# A Procedure to Quantify Interlaminar Damage in Refractory Composites by *In-Situ* Micro-X-Ray Computed Tomography

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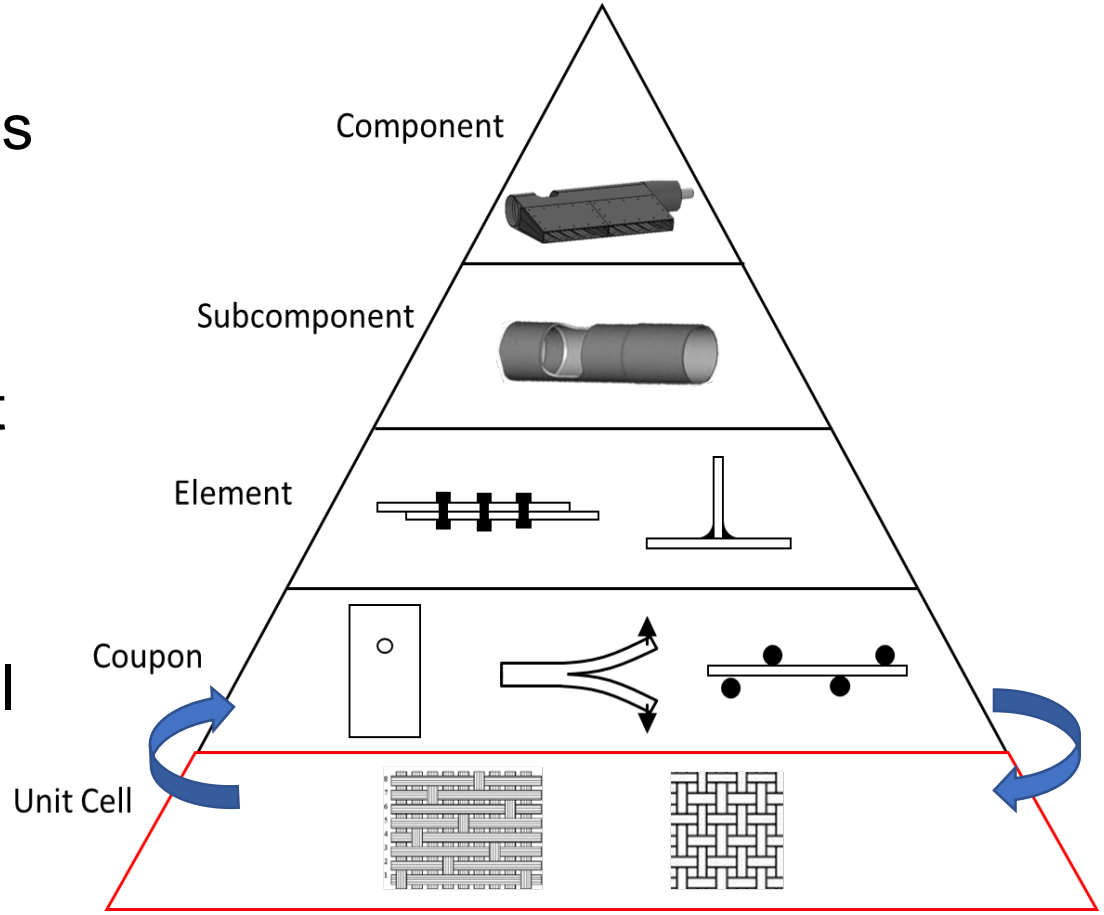
# Outline

- Introduction
- Test setup
- Data processing
- Concluding remarks

# Introduction

- Composite material maturation into a flight component is a lengthy and expensive process
- Developing models to predict material properties requires improved empirical data at the unit cell level
- Material databases will require fewer empirical tests if a feedback loop between a model and empirical observations can be improved



# Introduction, continued

**Goal**
Collect empirical data on the progressive failure of refractory composites to improve current simulations.

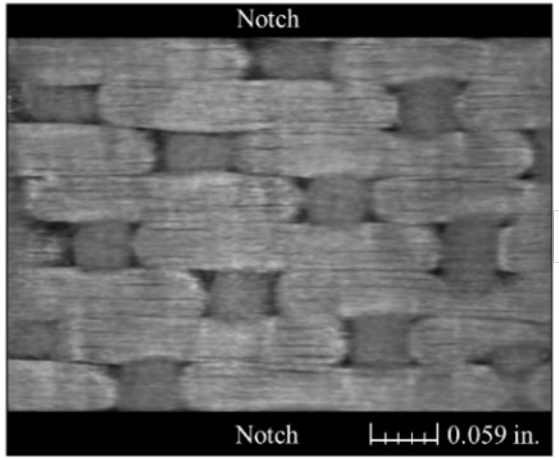
**Objective**
Develop a procedure to capture the progressive failure in ASTM-sized specimens throughout volume of the specimen.

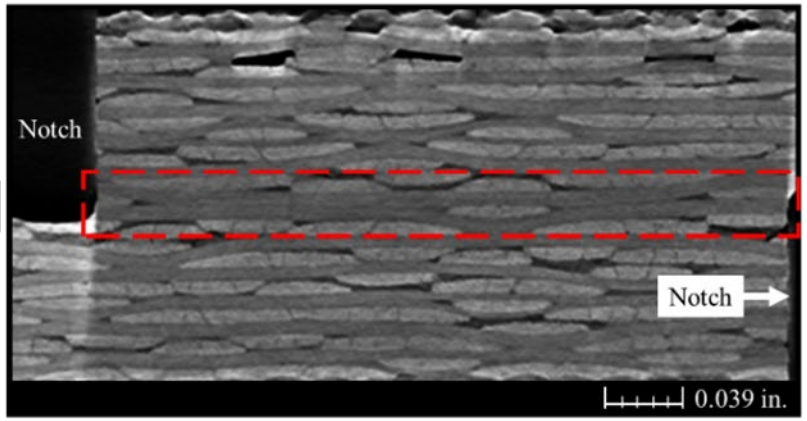
**Approach**
Test and observe specimens utilizing a load frame located within a micro-x-ray computed tomography (CT) machine in an iterative manner.

