National Aeronautics and Space Administration

The Effect of Local Geometric Variability on the Local Stress Distribution in Woven Ceramic Matrix Composites

Pete Bonacuse, Rob Goldberg
NASA Glenn Research Center
and
Subodh Mital
University of Toledo

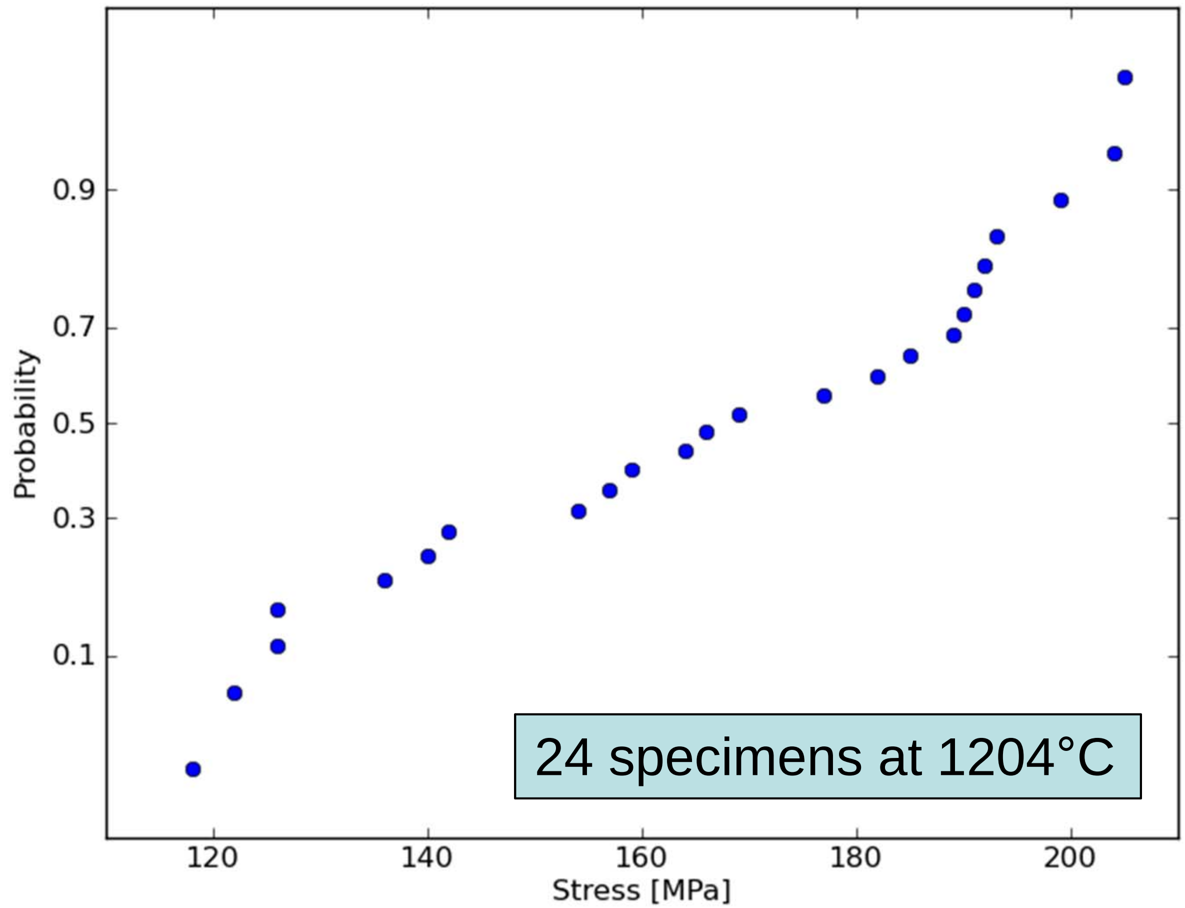
2012 Technical Conference
March 13-15, 2012
Cleveland, OH

Motivation

- There is known variability in measured (physical) properties of CMCs
- There is observed variability in the microstructure (tow spacing, ply alignment, nesting of adjacent plies, porosity, matrix thickness, etc.)

