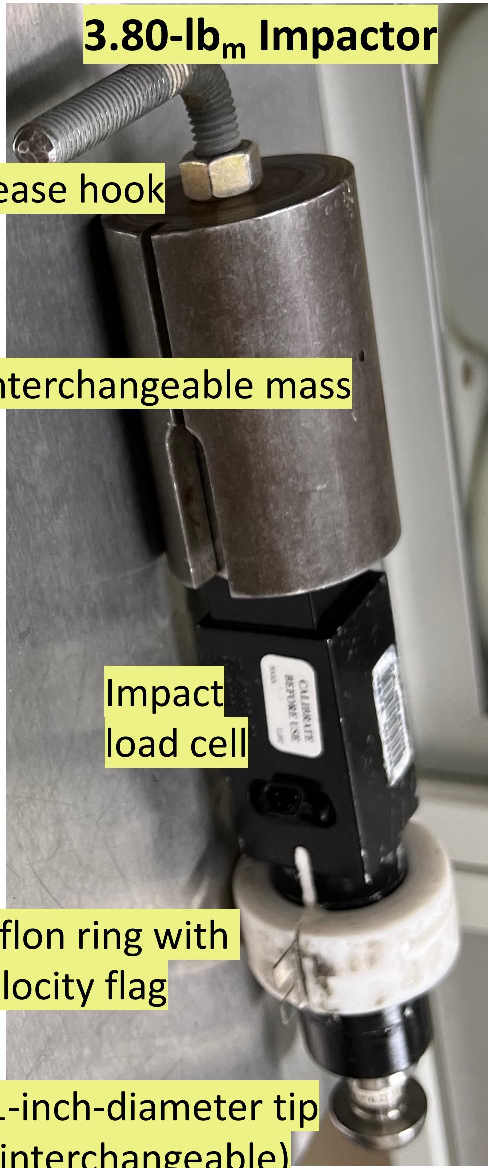


Eight through-bolts to
minimize edge movements

Impact Drop Tower



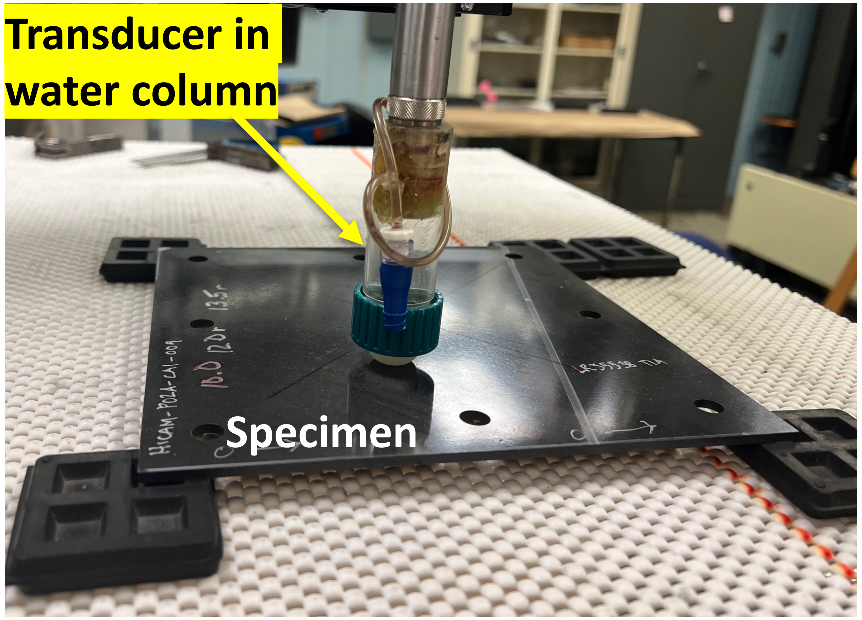
3.80-lb$_m$ Impactor

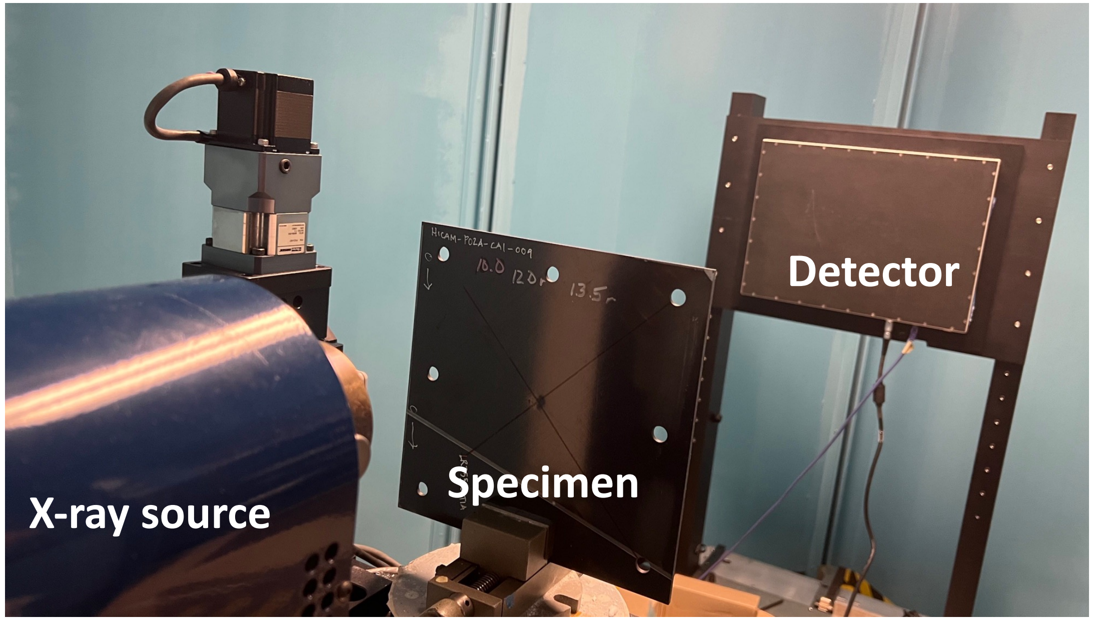


Data collected during impact:

- Force history (impact load cell)
- Impactor velocity (optical gate with flag)
- Back-surface center displacement (fiber-optic probe)

Post-Impact Data





Ultrasonic Scan

- 10 MHz focused transducer
- Spatial resolution of 0.005 inch
- Impact and back surface scans
- 2-inch by 2-inch scan area
- Stored time of flight data for post processing
- Time-of-flight (B-scan) data used to approximate depth

X-Ray Computed Tomography Scan

- 1.9-inch by 1.4-inch scan area
- 6.57 x 10^{-4} inch (16.7-micron) voxel size
- X-ray source: 70kV and 140mA

Delaminated Interfaces Determined Using UT Time-of-Flight and X-Ray CT data

Impact Surface [-45/0/+45/90/-45/0/+45/90 /-45/0/+45/90/90/+45/0/-45/ 90/+45/0/-45/ 90/+45/0/-45] Back Surface

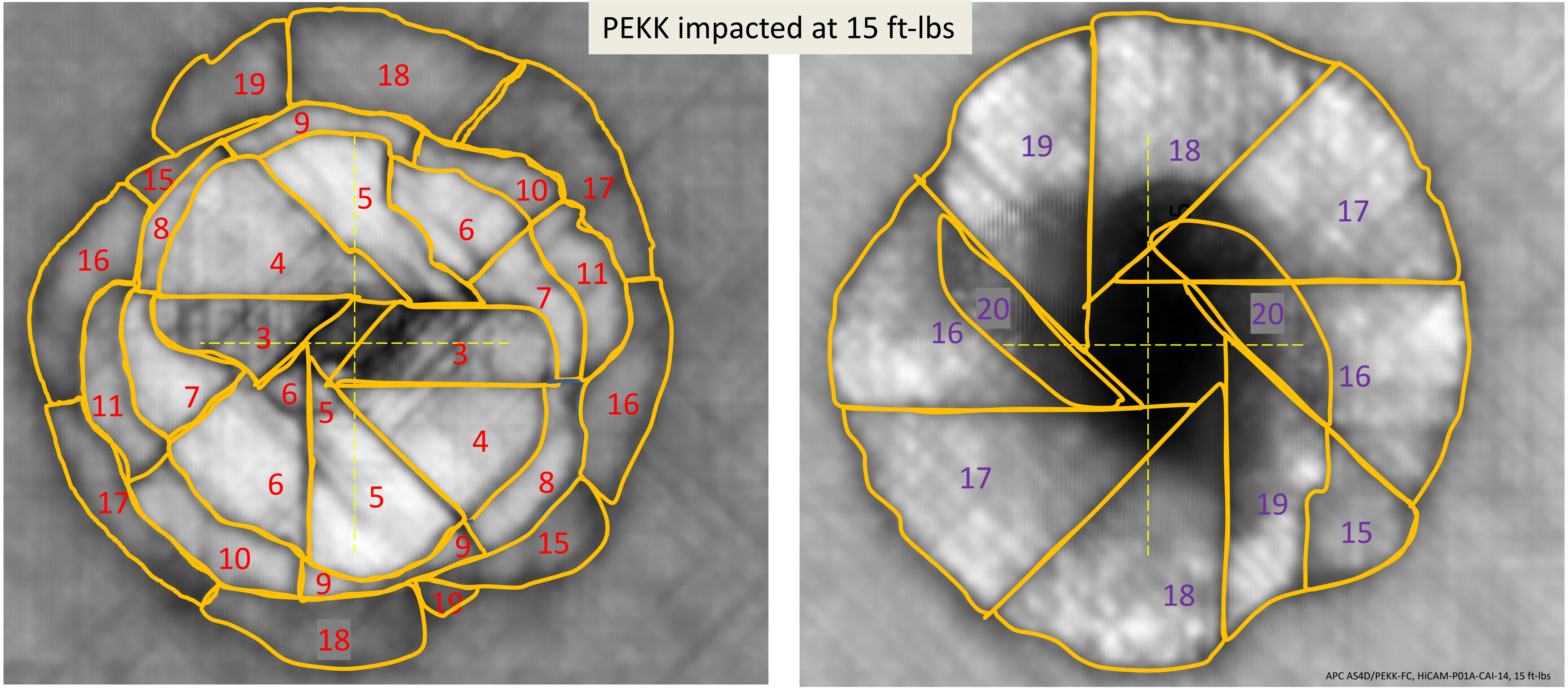
Interface #: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