# Specimens

## Interlaminar Shear (ILS)

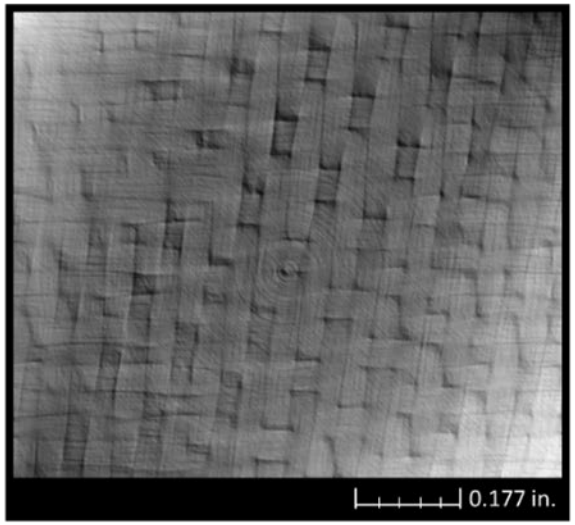
- Double Notch Shear (DNS)
- ASTM D3846
- 3.12 in. x 0.49 in.
- $[0/90]_{3s}$ warp align
- 8-Harness Satin Weave (HSW)
- Gage area 0.169 in²

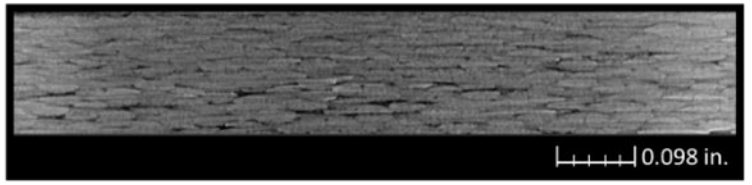



## Flat-wise interlaminar tension (ILT)

- ASTM D7291
- 1.0 in. x 1.0 in.
- $[0/90]_{3s}$ warp align
- 8-HSW
- Gage area 0.99 in²

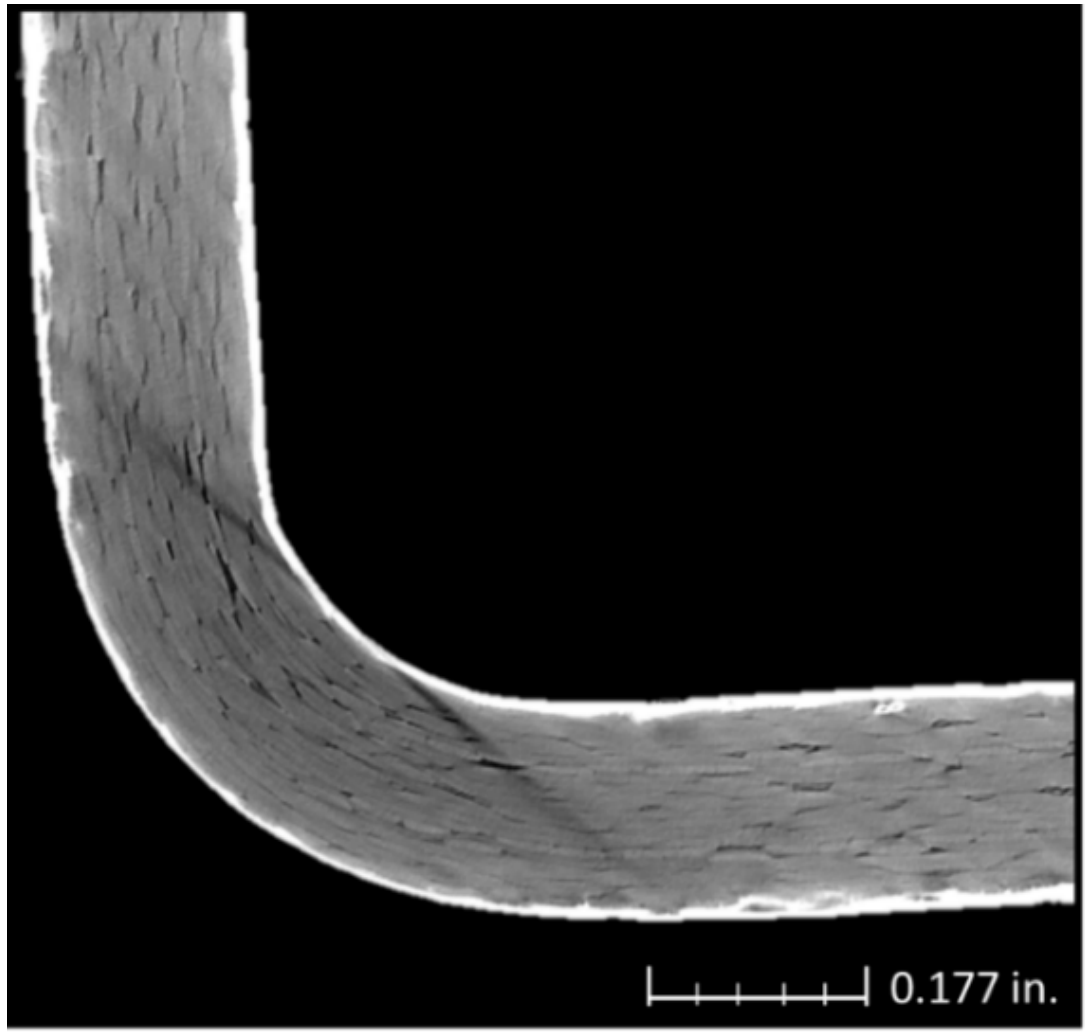


# Specimens, continued

Curve-Beam Interlaminar Tensile (CB-ILT)