Are they related and, if so, how?

SiC/SiC CMC Proportional Limit Strength*



*S. Kalluri, A. Calomino, and D. Brewer, presented at Fatigue 2002, June 3-7, 2004, Stockholm.

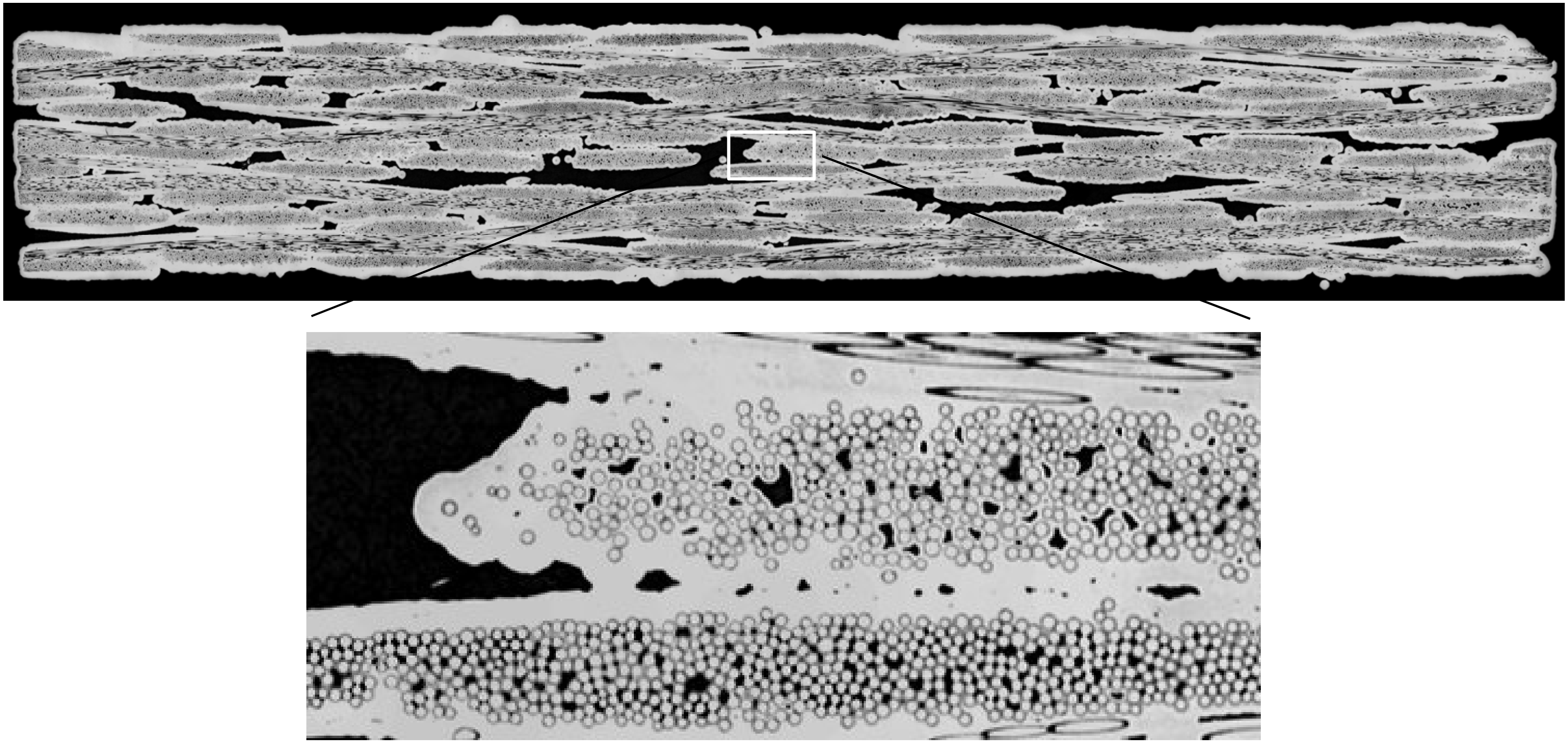
Goals

- Assess/characterize the variability in as-fabricated CMC microstructures (porosity, shape and separation of tows, ply misalignment, etc.)
- Determine how the characterized variability in the microstructure correlates with the known variability in CMC material properties (modulus, strength, thermal conductivity, etc.)
- Develop probabilistic models (based on the observed distributions in the composite microstructures) to predict the distributions in the composite thermal and mechanical properties