Delamination

Impact Side

Back Side (flipped left/right to match impact side UT)

PEKK impacted at 15 ft-lbs



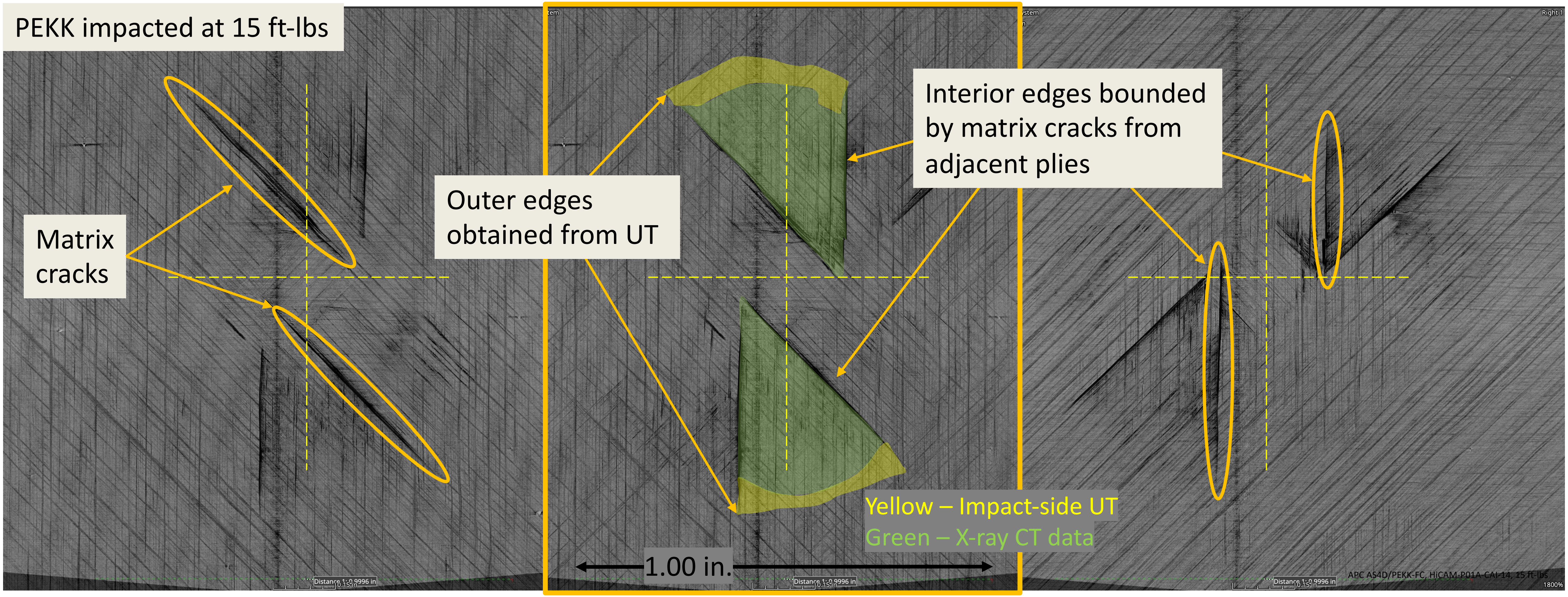
APC AS4D/PEKK-FC, HiCAM-P01A-CAI-14, 15 ft-lbs

Matrix Cracking and Delamination Maps Created Using UT and X-Ray CT Data

[-45/0/+45/90/-45/0/ +45 /90/-45/0/+45/90/90/+45/0/-45/ 90/+45/0/-45/ 90/+45/0/-45]

Interface #9

CT slice showing -45° ply | Delamination between -45° and 0° plies | CT slice showing 0° ply



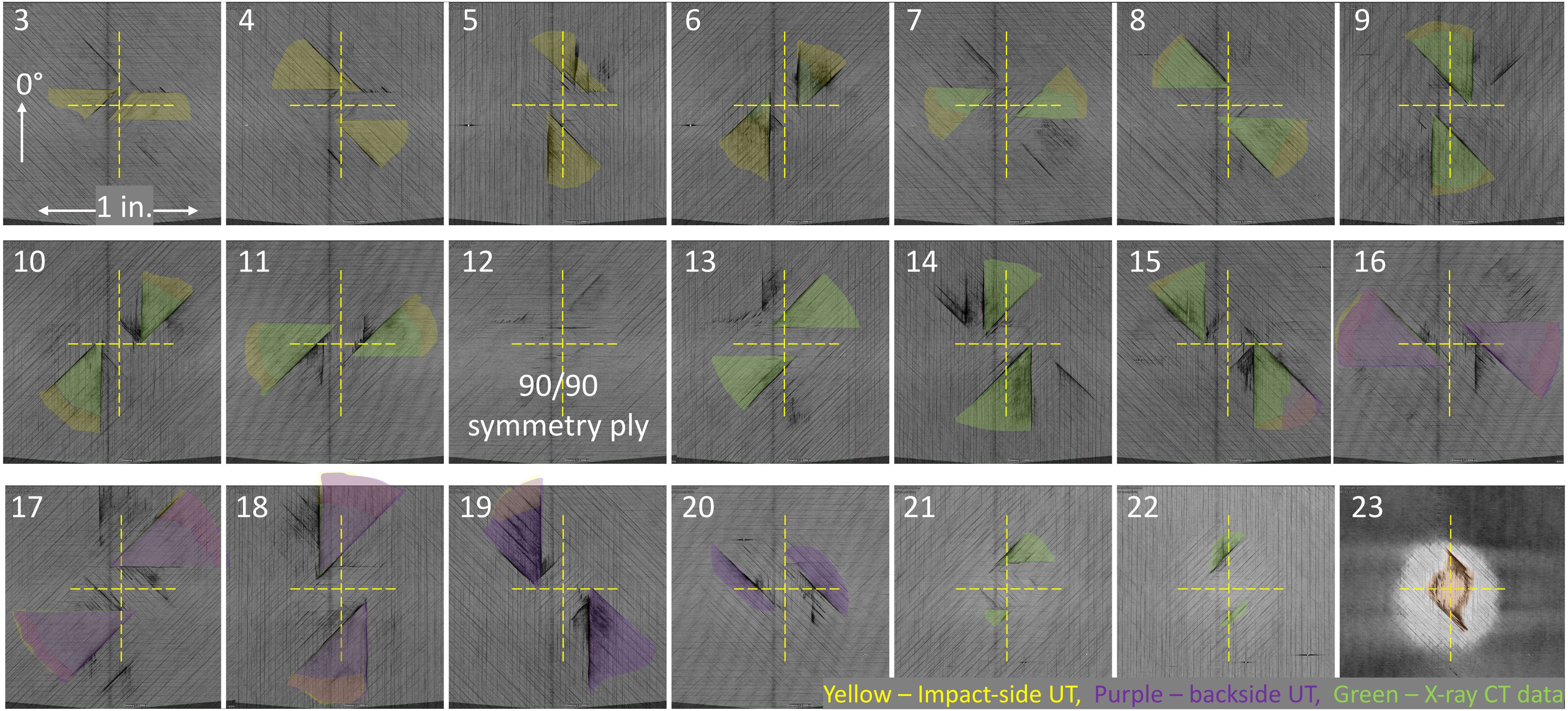
Note: Due to a deformed central section around the impact, a “thick slab” option was required to obtain complete damage images of non-planar damage

