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Sandia National Laboratories

Characterization of Heterogeneity and Mechanical Properties of SiC-SiC Composites

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U.S. DEPARTMENT OF ENERGY NNSA

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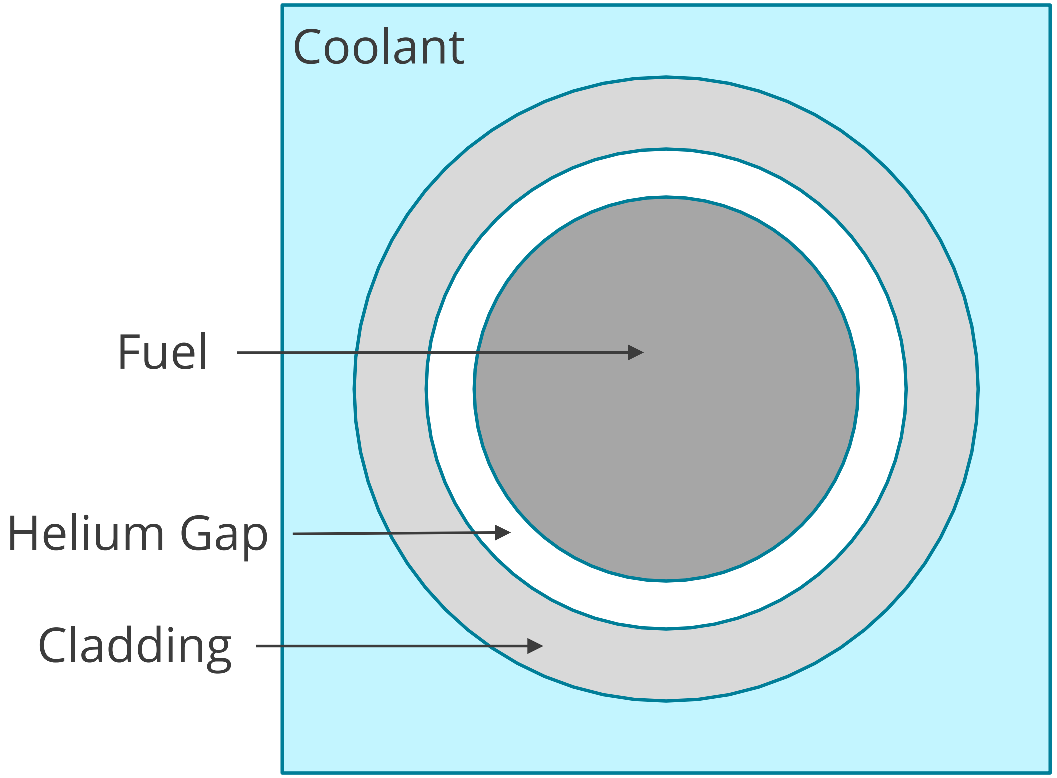
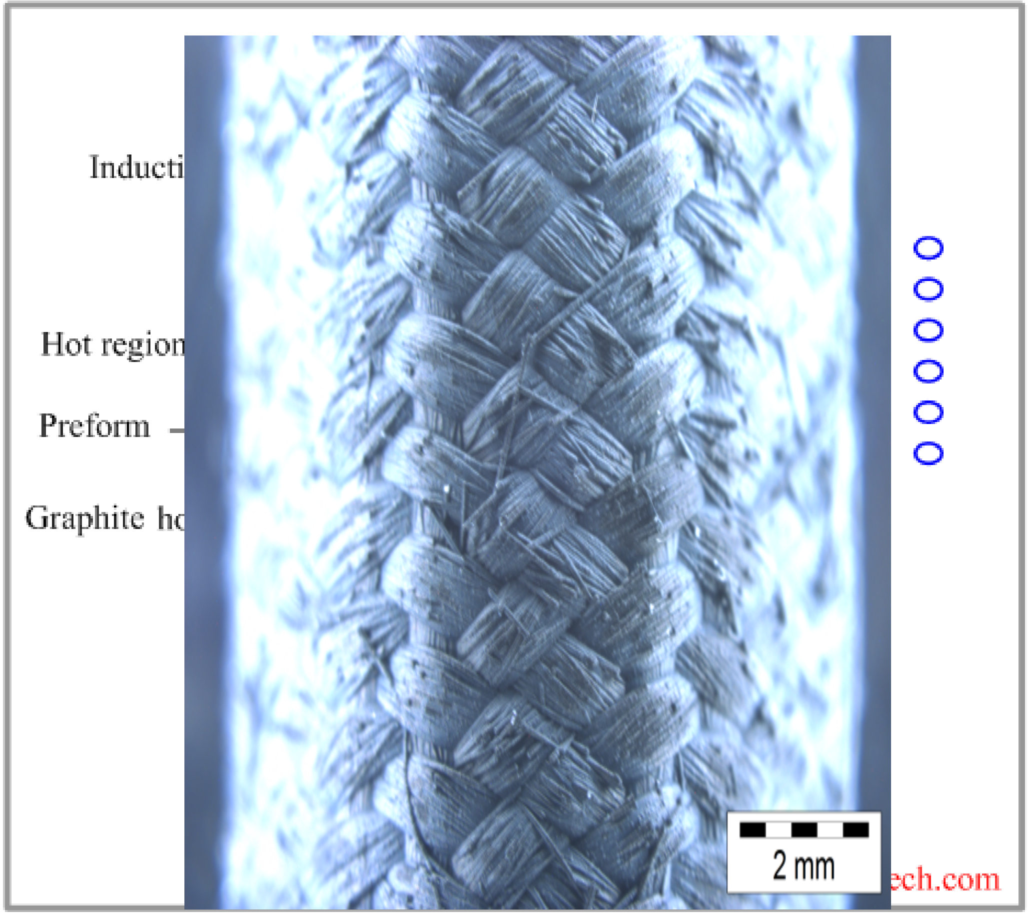
Nuclear Fuel Cladding

- Current nuclear fuel cladding is primarily a zirconium alloy
- Fails under very high temperatures and loses strength
  - Typically happens during Loss of Coolant Accidents (LOCA)
- Potential alternative is a SiC fiber reinforced tubular composite
  - Excellent chemical compatibility with coolant and fuel systems in high temperature gas cooled fast reactors



CVI SiC-SiC Composites

1. Hi-Nicalon Type-S SiC fibers (~10 μm diameter) are bundled and braided into tows to make a plain-weave configuration
2. 100-500nm thick PyC interphase layer is added by chemical vapor deposition
3. Matrix is densified throughout the composite via chemical vapor infiltration
4. Possible outer coating layer afterward (EBC, etc.)



Sources of Failure in SiC-SiC Composite Tubular Cladding

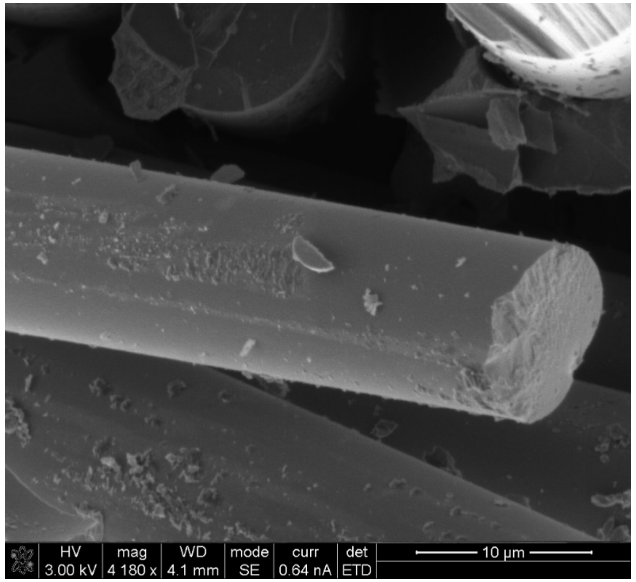
- Complex stress state
  - Prefilling of tubes with helium
  - Accumulation fission gas during operation
  - Fuel pellet swelling and pellet-cladding interactions
  - LOCA failures
  - Rapid temperature rise and uneven expansion of fuel pellet

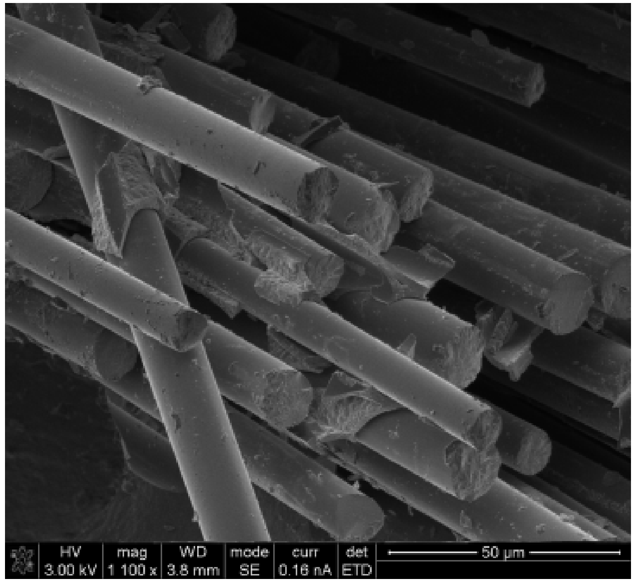
✓ Contributes to scatter in strength and uncertainty in performance

✓ Incorporation of strength variability into design for reliable operation

- Inherent microstructural heterogeneity
  - Constituents: fibers, interphase, and matrix phase
  - Geometry: fibers and tows in different orientations
  - Microstructural variabilities: porosity, local density fluctuations, tube thickness variations, weave architecture imperfections, etc