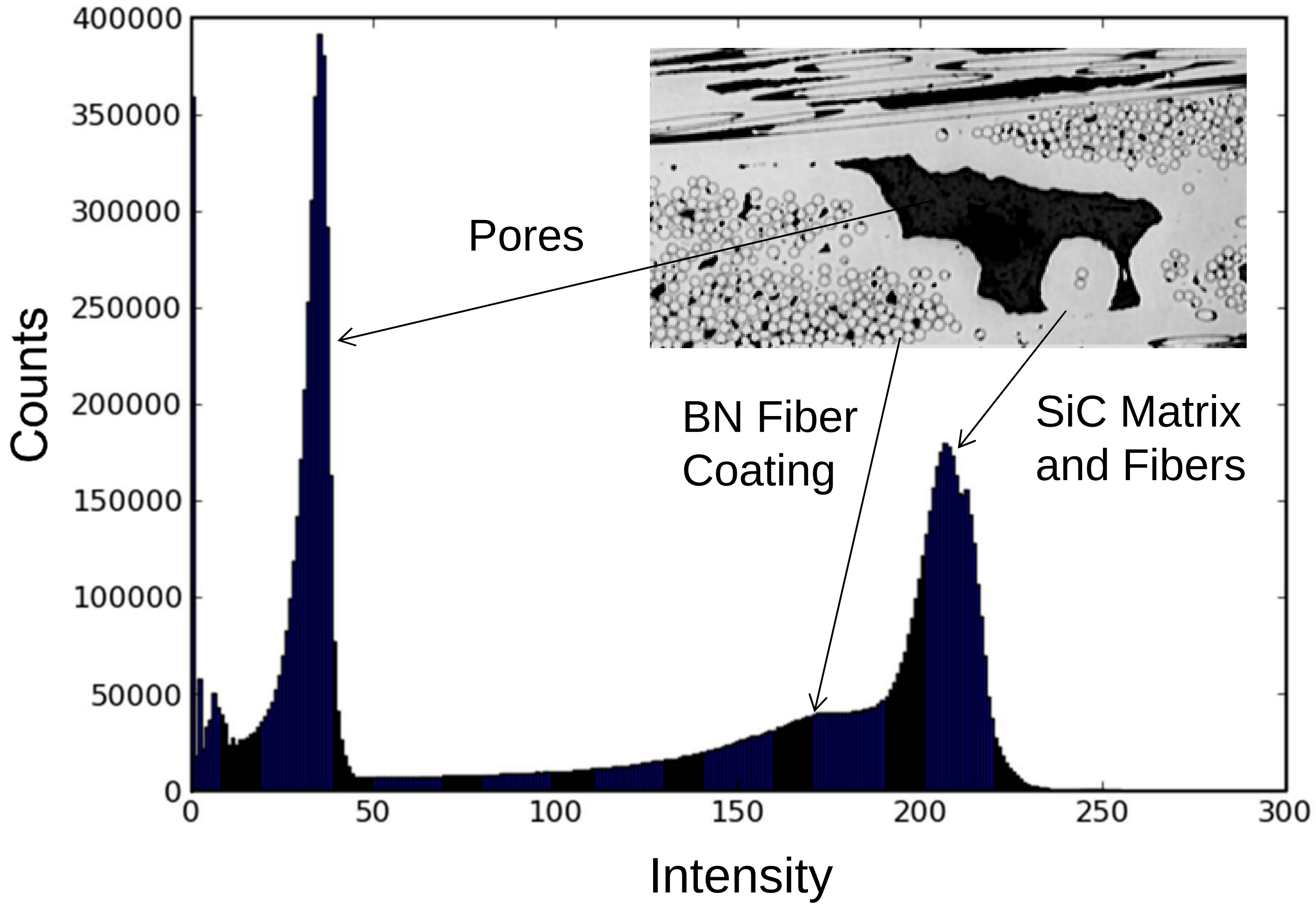
Serial Sectioning

- CVI SiC/SiC, 8-ply, 5-harness satin weave specimens: 12x12x2 mm
- Sequentially polished with a target removal rate of 0.2 mm per step
- Automated imaging system used to capture overlapping 50x magnification images (typically 12x3=36 images; each with 640x480 pixel resolution)