Full Delamination Analysis of PEKK Impacted at 15 ft-lbs

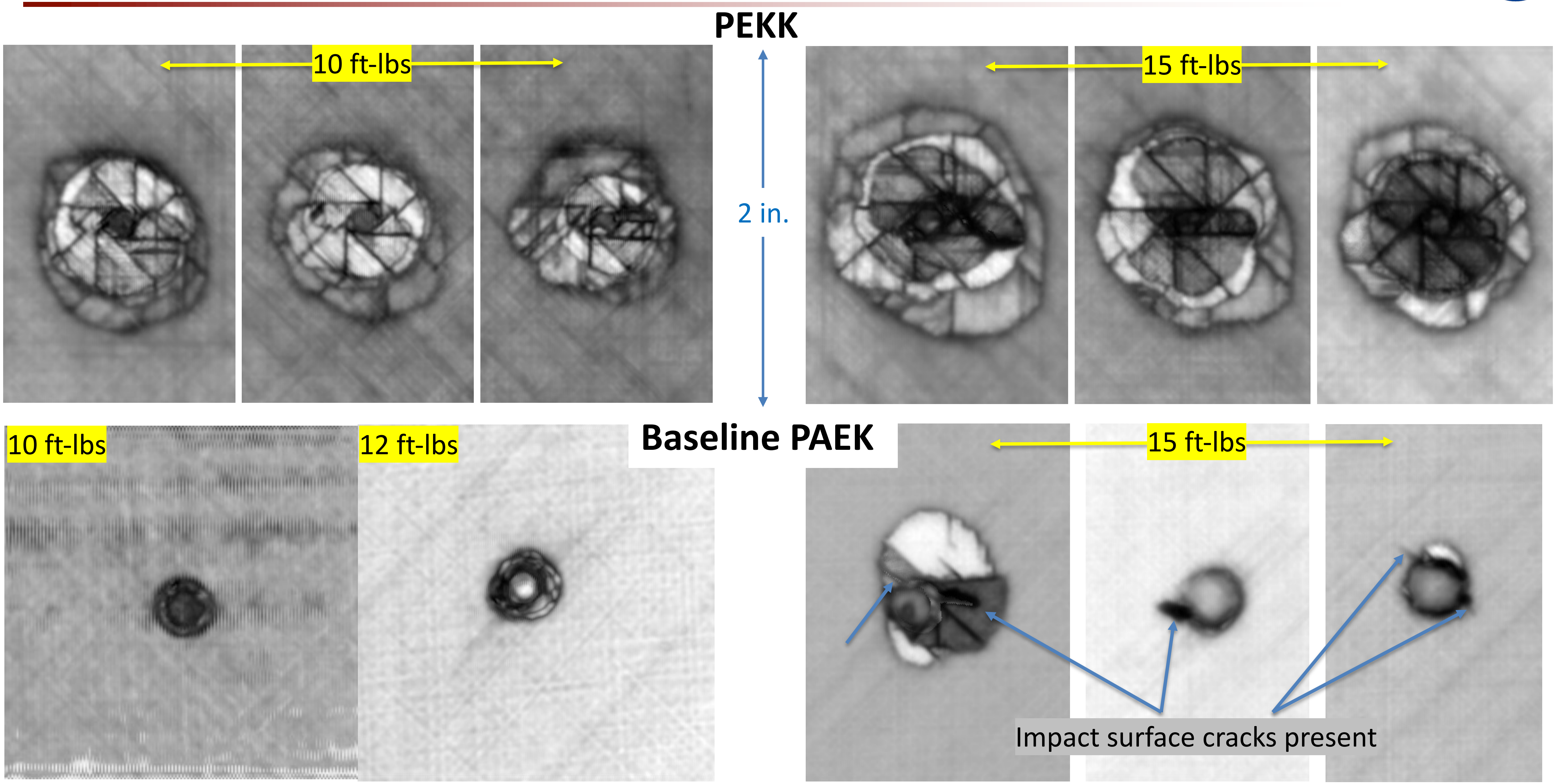
Impact Surface [-45/0/+45/90/-45/0/+45/90 /-45/0/+45/90/90/+45/0/-45/ 90/+45/0/-45/ 90/+45/0/-45]

Interface #: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

Delaminations

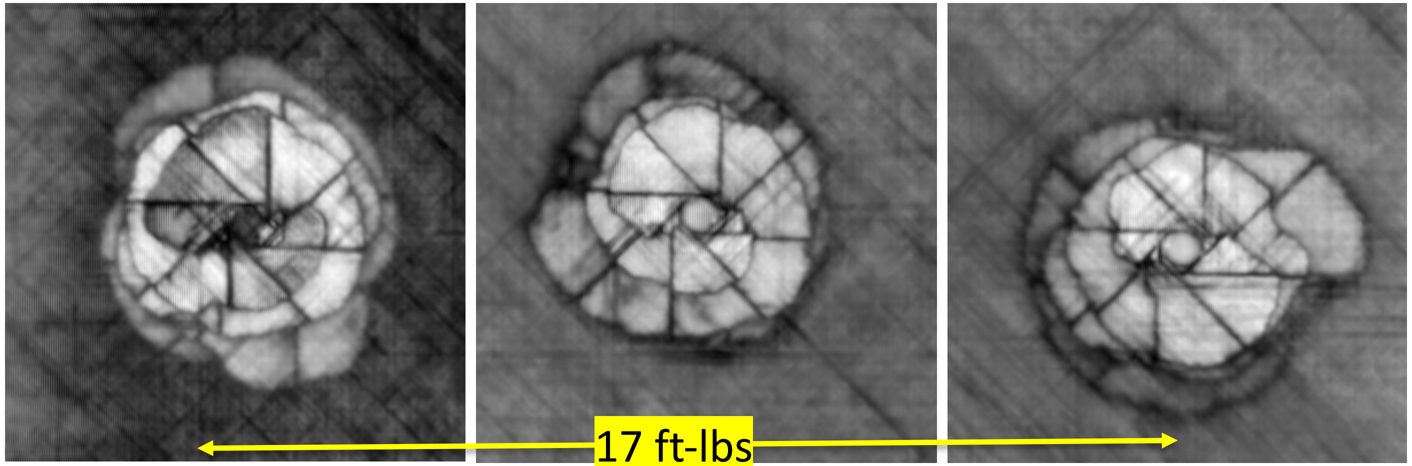


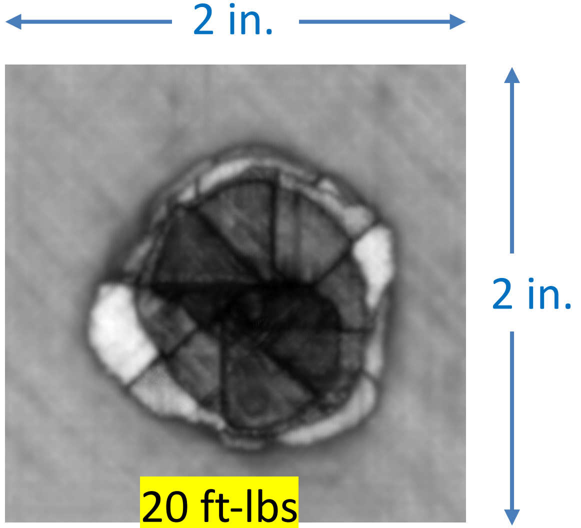
PEKK vs. PAEK Specimens: UT Scan Comparison at 10 ft-lbs to 15 ft-lbs



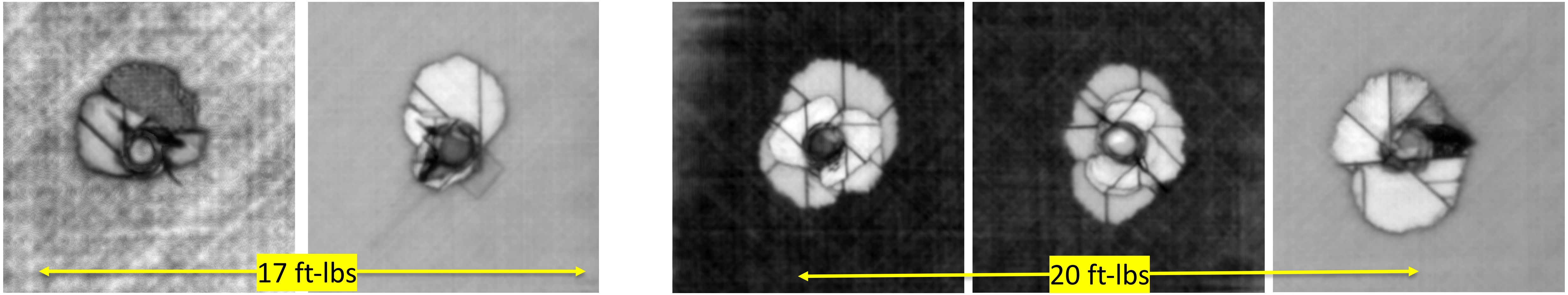
PEKK vs. PAEK Panels: UT Scan Comparison at 17 ft-lbs and 20 ft-lbs