Measuring Fiber Diameter

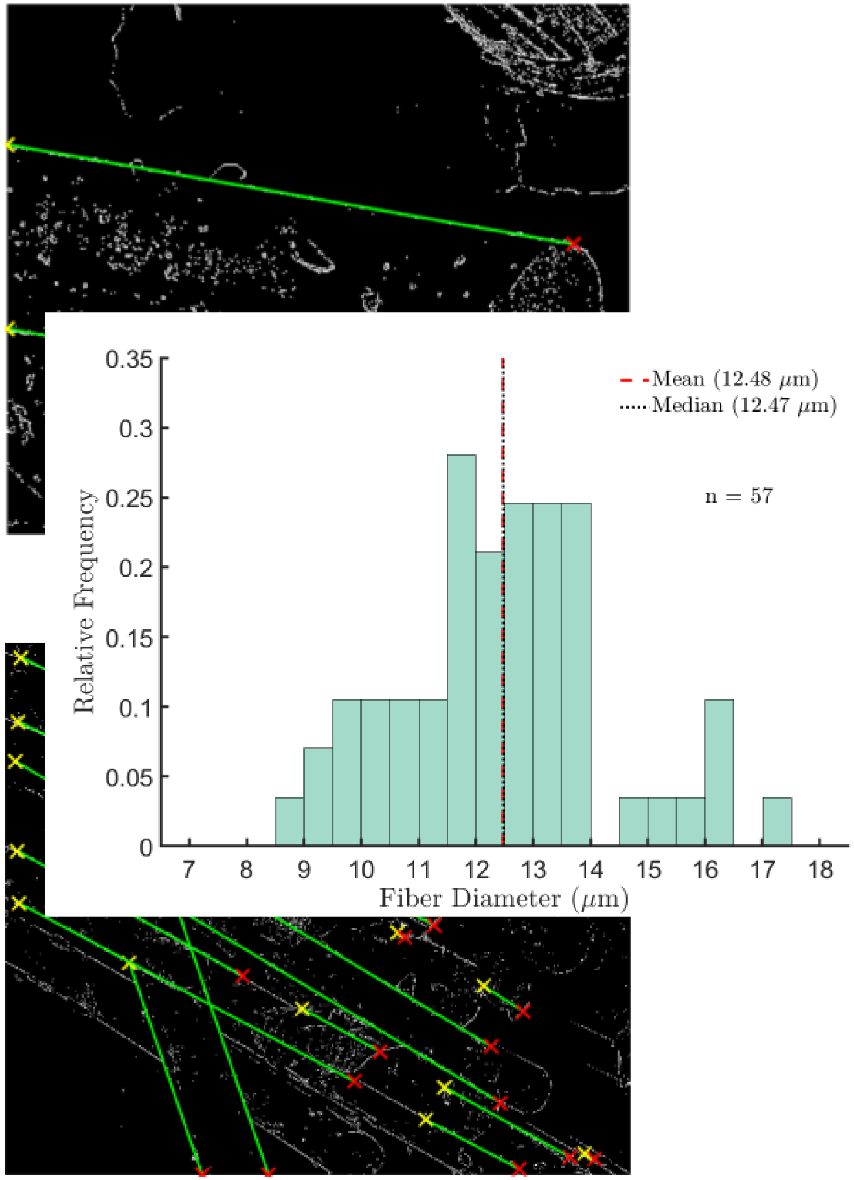




Gaussian blur

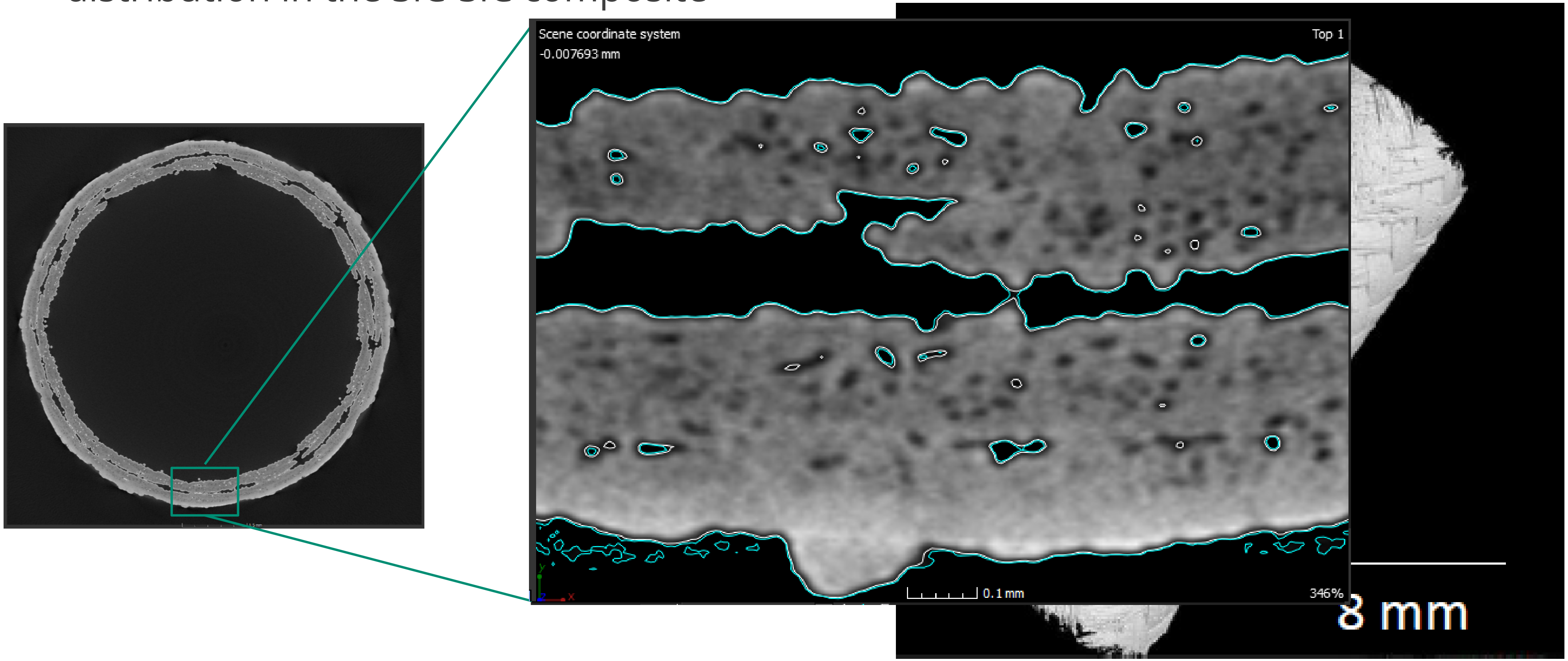
Roberts edge detection

Hough line transform

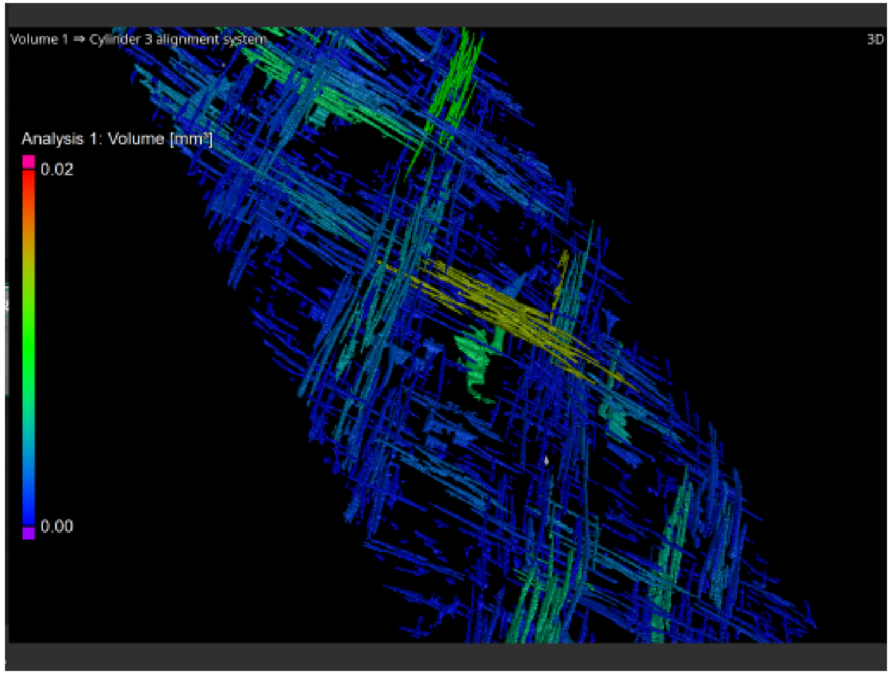


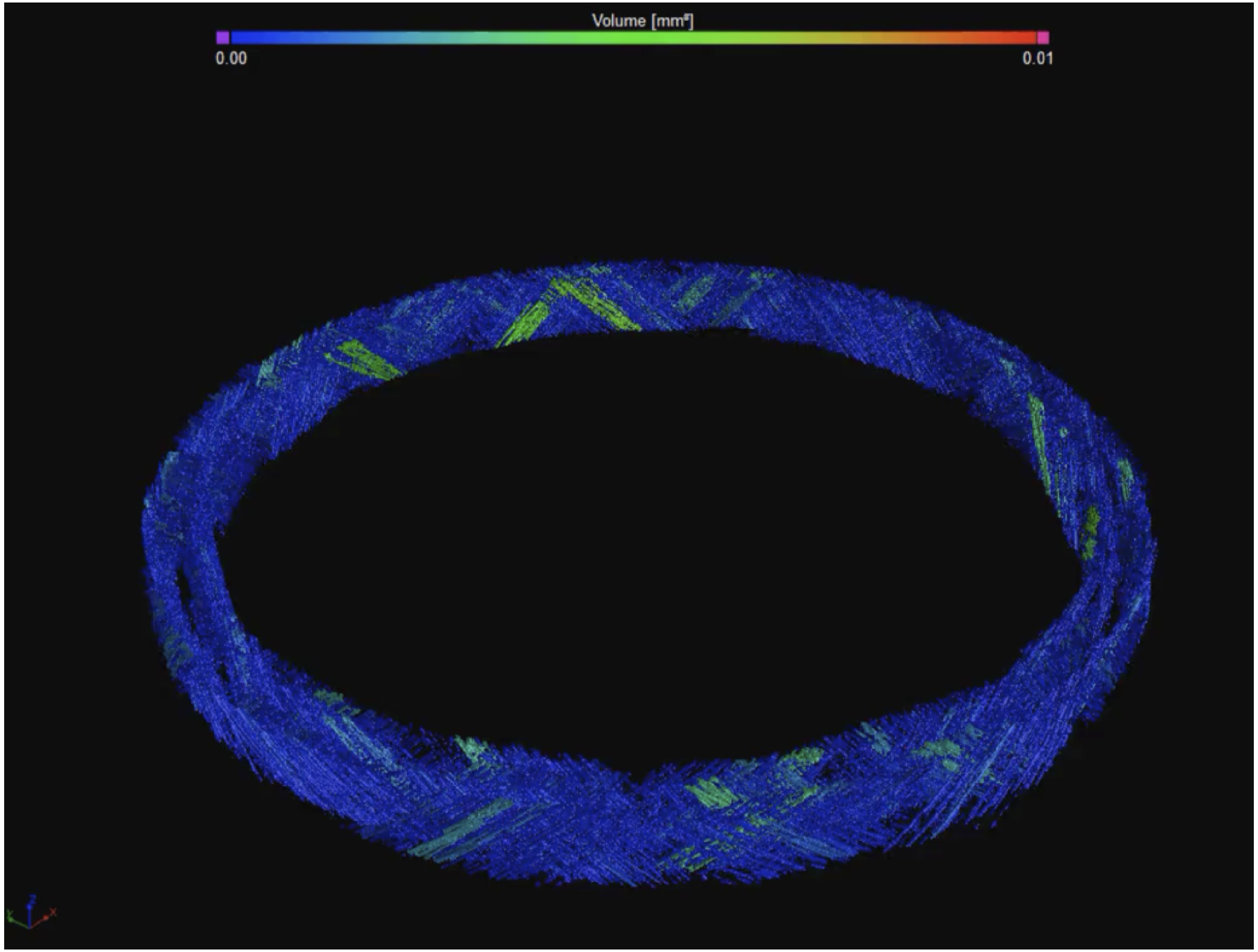
Porosity Distribution

Using X-ray computed tomography to measure the porosity shape, size, and distribution in the SiC-SiC composite



Porosity Distribution



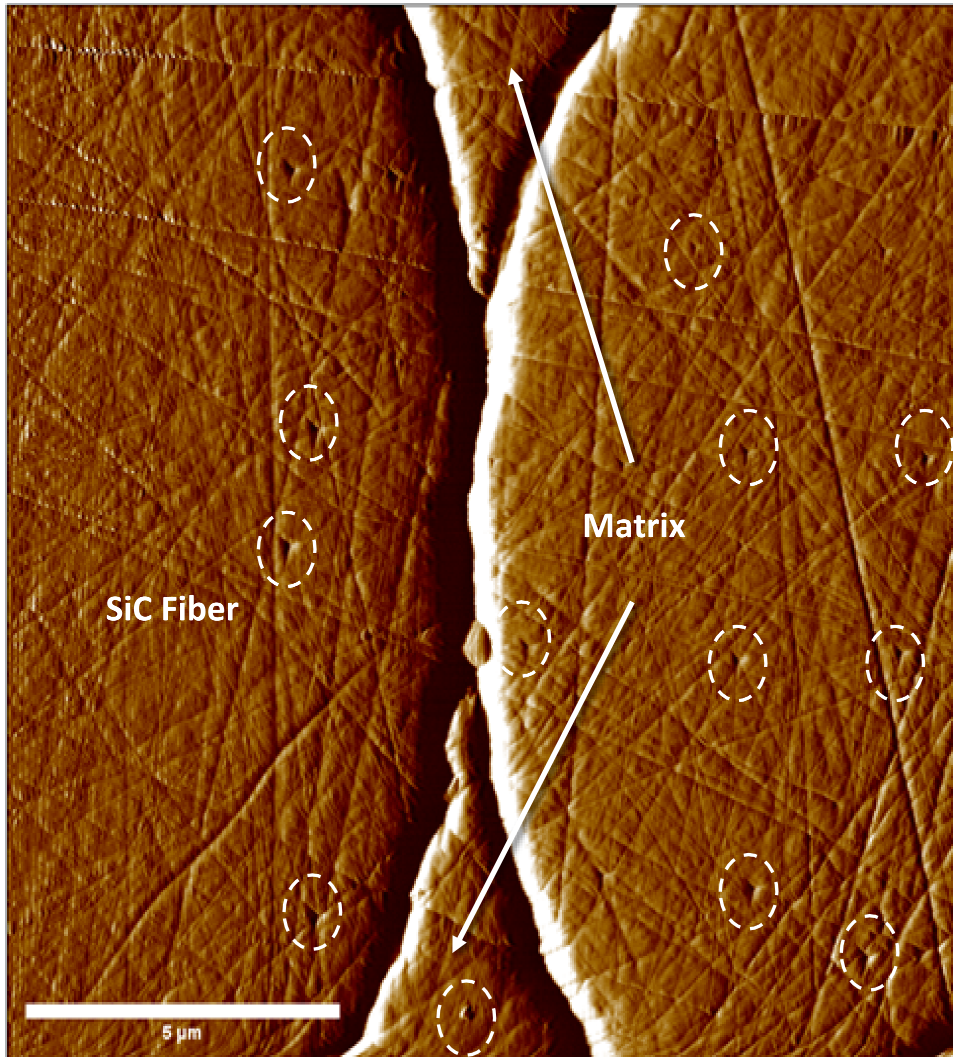


Nanoindentation

Fiber	Matrix
366 ± 36 GPa	477 ± 47 GPa

Indents were displacement-controlled at a depth of 200 nm with room temperature ambient conditions