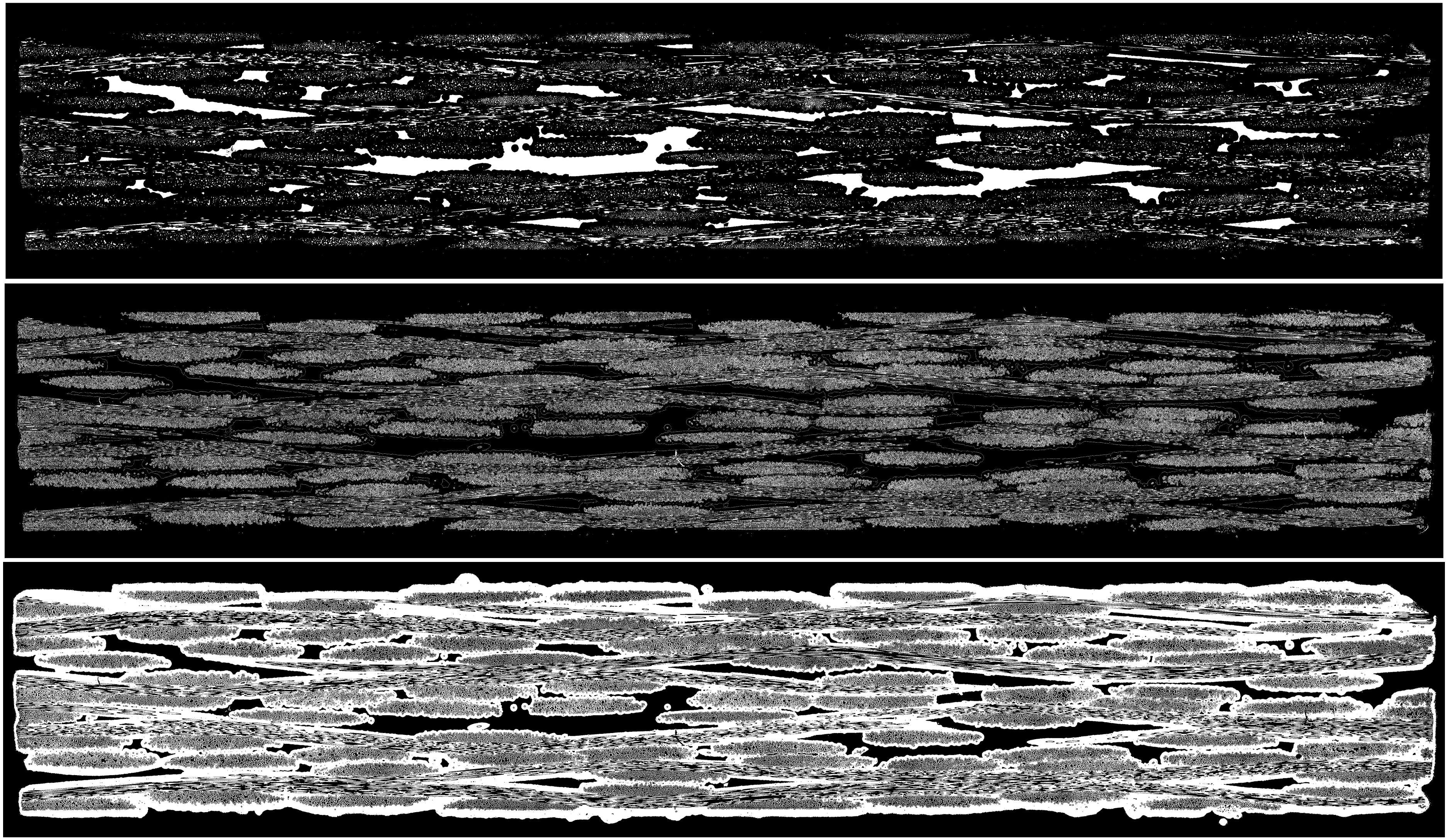
Typical CVI SiC/SiC Section Image



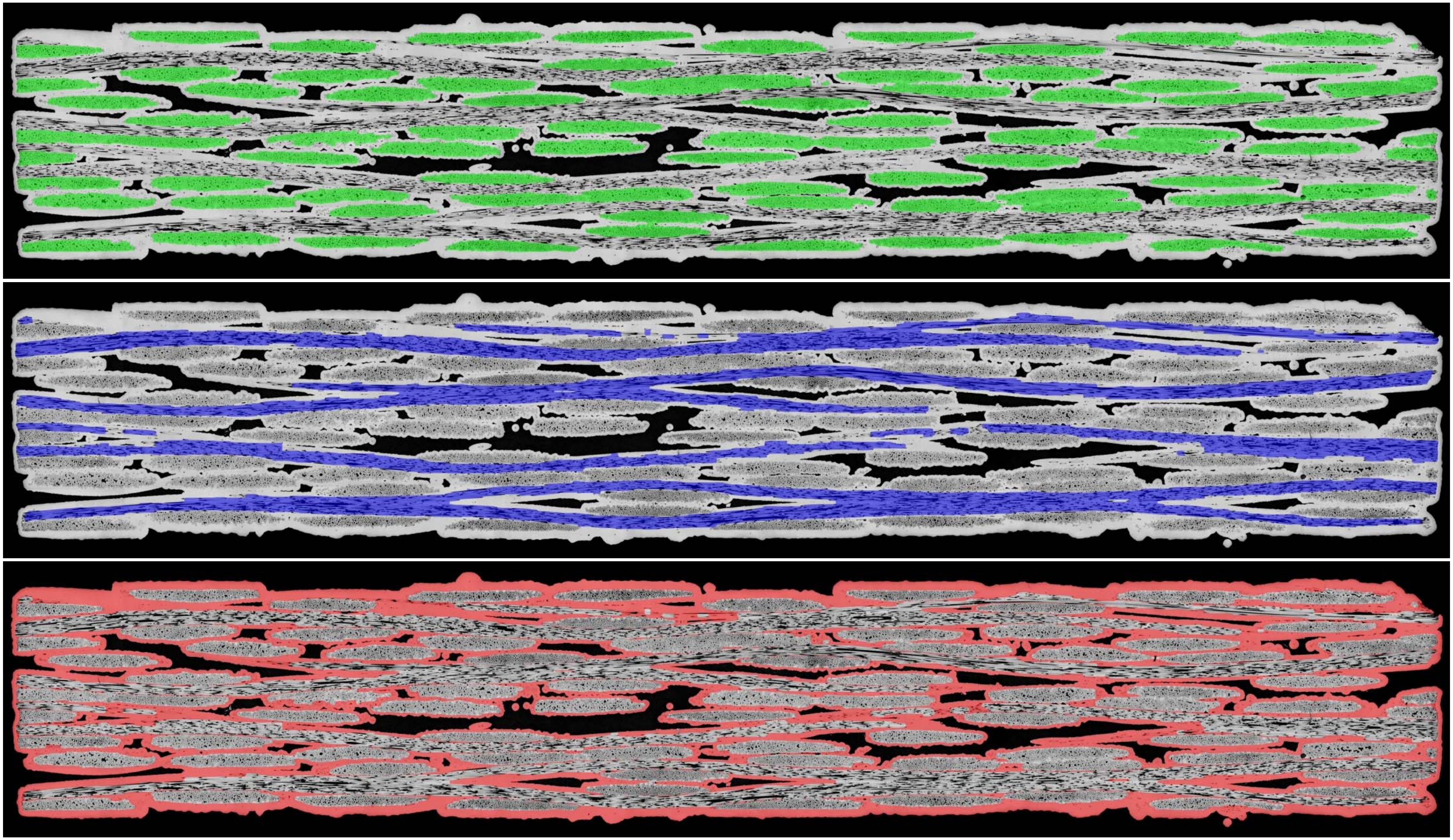
Histogram of Image Pixel Intensities



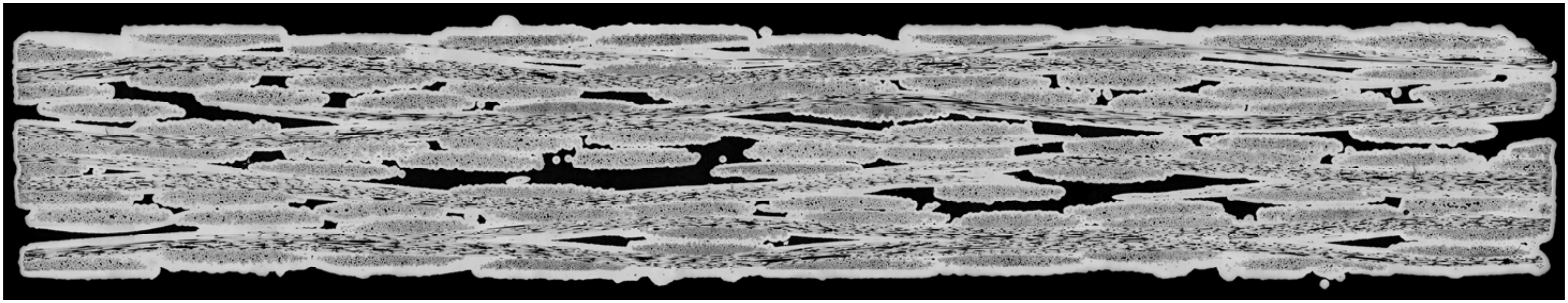