PEKK

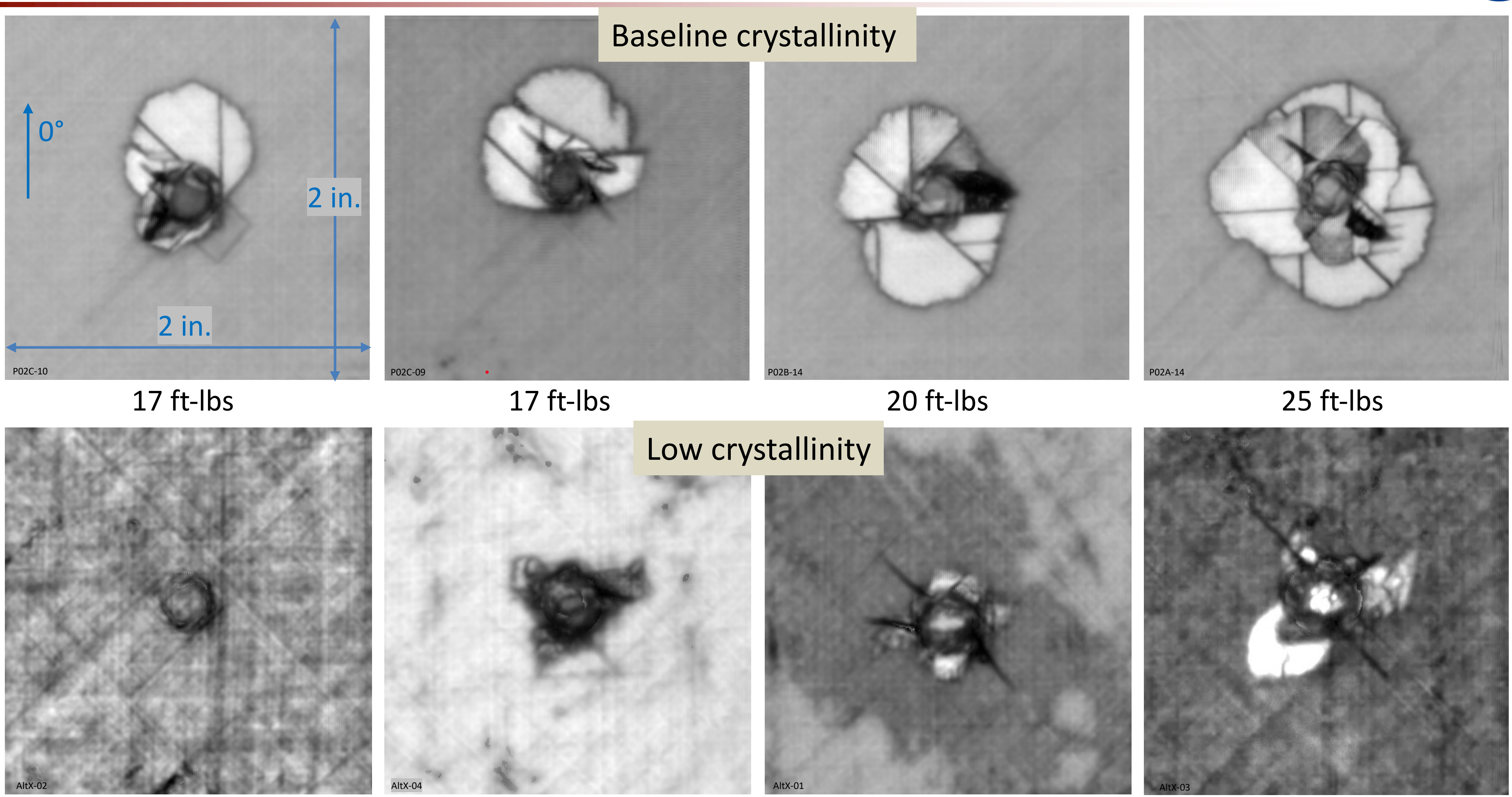




Baseline PAEK



Effects of Crystallinity on PAEK Specimens: UT Scan Comparison

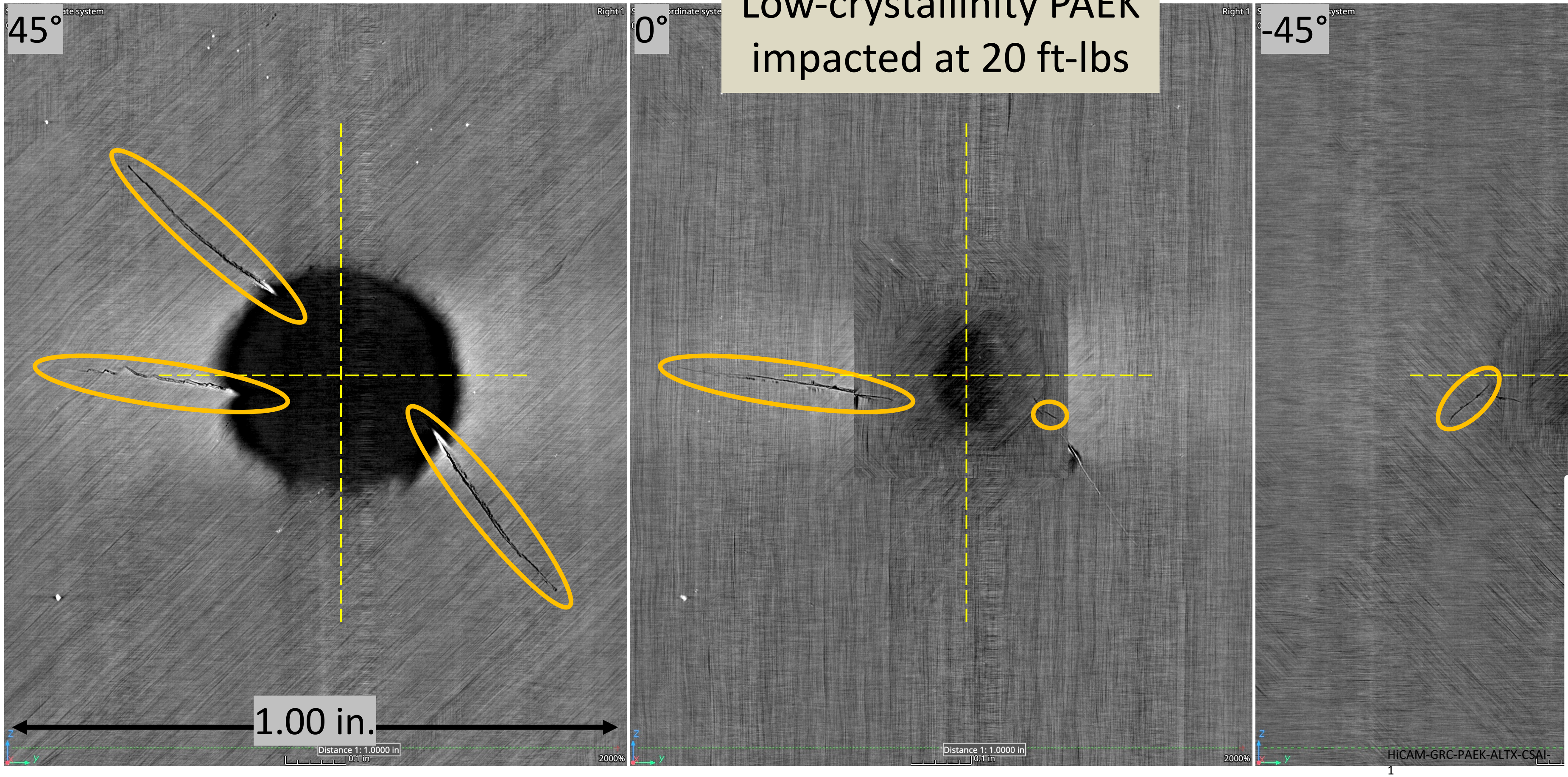


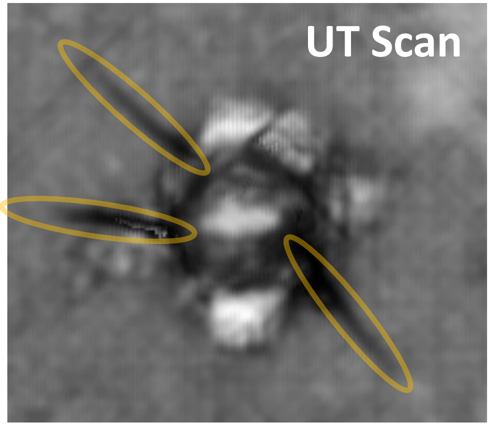
Near-Surface Fiber Fractures

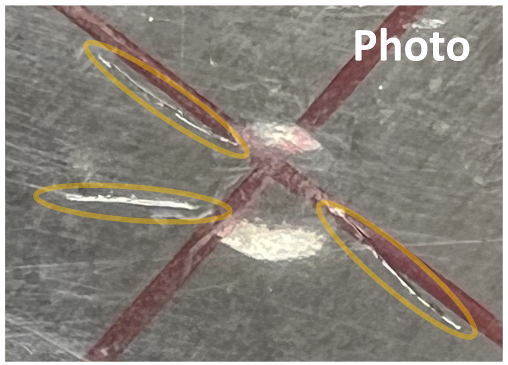
Impacts caused near-surface lines of fiber fracture in some specimens

- Observed only in PAEK specimens: ~50% of the baseline and all but one of the low-crystallinity specimens
- Fractures were generally perpendicular to the fiber directions
- Restricted to the top four plies near the impact surface