At least 10 indentations per constituent

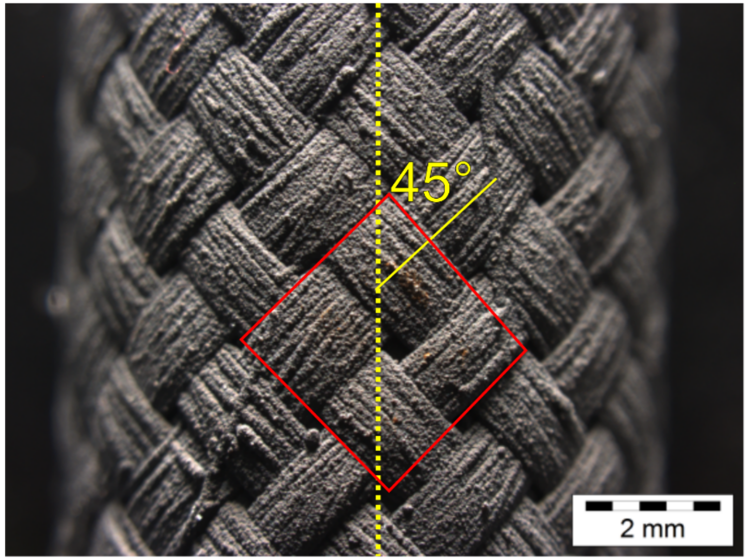


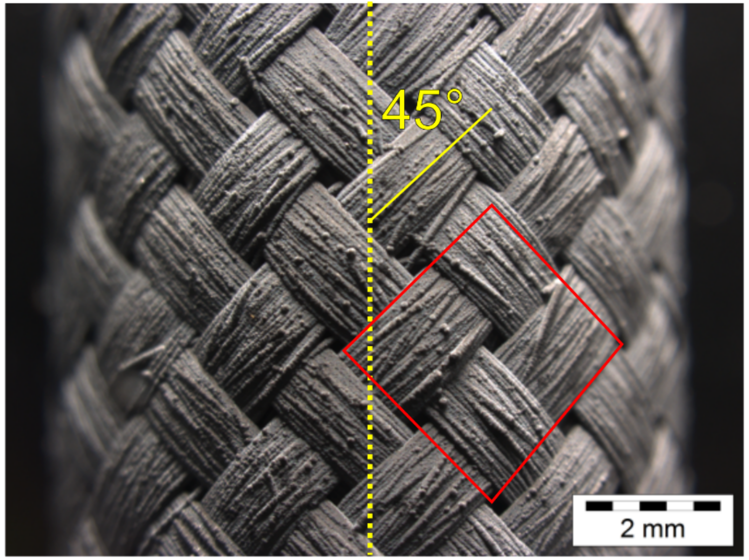
Mechanical Testing

- During operation, fuel pellet swelling and pellet-cladding interactions introduces complex stress states into the cladding.
- Furthermore, LOCA can cause a rapid rise in temperature causing uneven expansion of the fuel pellets, further introducing complexity into the stress state.
- Several different loading scenarios were chosen to examine how the material behaves to help give a full range of data for failure envelope validation:
  - Axial compression
  - Tensile hoop burst
  - Flexure