- ASTM D6415
- $[0/60/-60/0/60/-60]_S$ warp align
- 8-HSW
- SiC Coating



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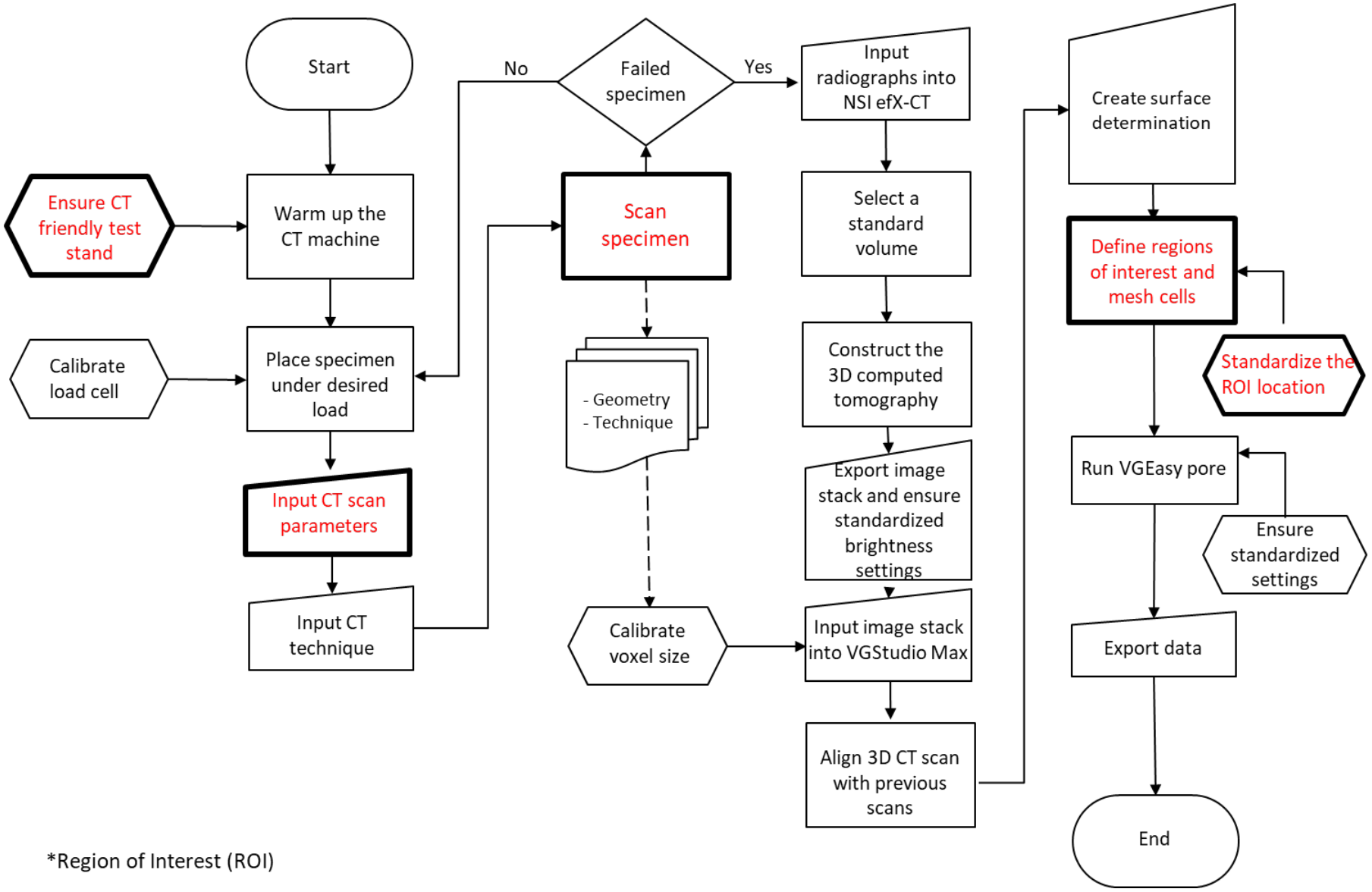
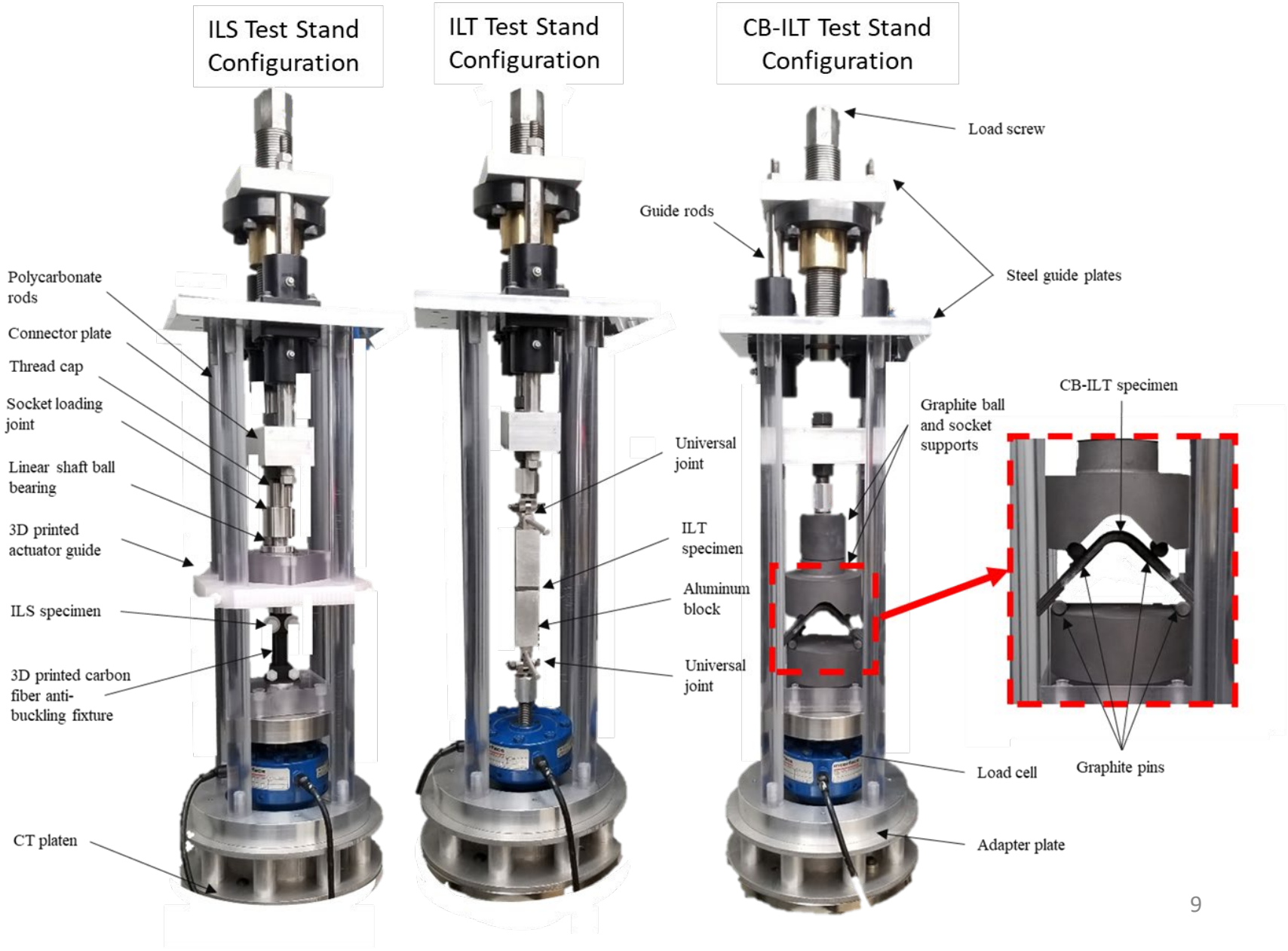
# Testing Procedure