Low-crystallinity PAEK impacted at 20 ft-lbs



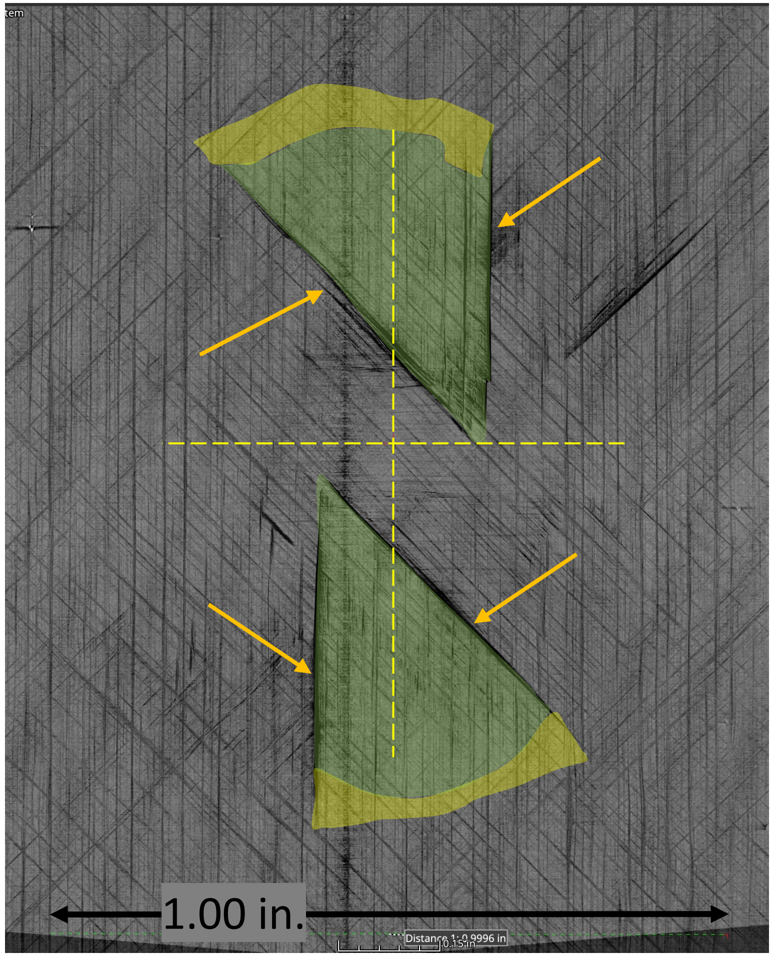




Typical Delamination Shapes in Each Interface

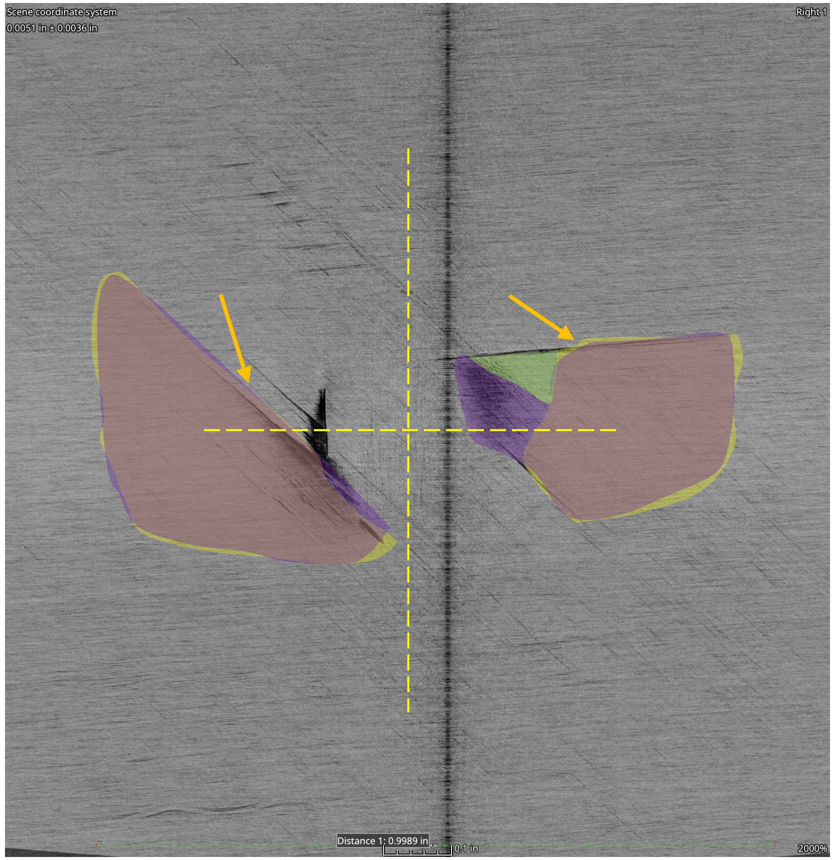
<u>PEKK</u>

Two pie-slice shaped delaminations with edges bounded by matrix cracks on two sides