Mechanical Testing - Architectures

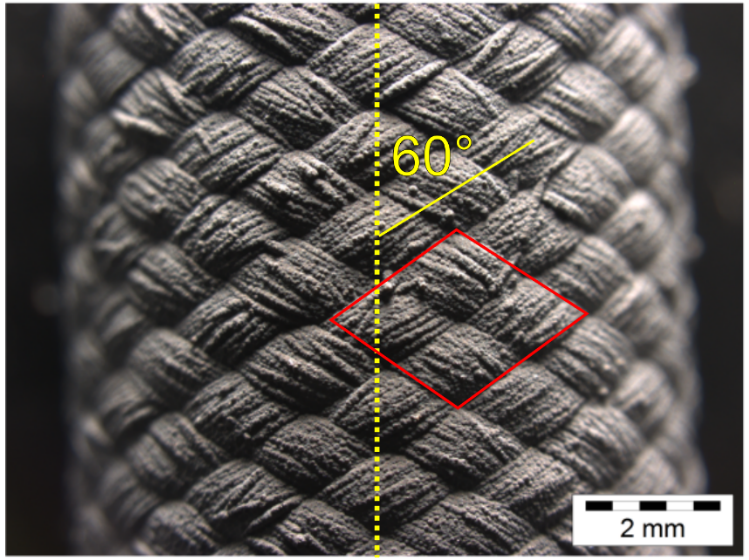
45° 2-ply
biaxial

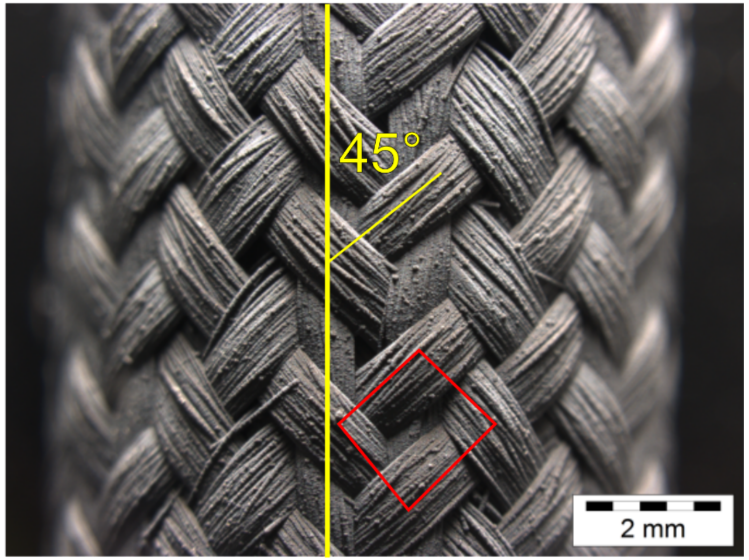




45° 3-ply
biaxial

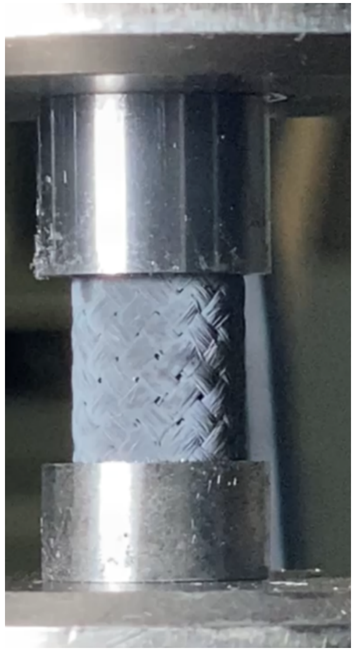
60° 2-ply
biaxial





45° 2-ply
triaxial

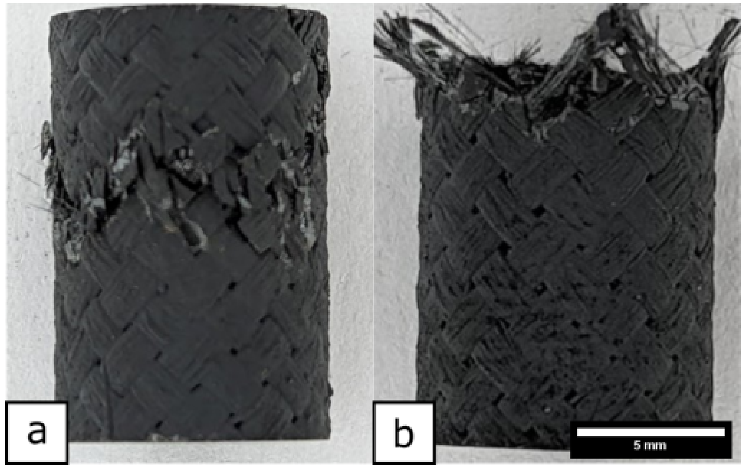
Axial Compression

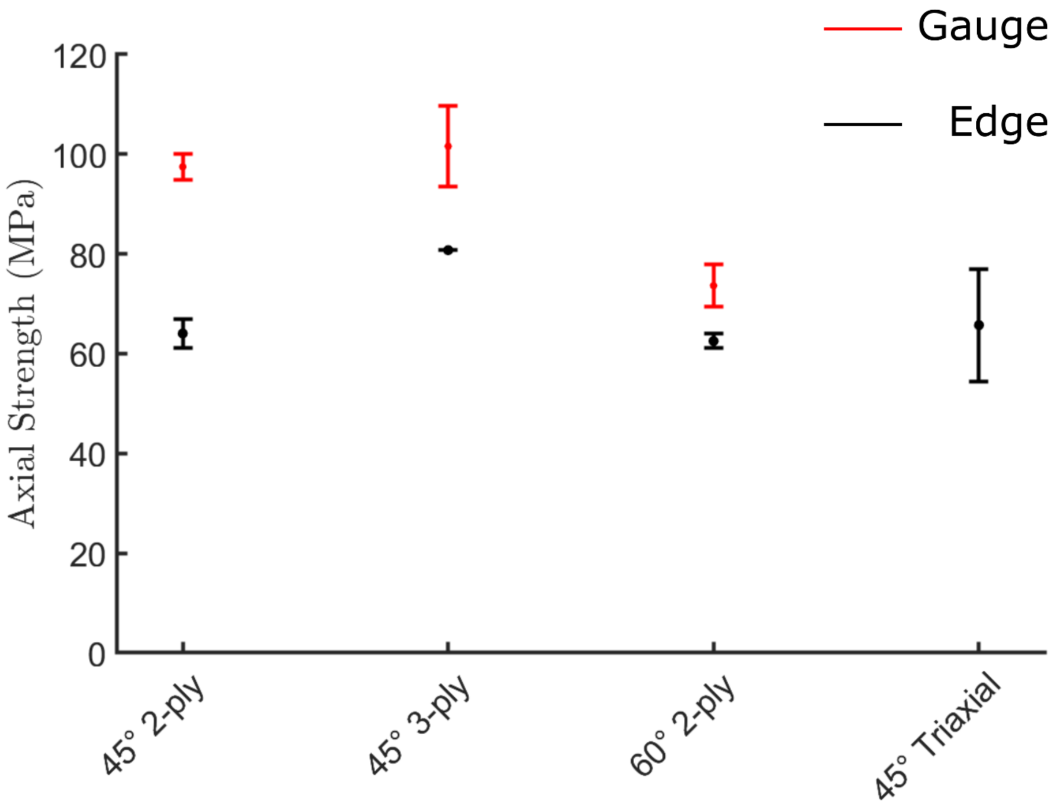


Two forms of failure identified:

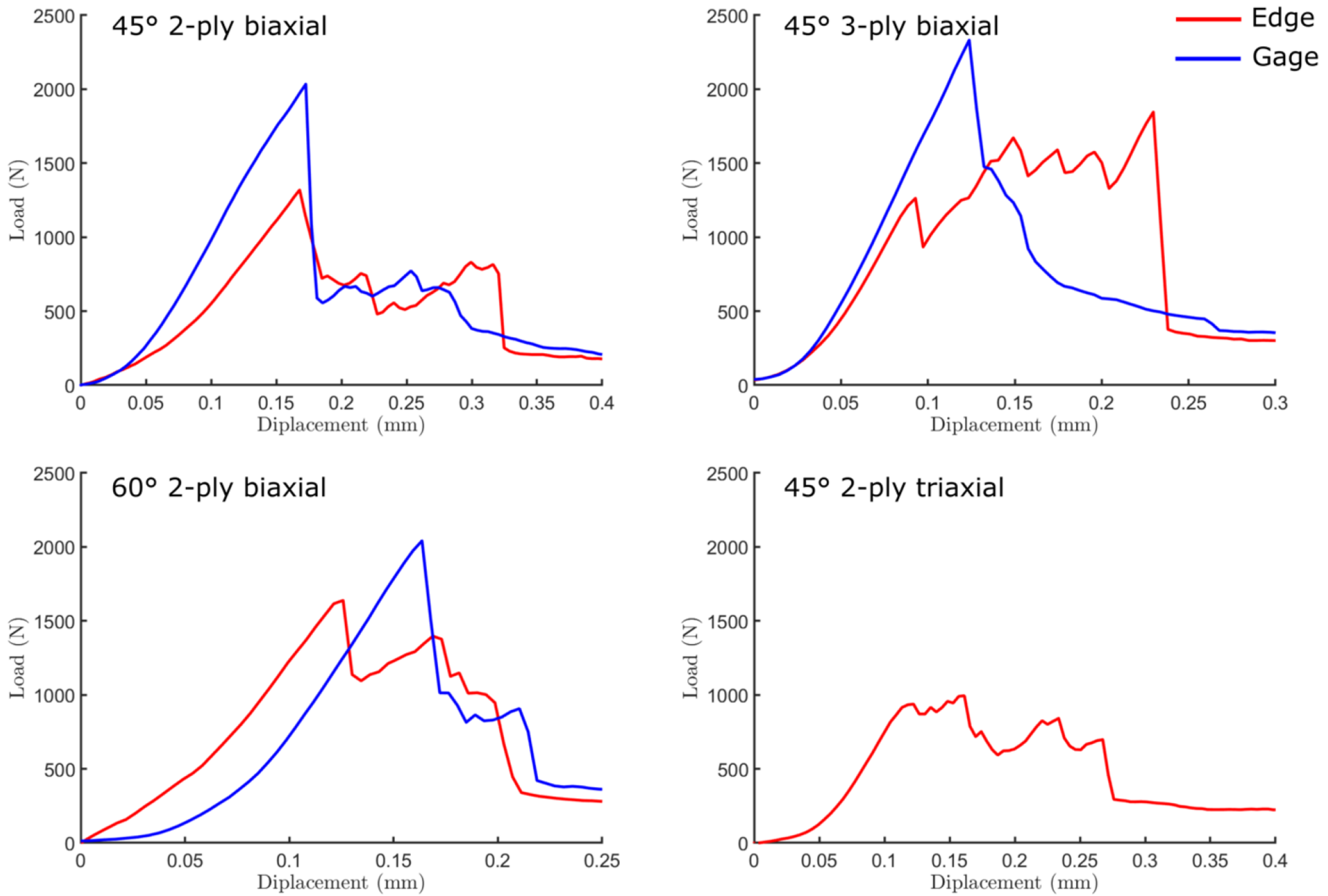
1. Macroscopic failure away from the loading surface (gauge)
2. Macroscopic failure in the vicinity of the loading surface (edge)