*Region of Interest (ROI)

# Test Stand Schematic

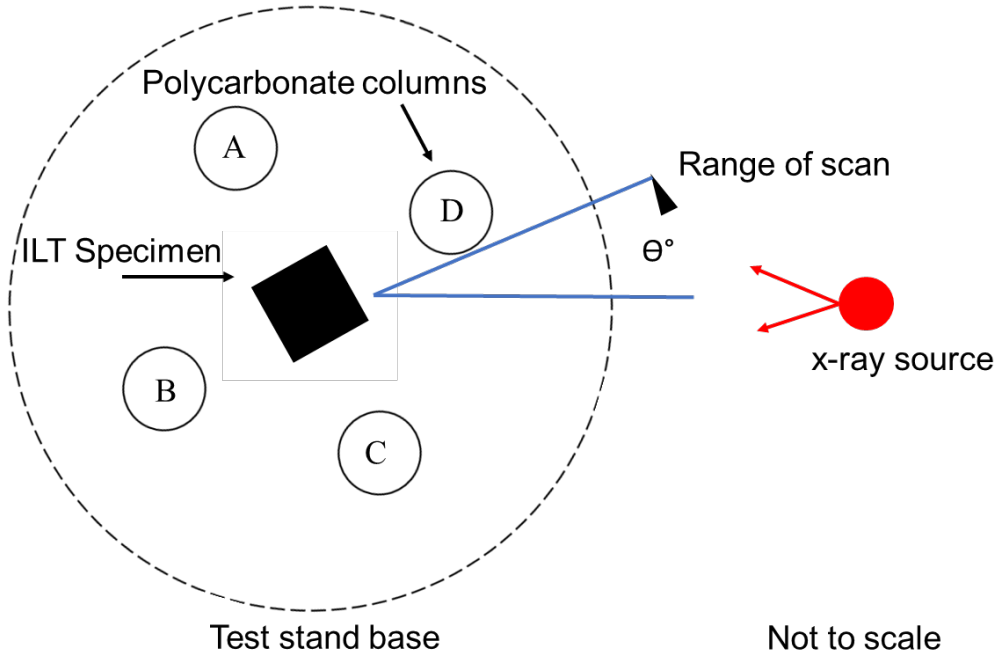
- Materials used in the vicinity of the beam are x-ray friendly
- Load frames are bolted to the CT platen
- Tests were loaded incrementally by hand
  - Interface 1201-BJ 10 Kip load cell
  - Interface model 9840 data acquisition system