<u>Baseline PAEK</u>

One or two delaminations with edges bounded by matrix cracks on one or two sides

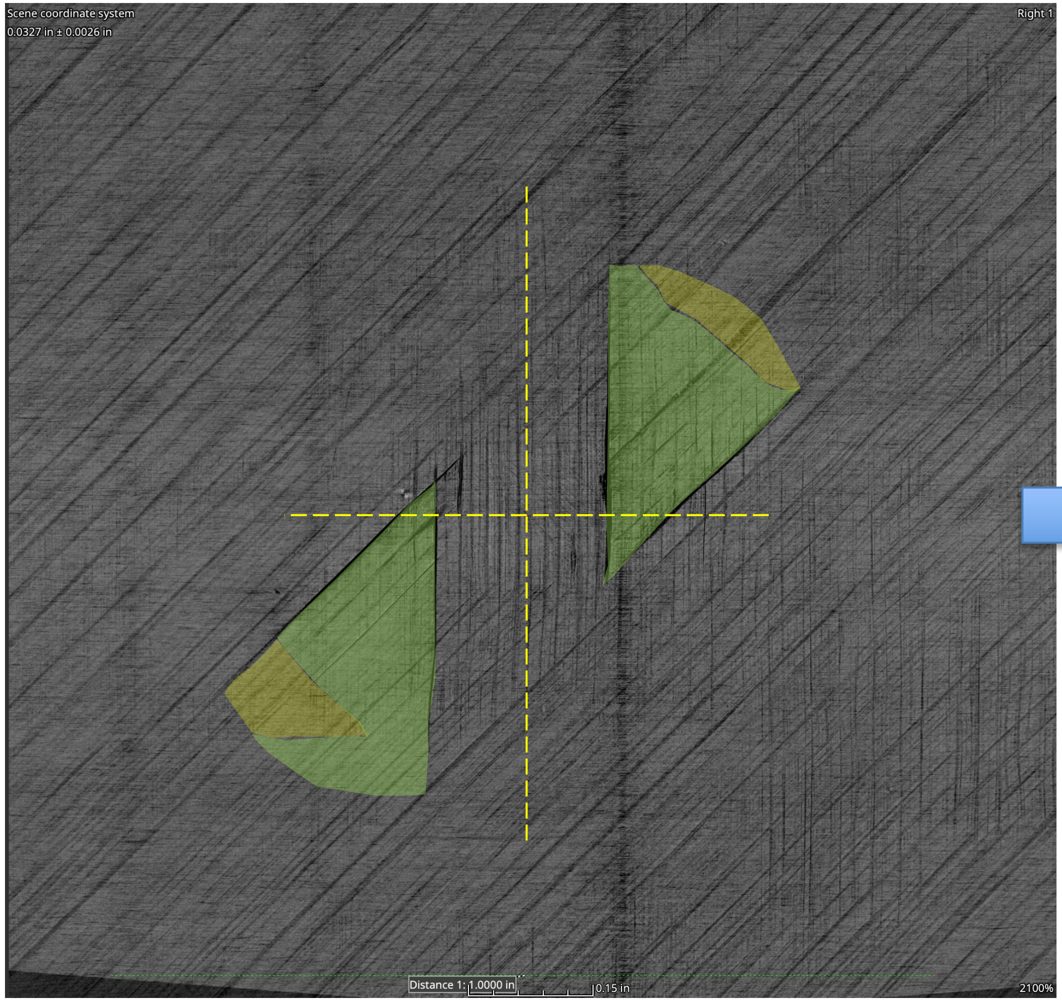


<u>Low-Crystallinity PAEK</u>

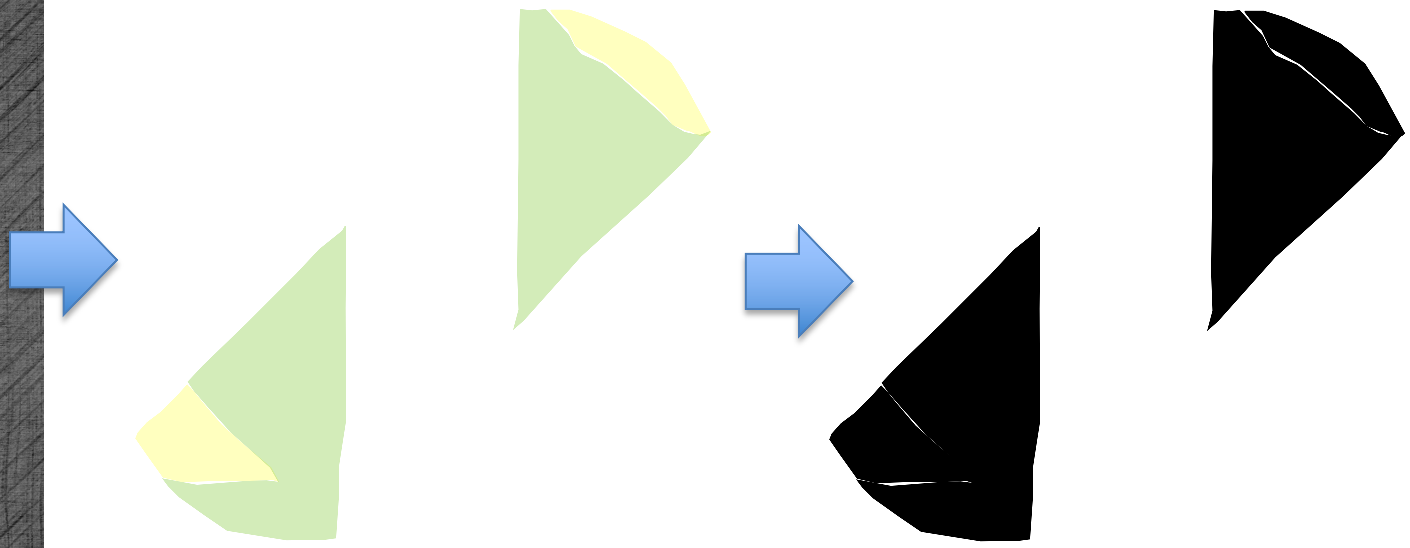
One or two delaminations, irregular shapes - not bounded by matrix cracks

Delaminated Area Calculation Per Interface

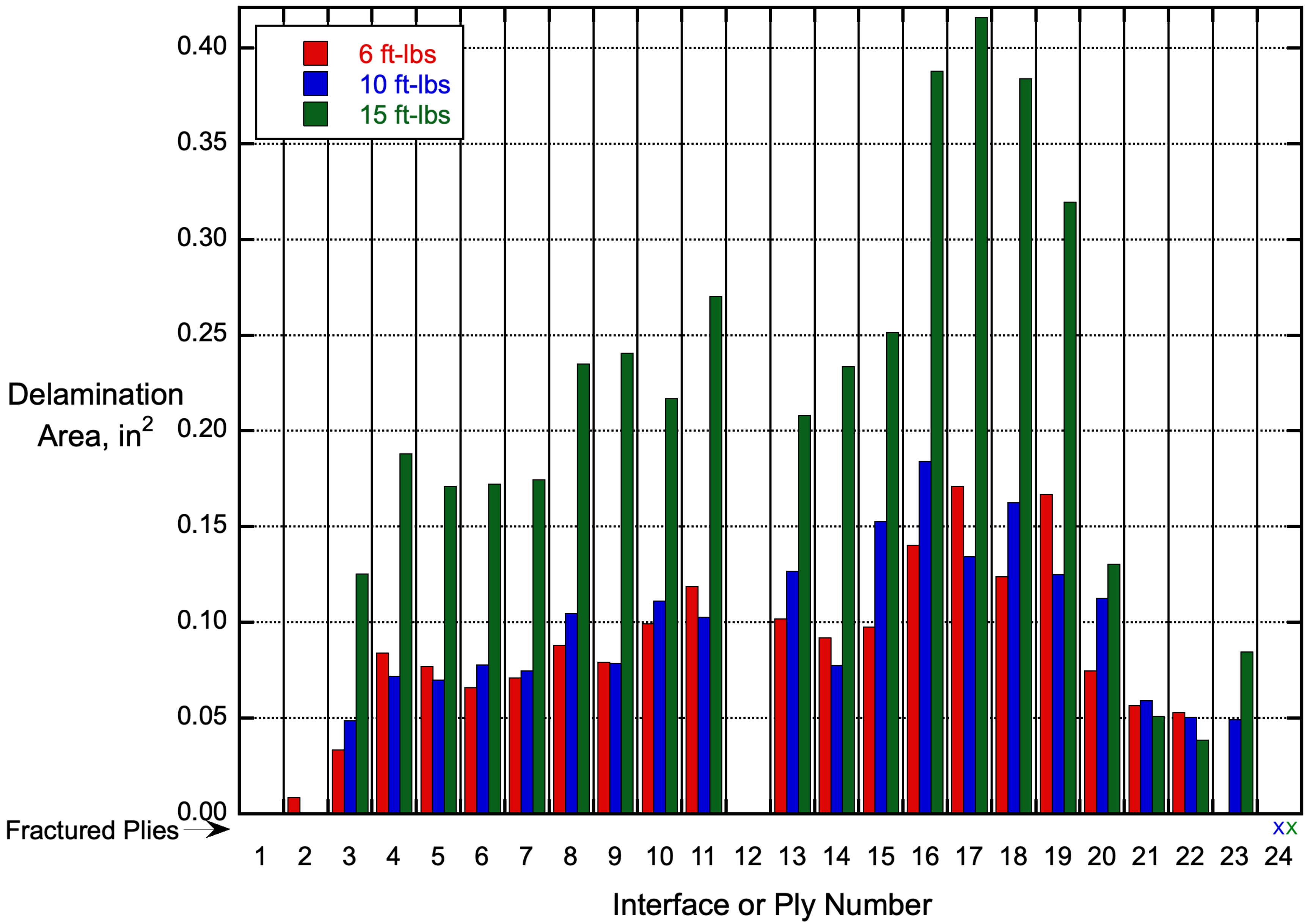
- All data except delamination images were removed from the damage analysis slides
- Slides were converted to an image stack
- Image stack was converted to black and white using the program ImageJ (National Institute of Health)
- Automated area calculations were performed using ImageJ on the stack and exported to a spreadsheet



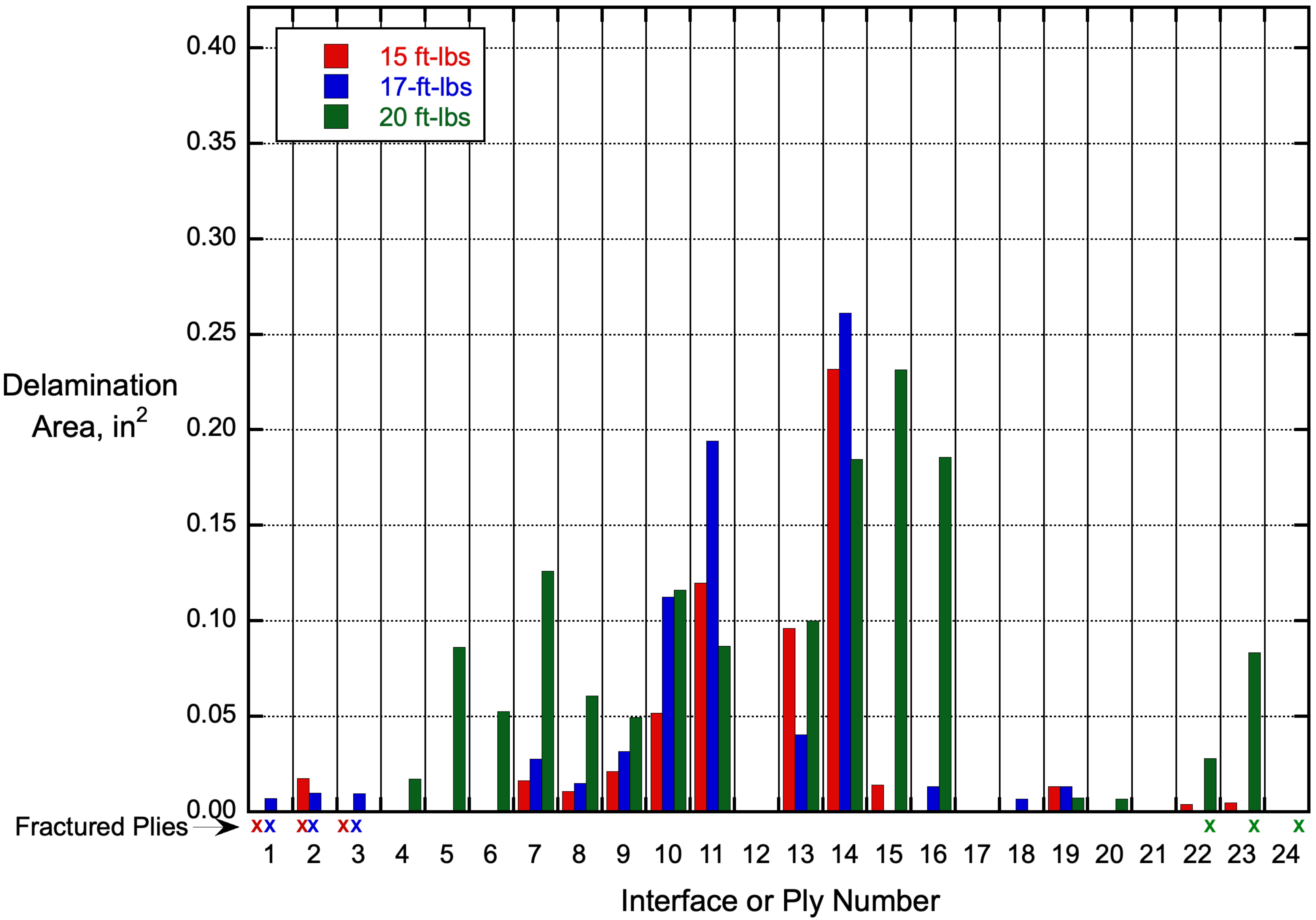
Calculation Check: 1-inch square placed at symmetry plane to verify area calculation for each specimen