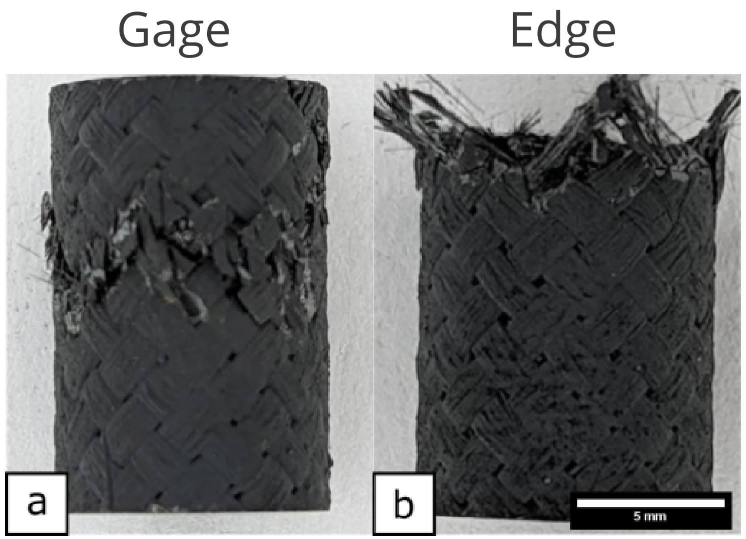
Gauge Edge





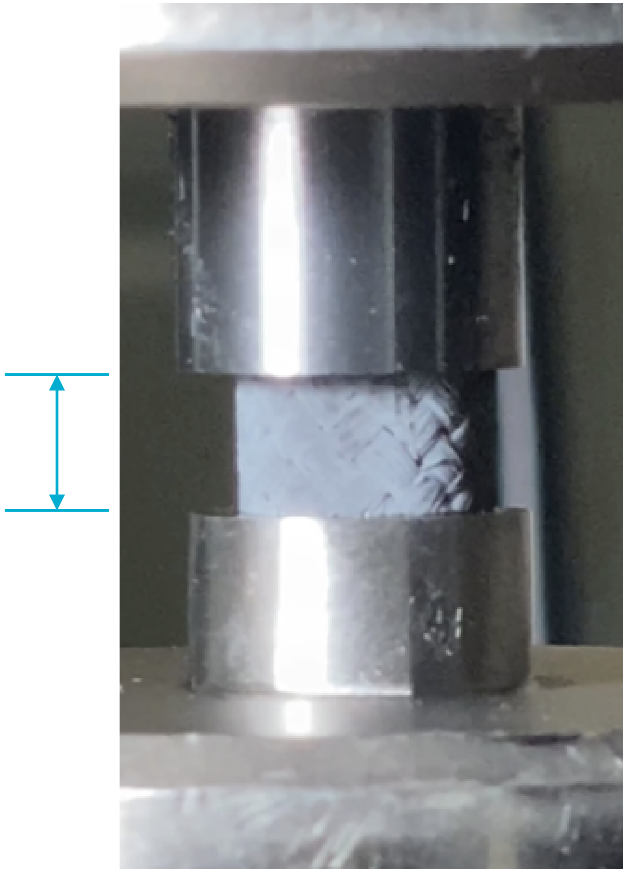
Axial Compression Load-Displacement Curves

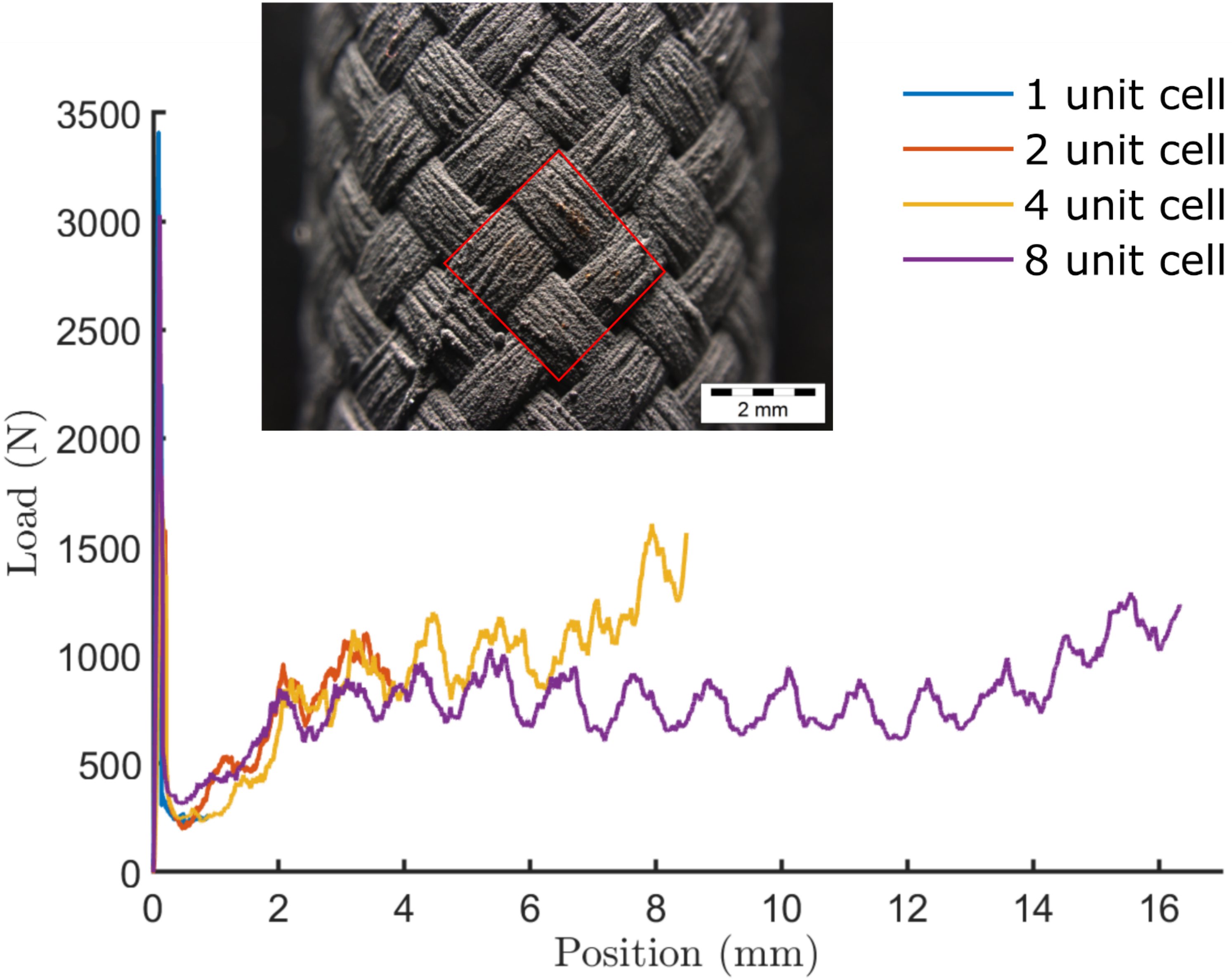




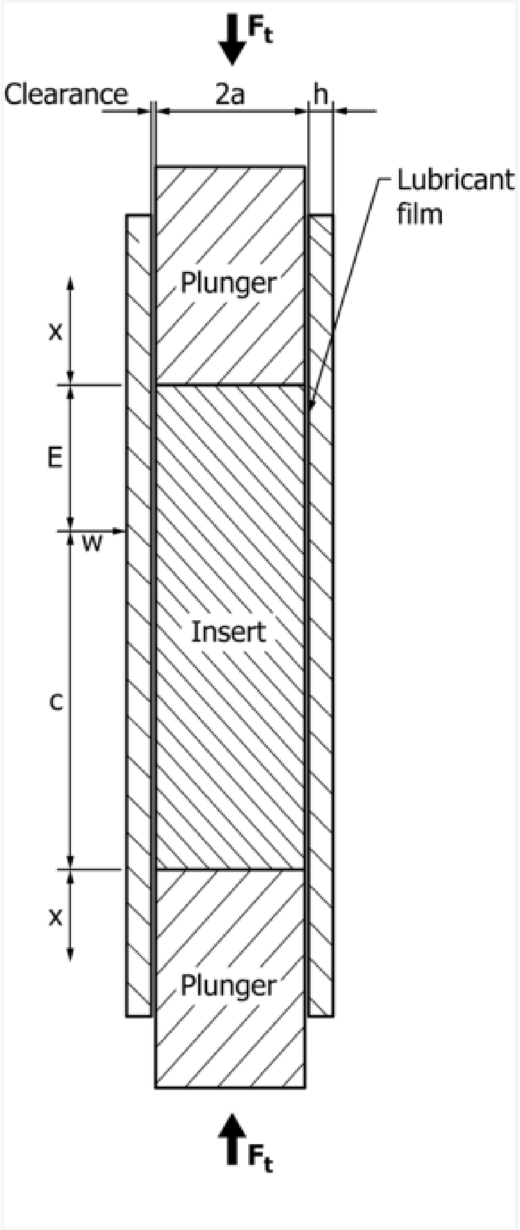
Varying Unit Cell Axial Compression

2
unit
cell





Tensile Hoop Burst



Composite is loaded via internal pressurization from radial expansion of an elastomeric insert

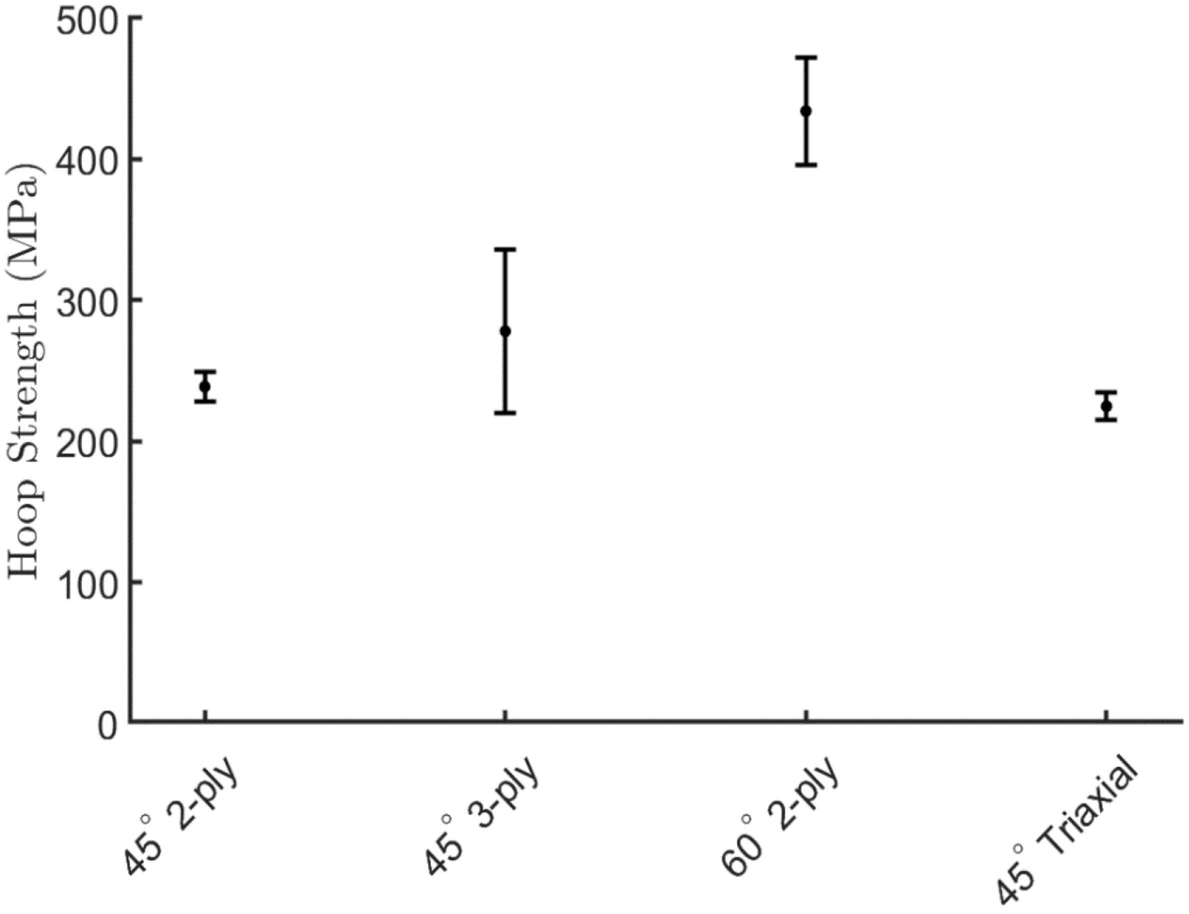
Elastomeric insert expands under uniaxial compressive loading of pushrods and exerts a uniform radial pressure on the inside of the SiC-SiC tube