# X-Ray Scan Configuration

North Star Imaging (NSI) X3000 CT machine with Varian detector

- Voxel resolution
- Minimum voxel resolution for feature detection




## CT Scan Parameters

| Test | Voltage (kV) | Current (μA) | Rotation Speed (degrees/s) | Platen Left/Right (in.) | Platen Up/Down (in.) | Detector Up/Down (in.) | Platen Magnitude (in.) | Detector Magnitude (in.) |
|---|---|---|---|---|---|---|---|---|
| ILS | 80 | 180 | 1.8 | 0 | -2.957 | 0 | 2.638 | 39.370 |
| ILT | 80 | 180 | 1.8 | 0 | -11.430 | 0 | 5.598 | 39.370 |
| CB-ILT | 60 | 180 | 1.8 | 0 | -11.600 | 0 | 6.900 | 39.370 |

## CT Technique Parameters

| Test | Projection (Count) | Frame Averaging (Count) | Delay (seconds) | Range of Scan (degrees) | Voxel Resolution (in.) | Minimum Voxel Resolution Feature Detectability (in.) |
|---|---|---|---|---|---|---|
| ILS | 330 | 5 | 1 | 48 | 3.35E-05 | 5.02E-05 |
| ILT | 840 | 5 | 1 | 118 | 2.46E-05 | 1.40E-04 |
| CB-ILT | 800 | 5 | 1 | 68 | 8.50E-04 | 3.40E-03 |

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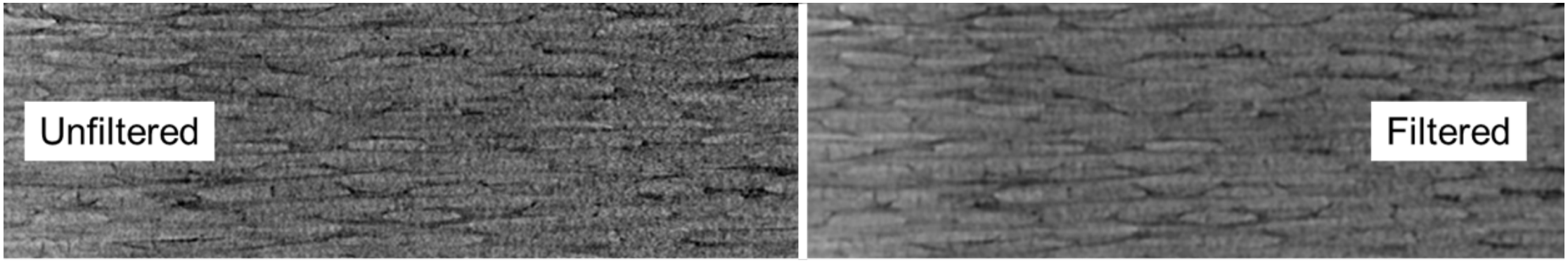
# Image Filtering

All ILT data required image filtering before performing an image analysis

- Conducted adaptive Gaussian function
  - A lowpass filter - focuses on the attenuation of grayscale intensity
  - Linear - replaces the voxel with a weighted summation of the value from its surrounding neighbor
  - Standard deviation in the grayscale value decreased 13.8% with the addition of the filter



# Directional Variability

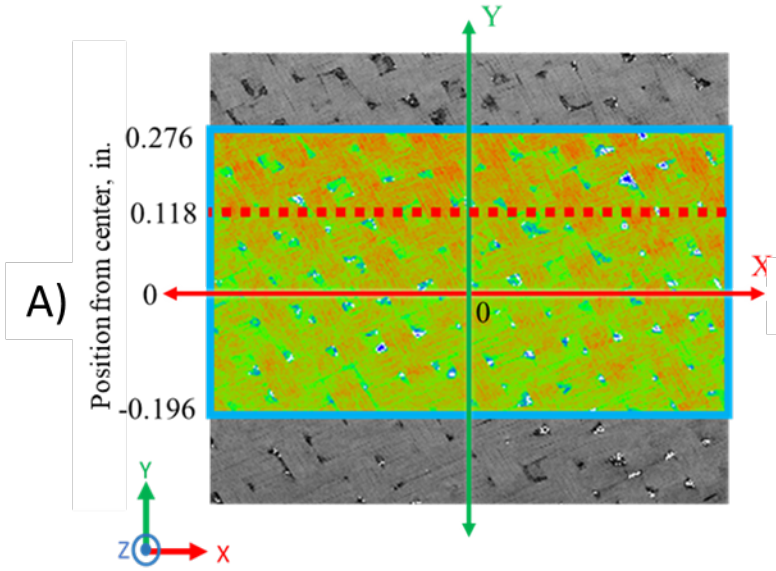
Quantifies the uniformity of the grayscale value throughout the volume of the reconstruction