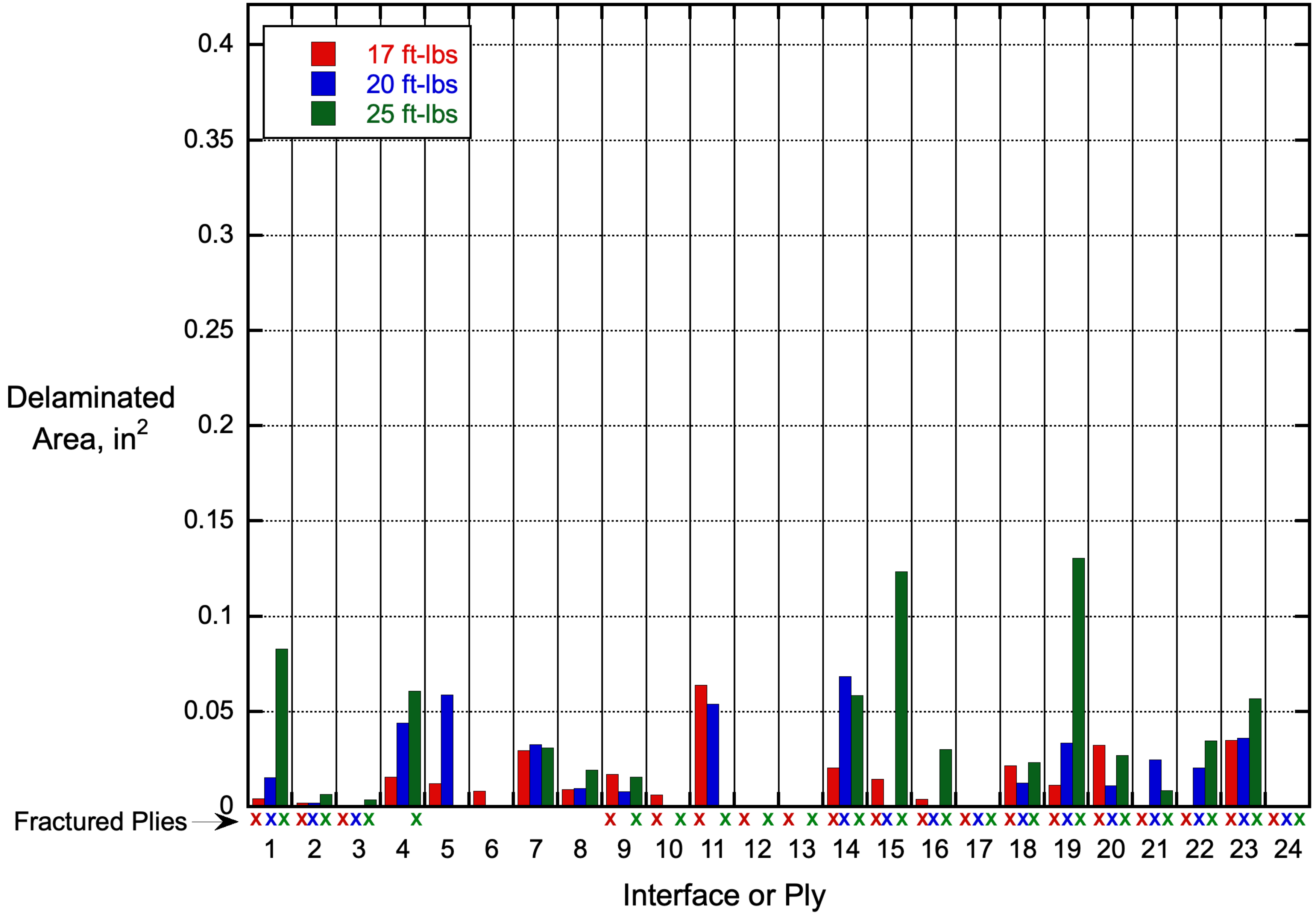
Damage by Interface/Ply for PEKK Specimens



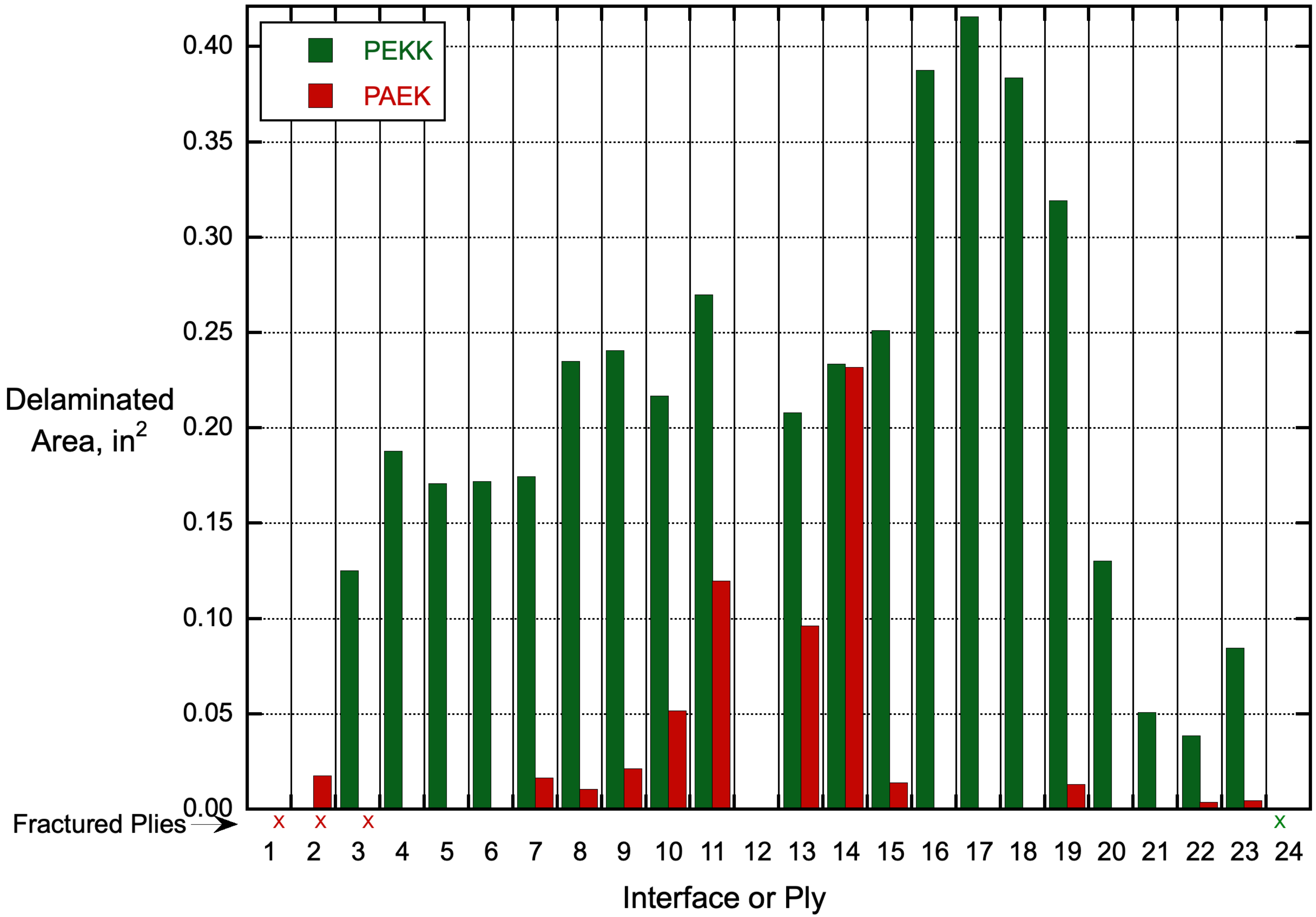
Damage by Interface/Ply for PAEK Specimens