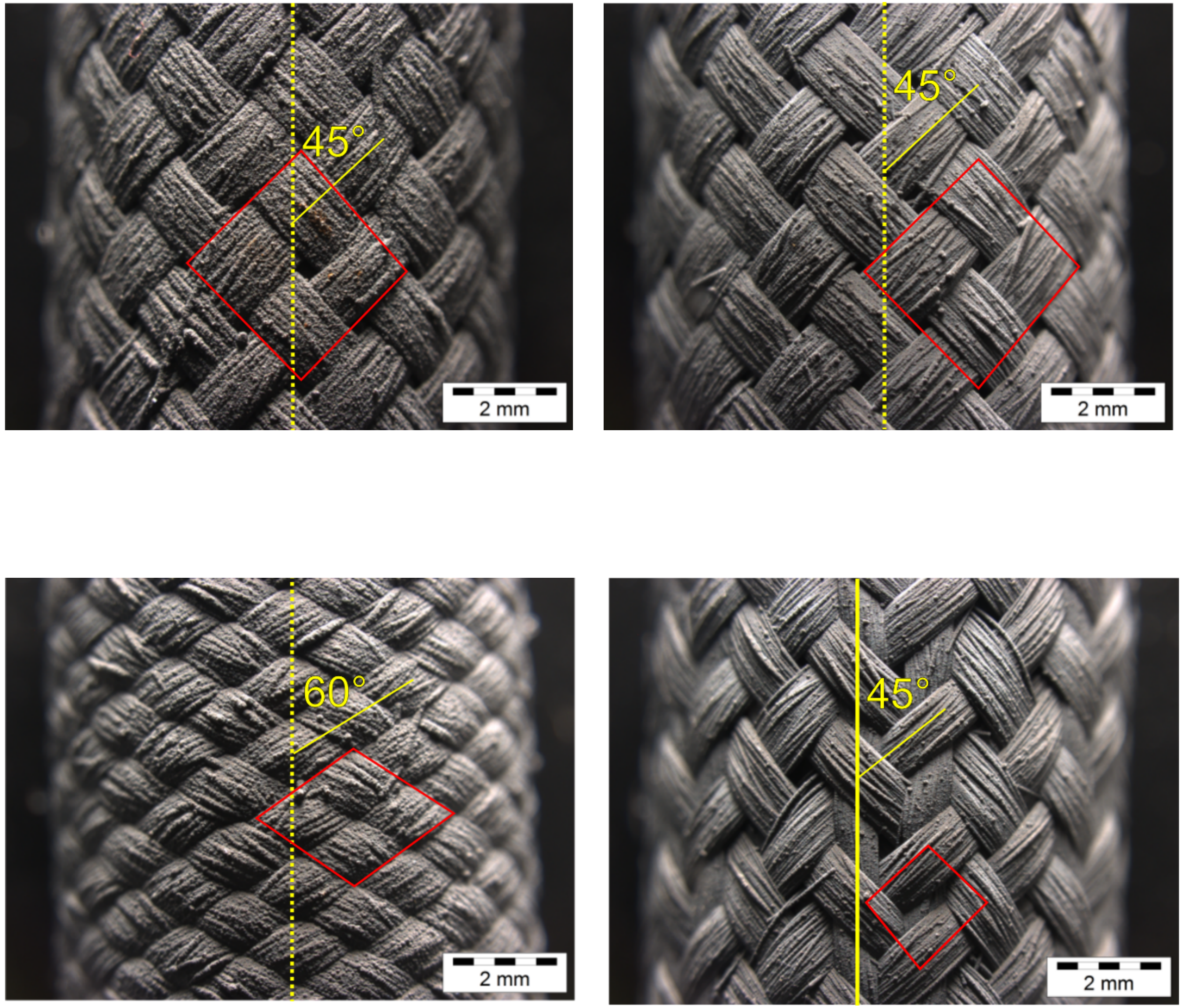
Hoop tensile strength determined from the resulting maximum pressure

$$P = \frac{F}{\pi r_i^2}$$

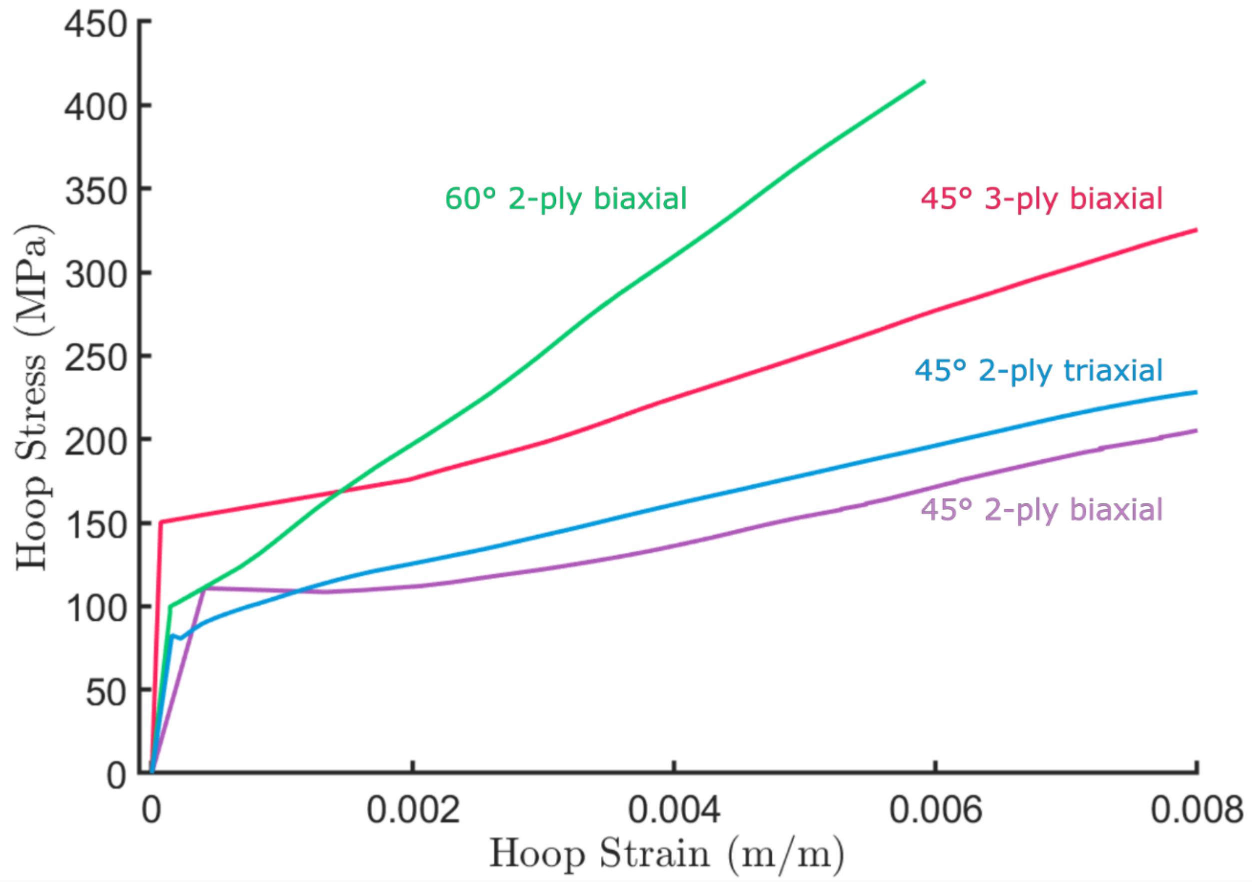
$$\sigma_{hoop} = \eta_m P \frac{2r_i^2}{(r_o^2 - r_i^2)}$$