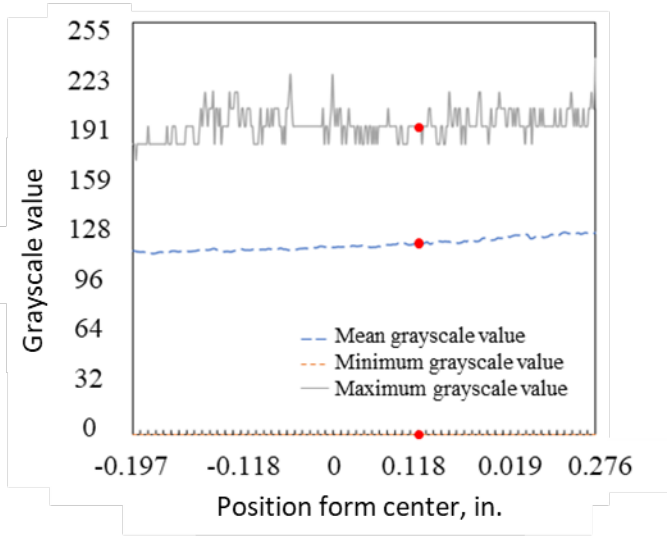
A) CT slice of the ILT baseline scan

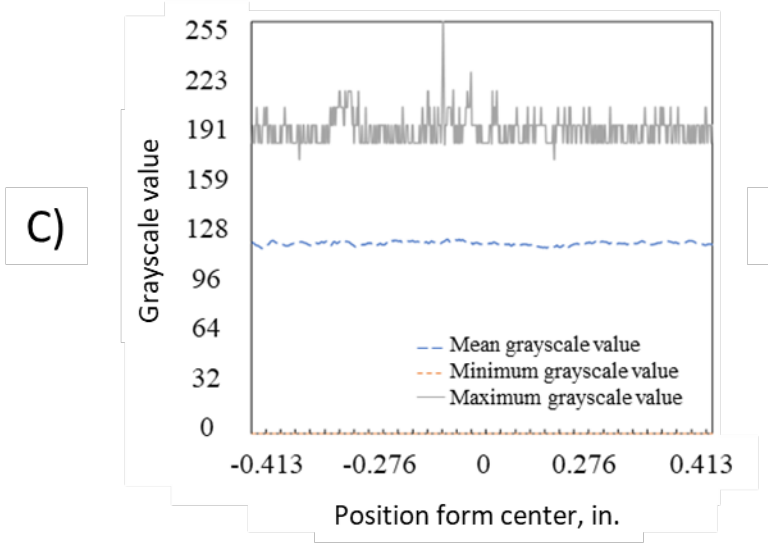
B) X-directional variability of grayscale value

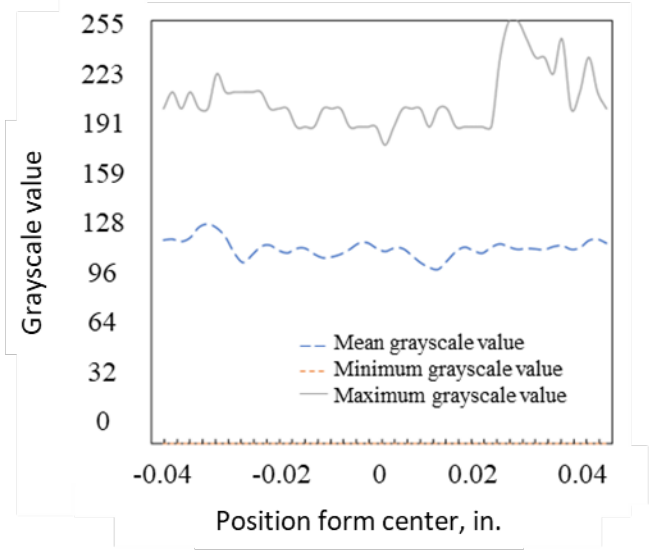
C) Y-directional variability of grayscale value