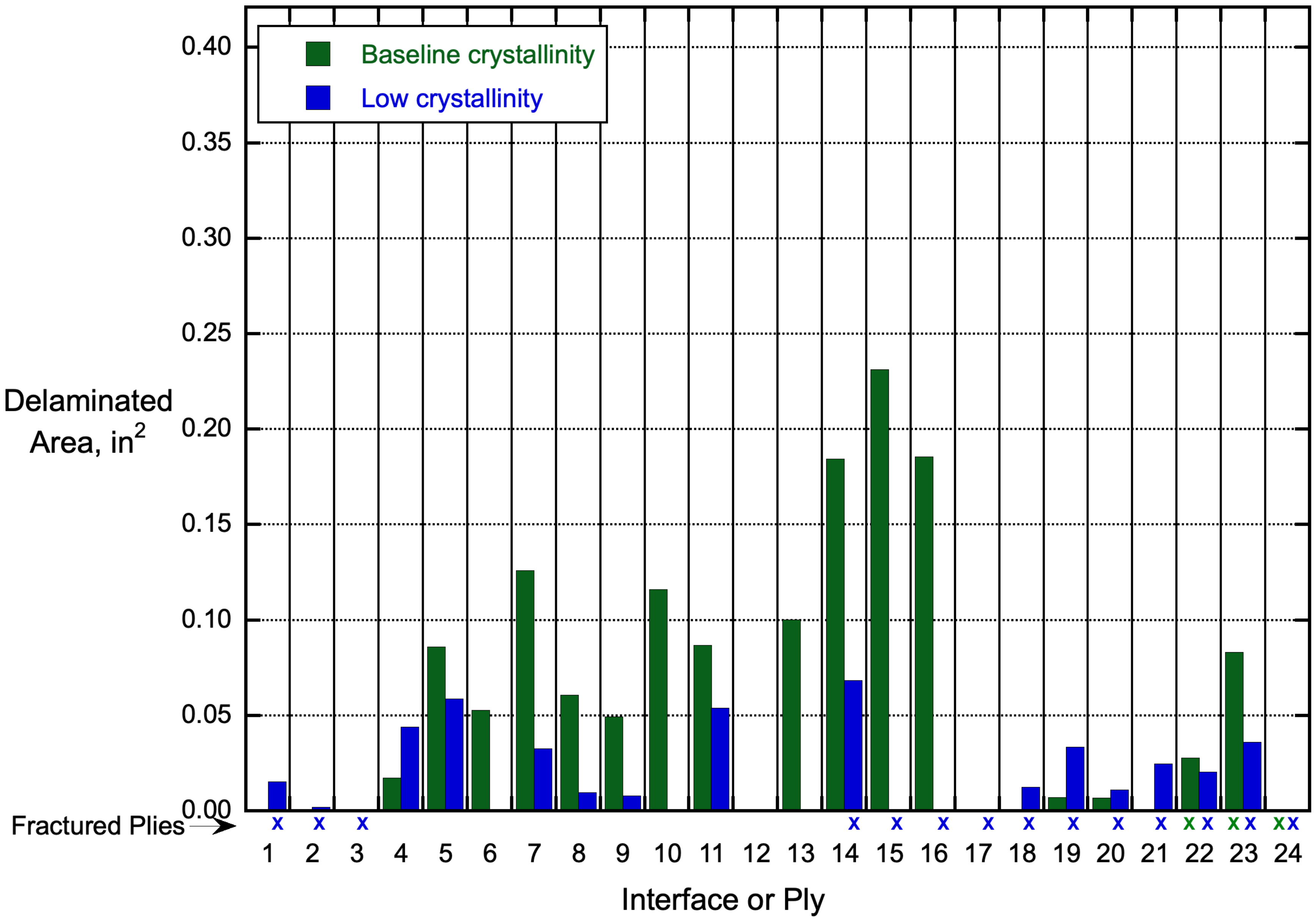
Damage by Interface/Ply for Low-Crystallinity PAEK Specimens



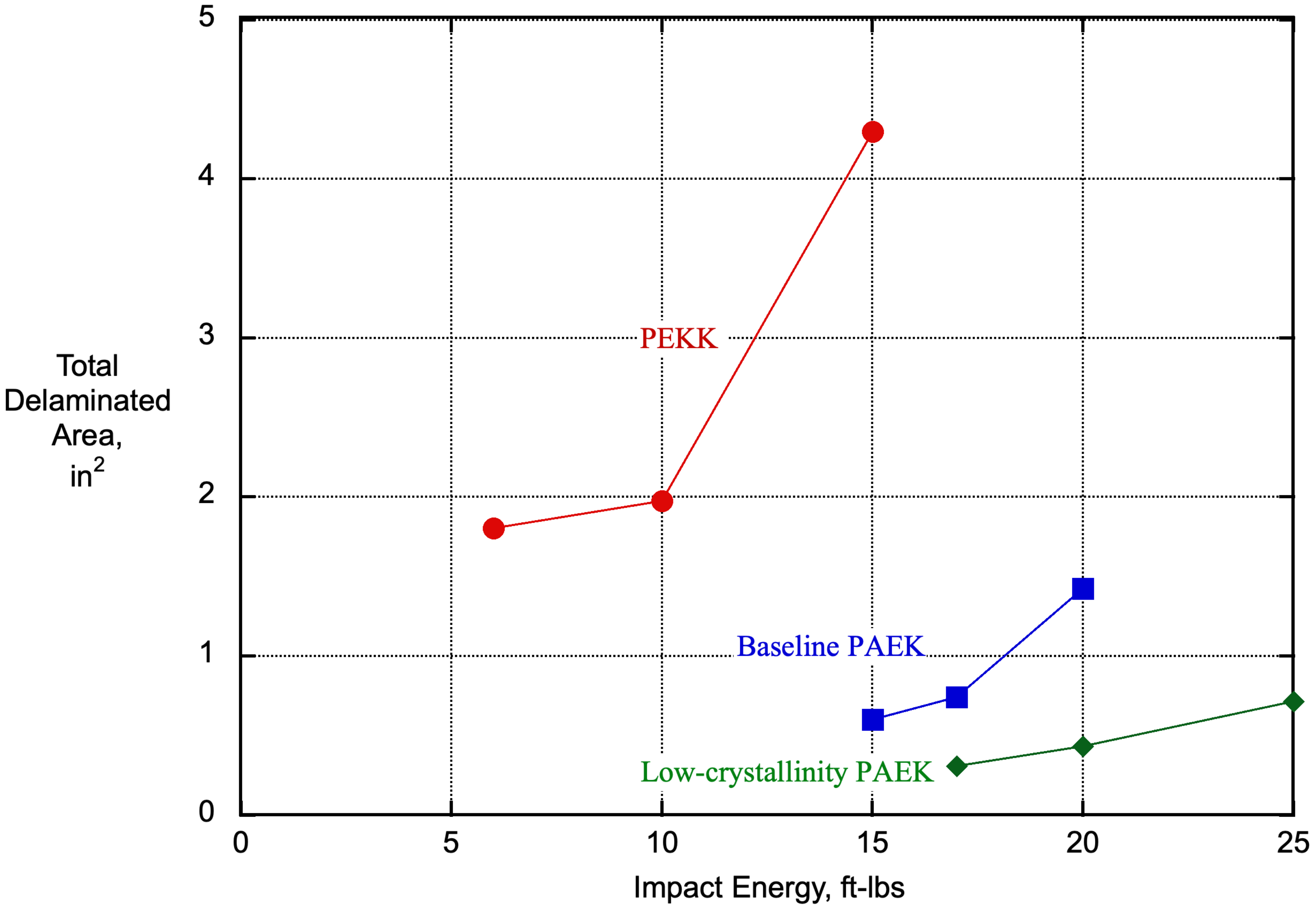
Damage Comparison of PEKK and PAEK Specimens at 15 ft-lbs



Damage Comparison of Baseline and Low-Crystallinity PAEK Specimens at 20 ft-lbs



Comparison of Total Delaminated Area



Summary

- **Testing**: 34 impact tests were performed and detailed ply-by-ply damage maps were created for three PEKK, three baseline PAEK, and three low-crystallinity PAEK specimens.
- **Damage Initiation:** PEKK: ~6.0 ft-lbs. Baseline PAEK: ~10 ft-lbs. Low-crystallinity PAEK: ~17 ft-lbs
- **Delaminated Area:** For a given impact energy: PEKK > baseline PAEK > low-crystallinity PAEK
- **Delamination Pattern:**
  - **PEKK Specimens:** Rotating fan of two pie-slice shaped delaminations that spiraled through the thickness (similar to thermosets). Largest delaminations located at 75% of thickness from front surface.
  - **Baseline PAEK Specimens:** Asymmetrical delamination pattern. Delamination bounded by a one or two matrix cracks. Largest delaminations near the center thickness.
  - **Low-Crystallinity Specimens:** Discontinuous between adjacent interfaces. Single unbounded delaminations with irregular shapes. Damage distributed through the thickness.
- **Fiber Fracture:**
  - **PEKK Specimens:** Small amount of fiber damage limited to a few back-surface plies
  - **Baseline PAEK Specimens:** Fiber fractures on impact-side near-surface plies and near back surface
  - **Low-Crystallinity Specimens:** Fiber fractures in impact-side near-surface plies with extensive fiber fractures observed throughout the thickness
- **In General:** The overall impact damage response shifts from primarily delamination in the PEKK specimens to primarily fiber damage in the tougher low-crystallinity PAEK specimens.