Pores, Fiber Coating, and Matrix

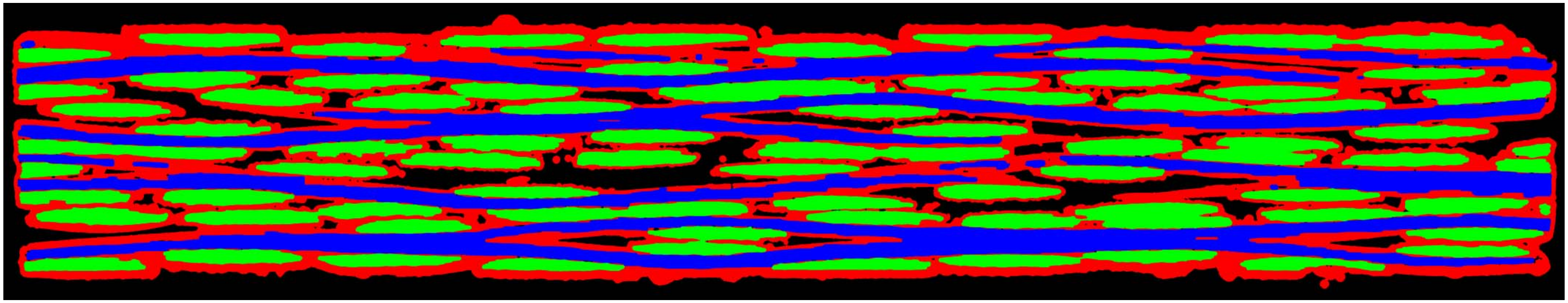


Automated Extraction of Microstructure



Segmented SiC/SiC CVI Composite





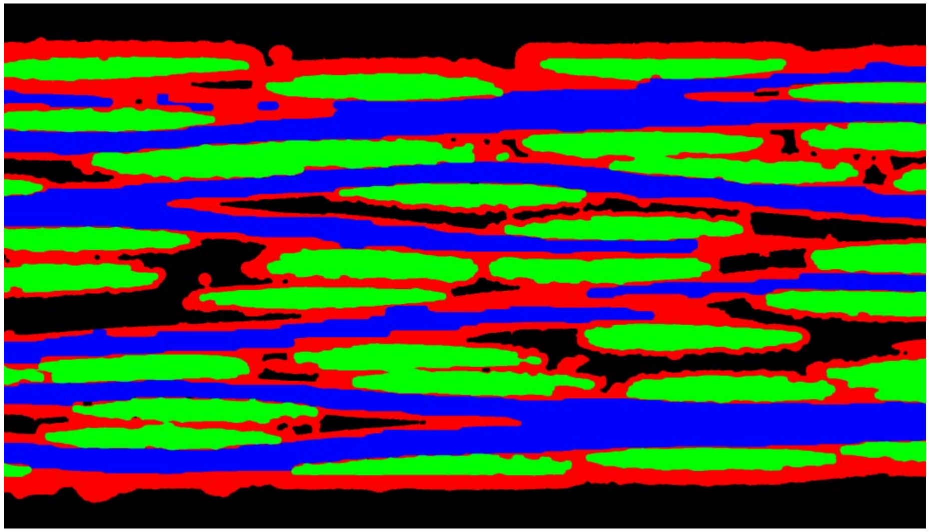