D) Z-directional variability of grayscale value



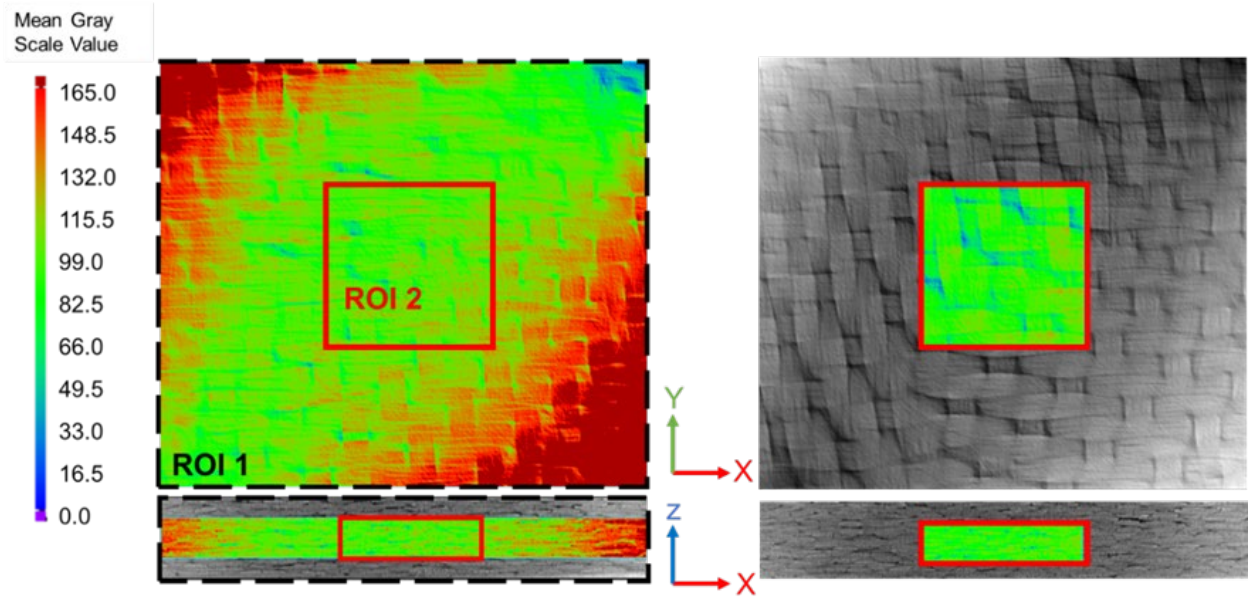



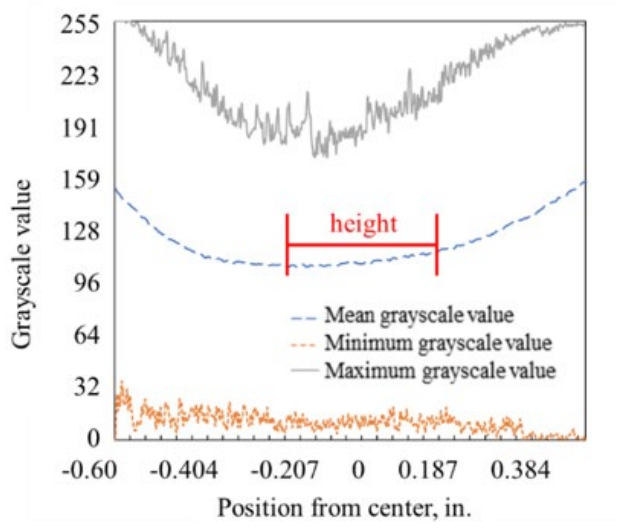



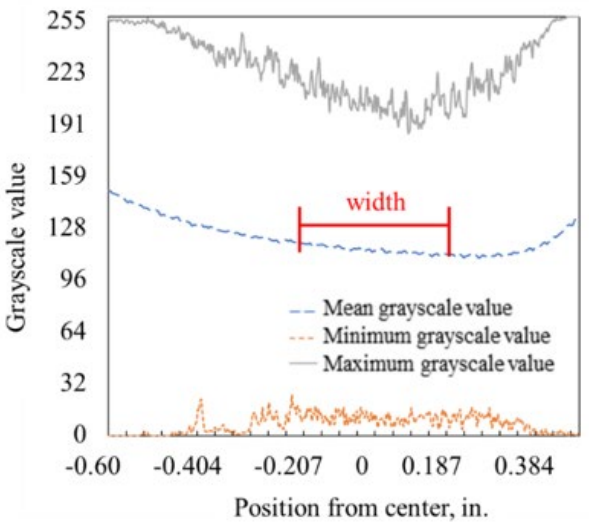
# Directional Variability, continued

- Used grayscale deviation for region of interest (ROI) placement for ILT analysis
  - XY grayscale variability analysis heat map
- Aspire to have the ROI mean and standard deviation (SD) grayscale value be close to the baseline scan

| | Baseline Scan | | ROI 1 | | ROI 2 | |
|---|---|---|---|---|---|---|
| | X-Direction | Y-Direction | X-Direction | Y-Direction | X-Direction | Y-Direction |
| Mean | 117.86 | 117.65 | 126.45 | 122.25 | 100.67 | 114.92 |
| Standard Deviation | 3.8 | 1.04 | 19.46 | 20.97 | 2.38 | 3.11 |
| Count | 347 | 349 | 344 | 343 | 231 | 231 |
| 95% Confidence Interval Mean ± | 0.4 | 0.11 | 2.06 | 2.22 | 0.31 | 0.4 |
| Covariance, % | 3.22 | 0.88 | 15.39 | 17.15 | 2.36 | 2.71 |