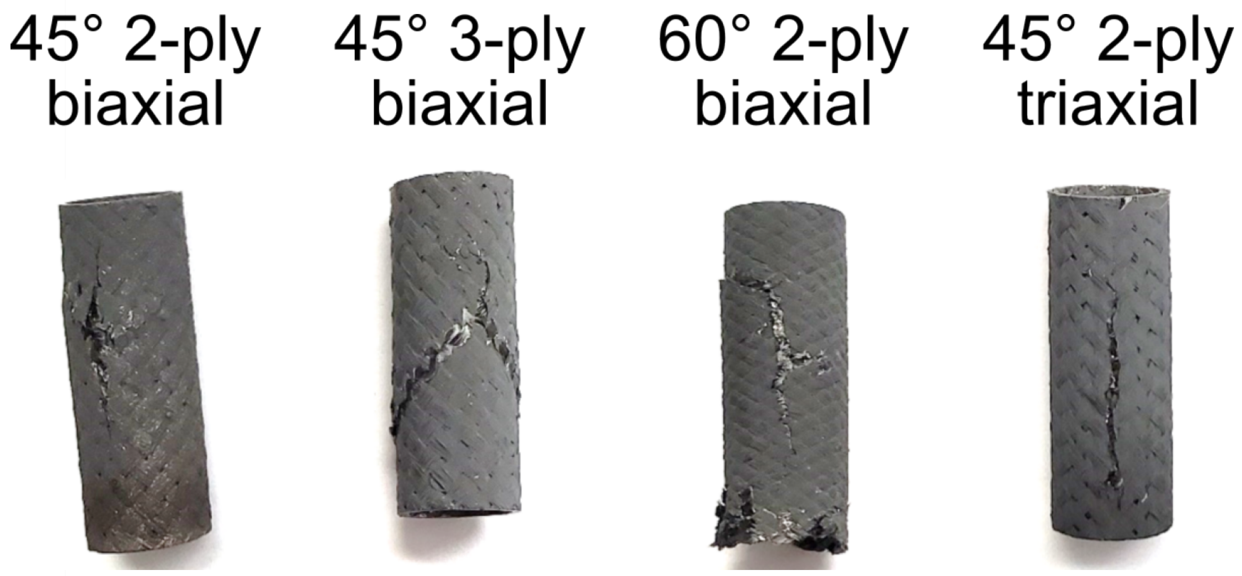
Tensile Hoop Burst – Strength Results





Tensile Hoop Burst – Stress/Strain Curves





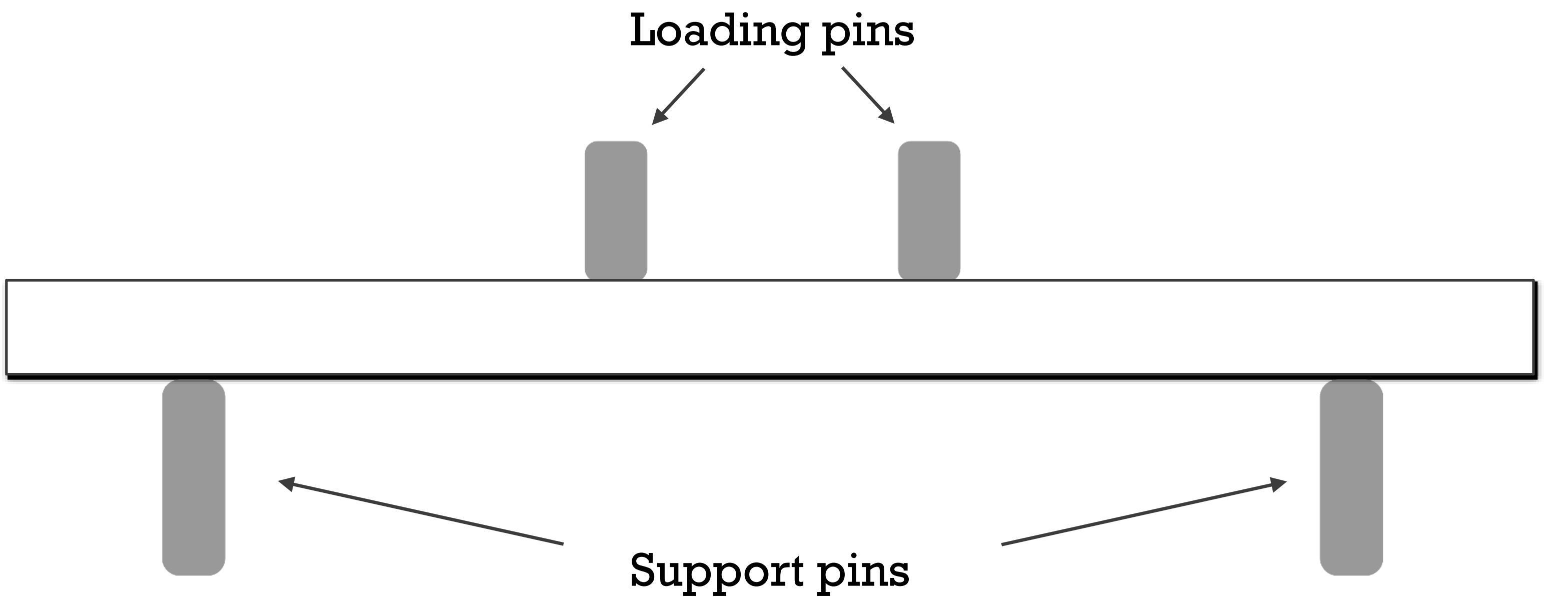
Tensile Hoop Burst - 45° 3-ply Biaxial Failure Mode

t = 0s

t = 0.2s

t = 0.4s

Flexural Test

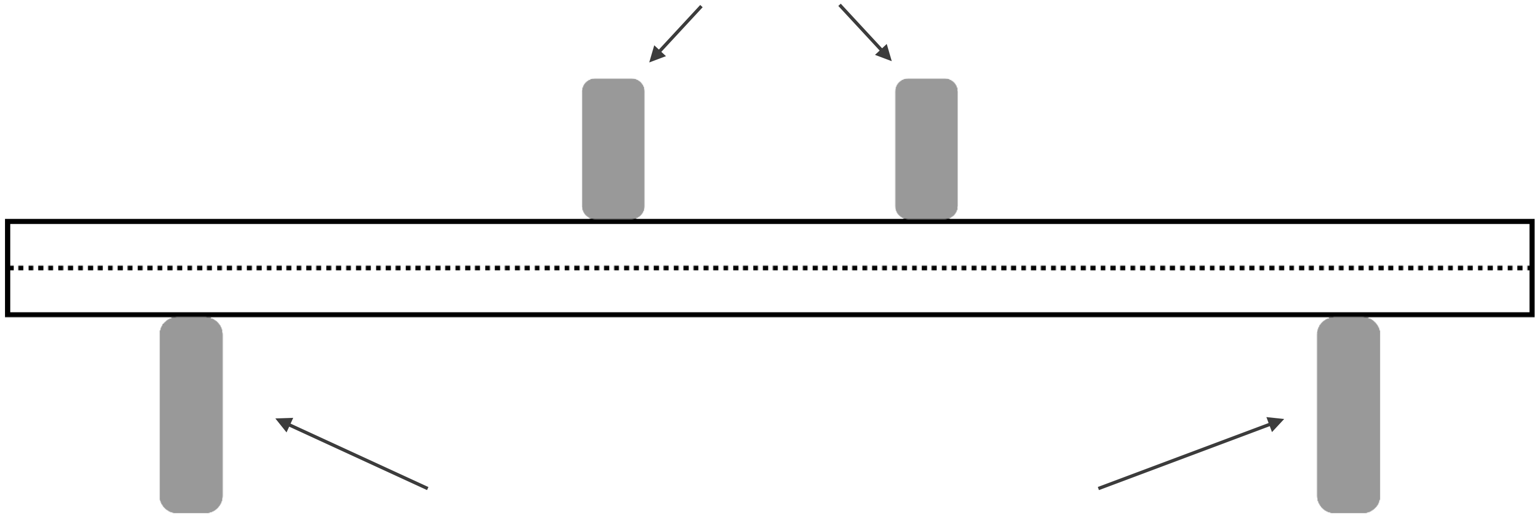


Failure of a ceramic specimen is often a function of a critical surface flaw.

These critical flaws require a tensile stress state to grow.

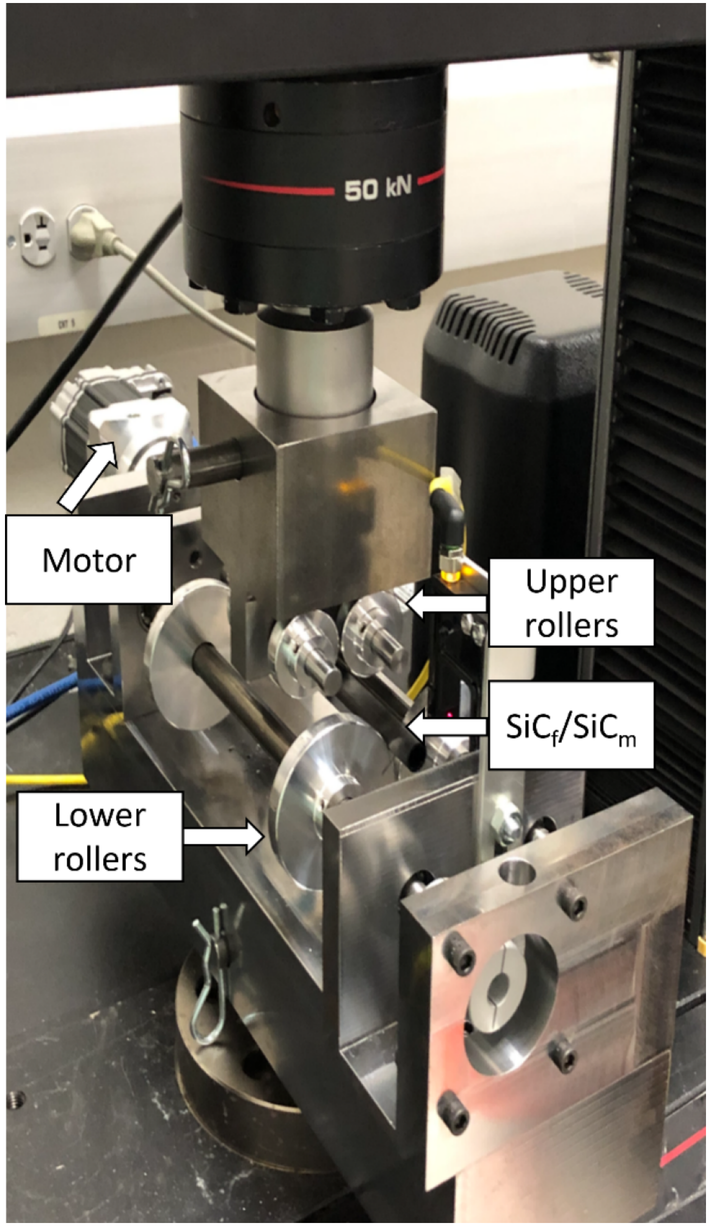
The traditional 4-point bend test does not always subject the critical flaw to a tensile stress state.