Red – SiC matrix
Green – Transverse sectioned tows
Blue – Longitudinally sectioned tows
Black – Pores

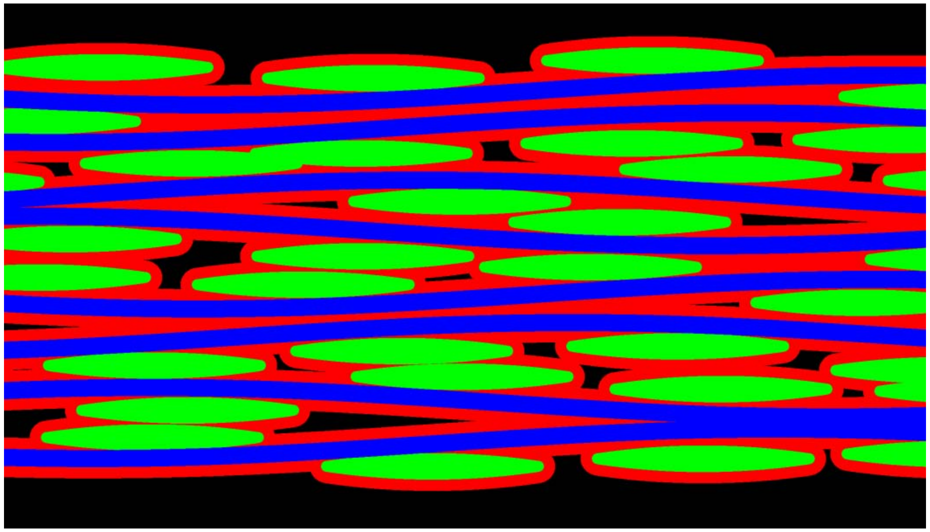
Distributions of Constituent Parameters

- Pores
  - Area
  - Maximum Length
  - Aspect Ratio
  - Shape Parameters (e.g. Compactness)
- Transverse Sectioned Tows
  - Area
  - Width
  - Aspect Ratio
  - Within Ply Tow Spacing
- Matrix Thickness