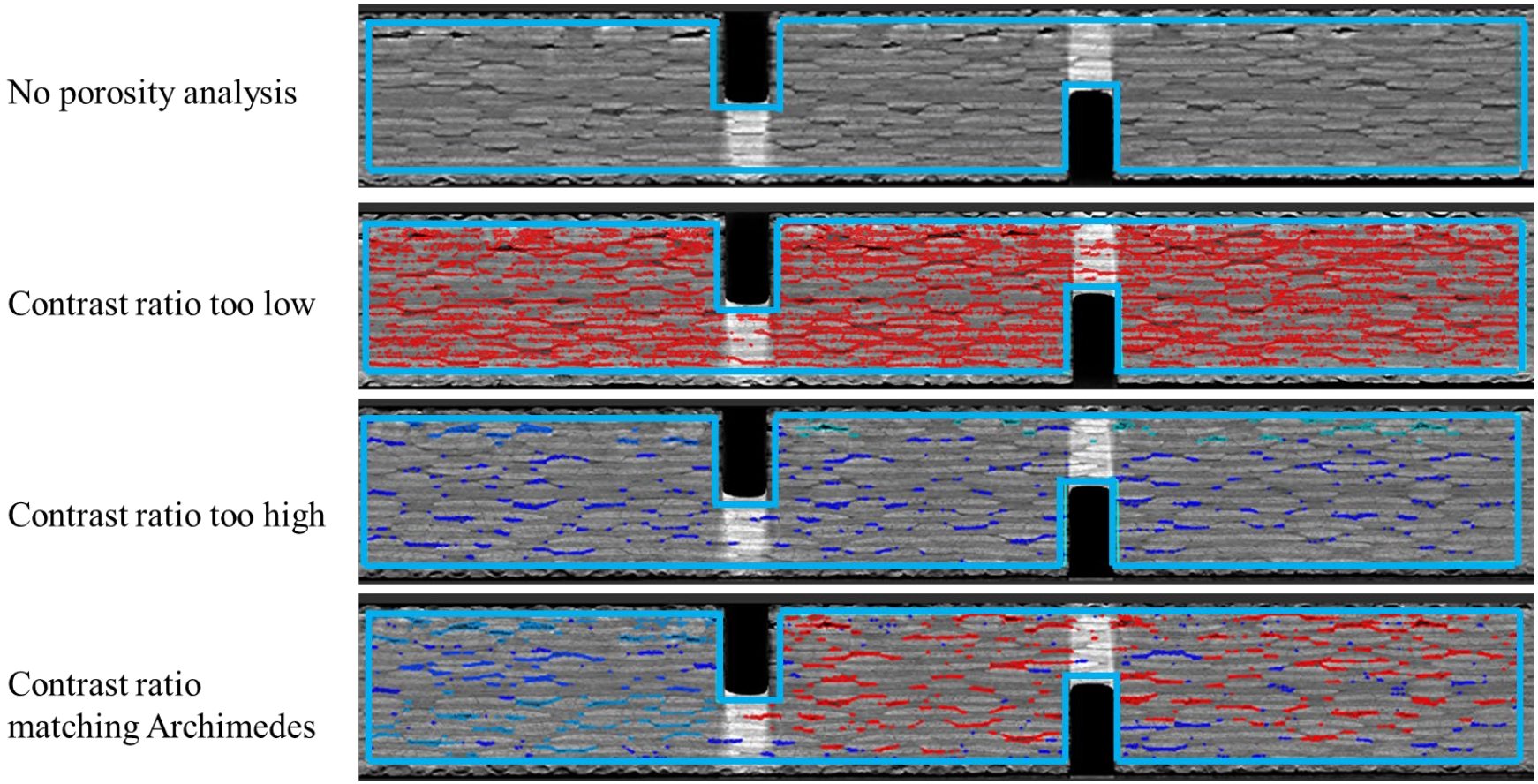


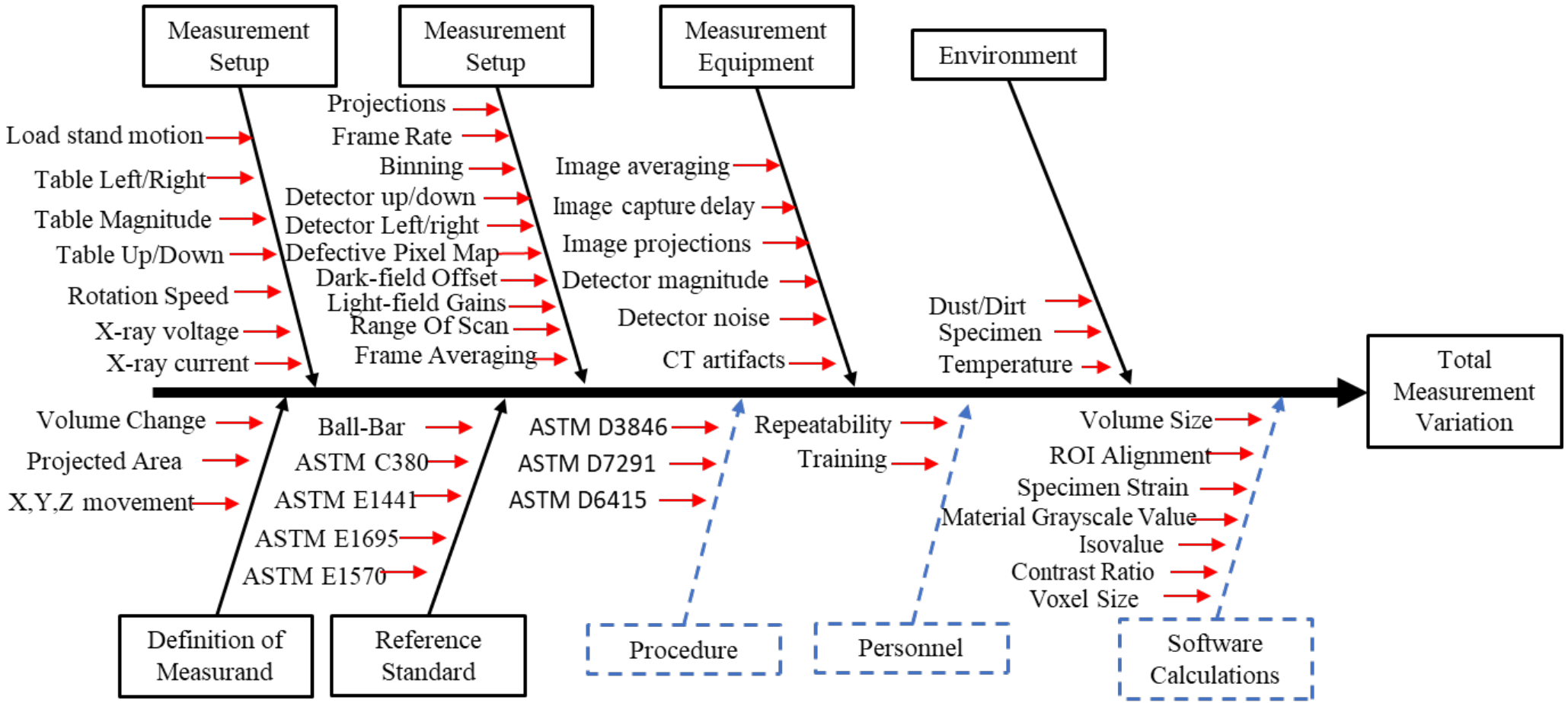
# Porosity Analysis

Used VGStudioMax porosity inclusion analysis to capture pores and damage



# Sources of Uncertainty

While an uncertainty quantification has not yet been completed, identifying the sources is the first step



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# Concluding Remarks

**Developed a procedure to capture the progressive failure in ASTM-sized specimens throughout volume of the specimen**

**Discussed the details on**

- CT test stand configuration
- Created a micro-x-ray CT configuration
  - CT Scan Parameters
  - CT Technique
- Data processing
  - Image filtering
  - Directional variability
  - Porosity analysis

**Sources of uncertainty**

# Acknowledgements

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**NASA Langley Structural Mechanics and Concepts Branch**