Flexural Test

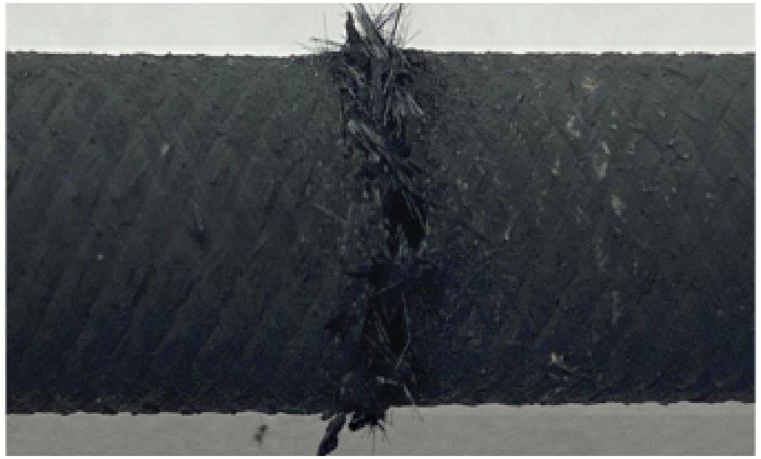


Instead, rotate the specimen as it is being loaded via rollers and it will have a higher probability to expose the critical flaw.

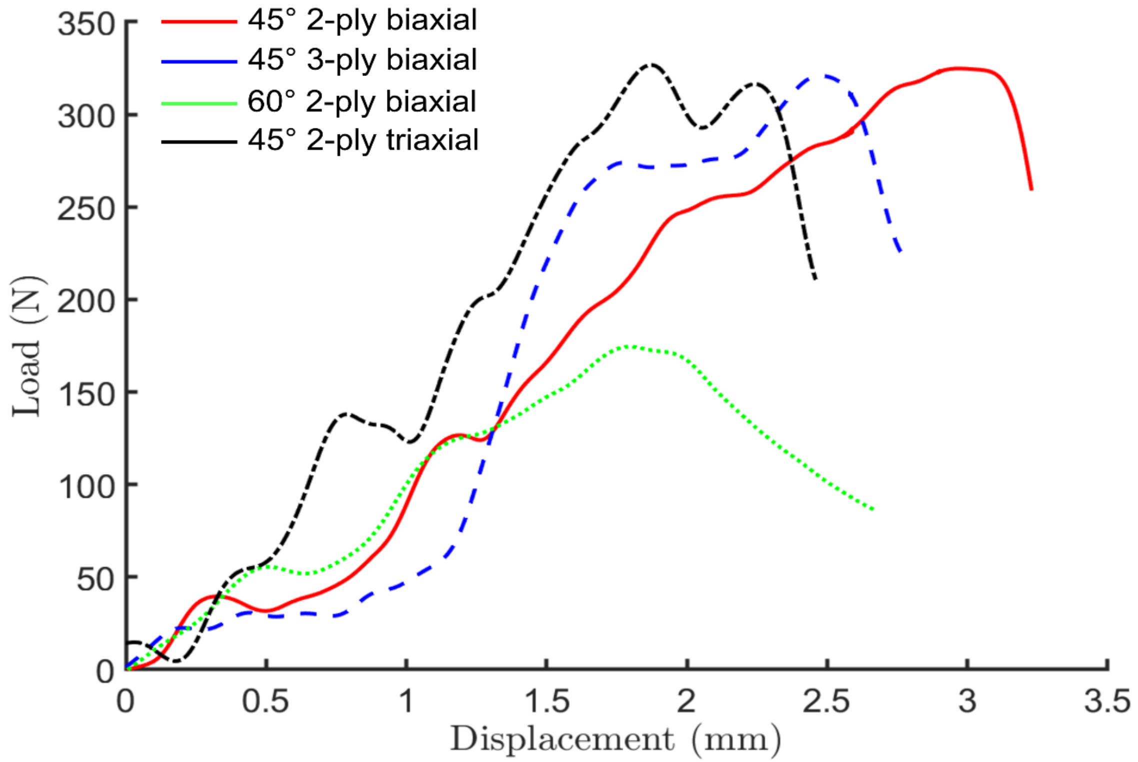
Novel Rotating Flexural Test Design

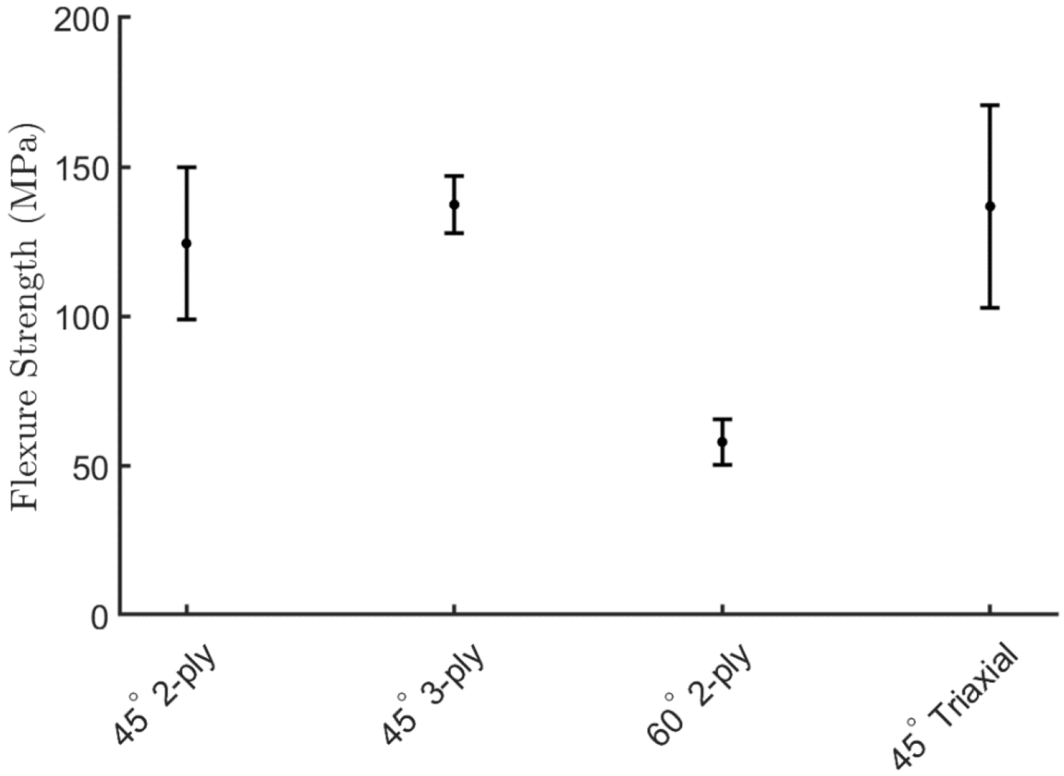


Flexural Test - Results



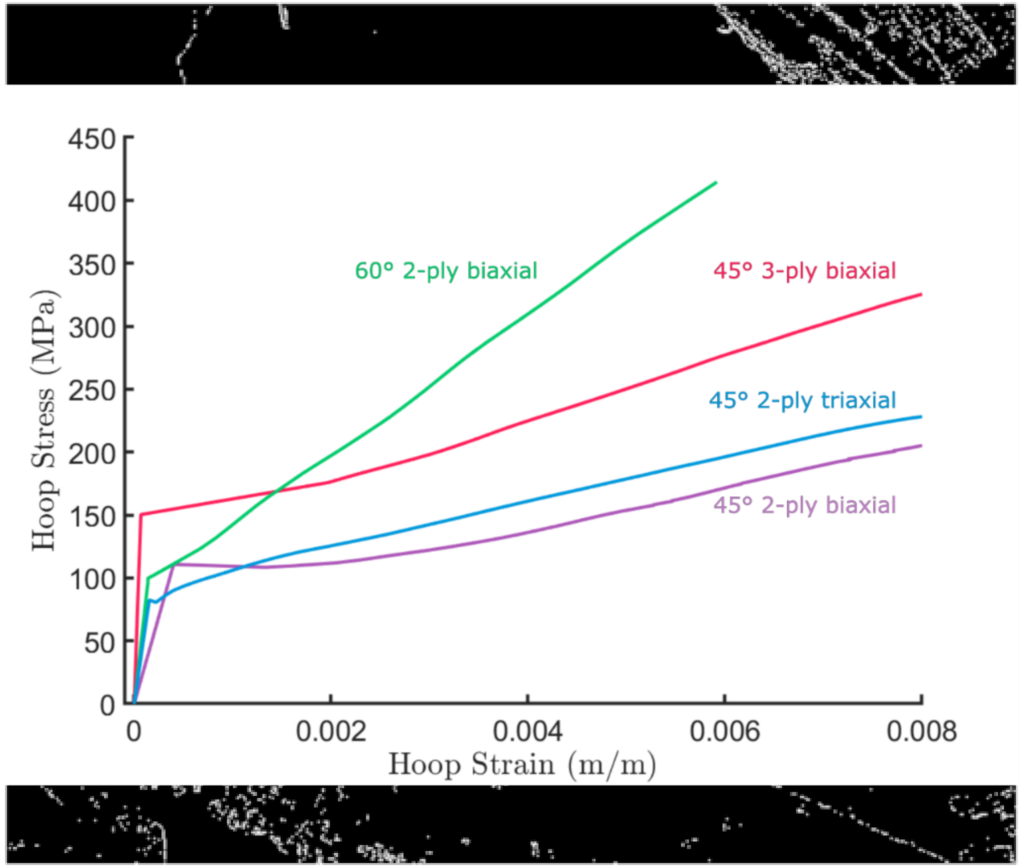
$$\sigma_f = \frac{P_{max}(L_o - L_i)r_o}{4\left[\frac{\pi\left(r_o^4 - r_i^4\right)}{4}\right]}$$





Summary

- Heterogeneity was quantified using digital image processing algorithms and other methods
  - Fiber diameter
  - Porosity Distribution
  - Braiding angle
  - Nanoindentation
- Used a variety of loading scenarios and stress states to identify the composite's architecture influences
  - Axial compression
  - Tensile hoop burst
  - Novel rotating flexural



Acknowledgements

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GENERAL ATOMICS

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