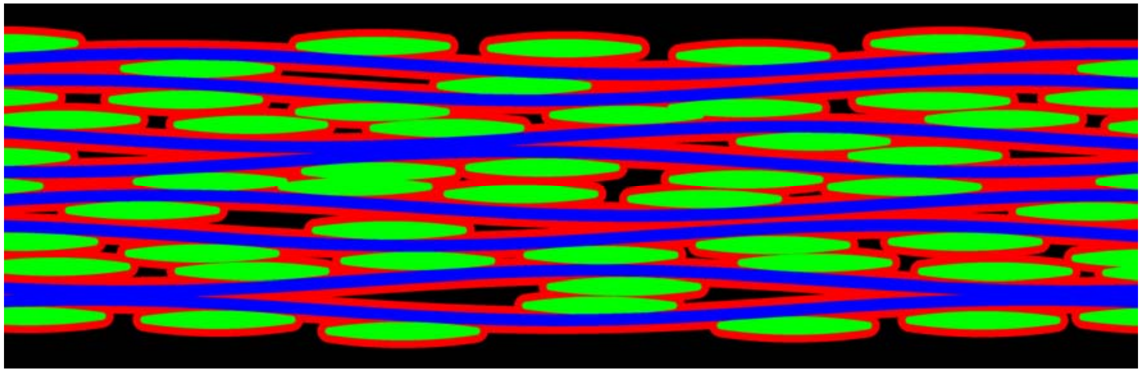
2D Models from Sectioned Images

- Construct “simplified” models suitable for FEM analysis while maintaining much of the variability found in a sample section
- Approximations:
  - Uniform transverse tow size and shape
  - Longitudinal tows with uniform thickness; sinusoidal
  - Matrix grown uniformly on the tows

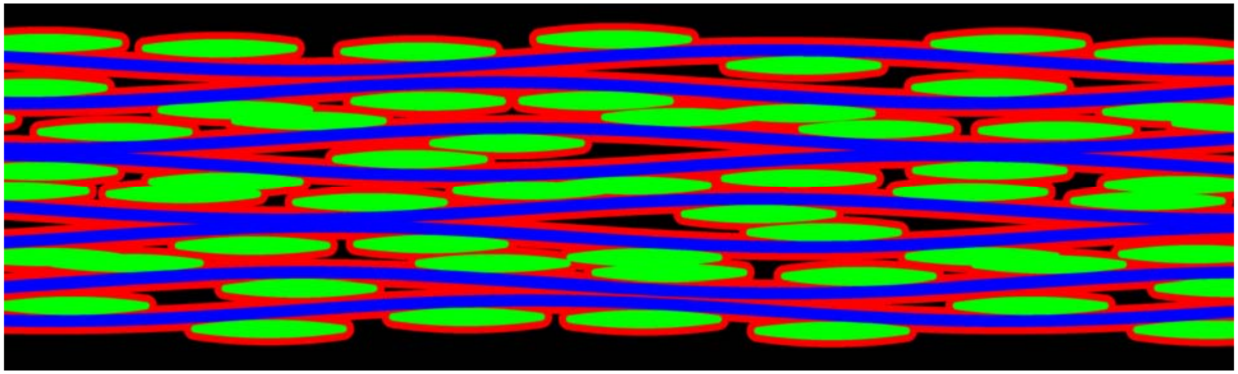




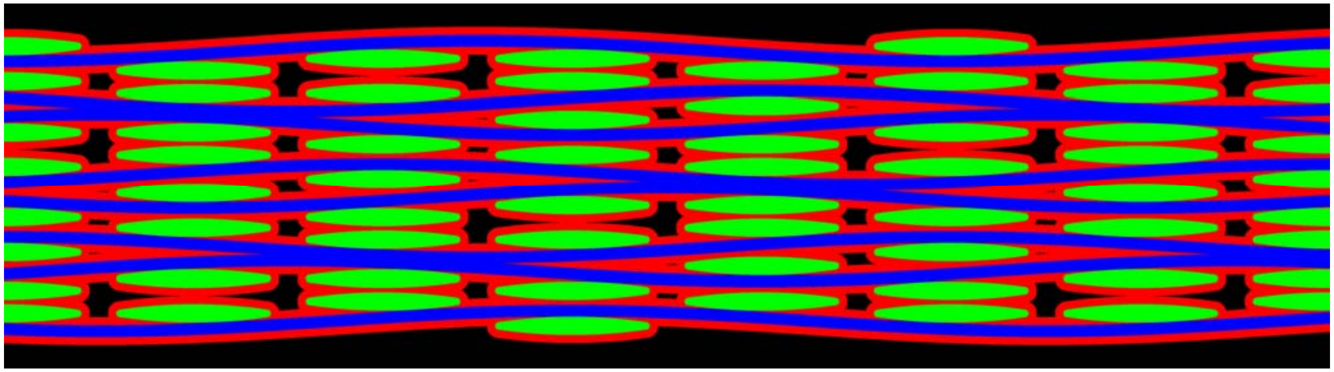
Three Cross Section Models



Section 03

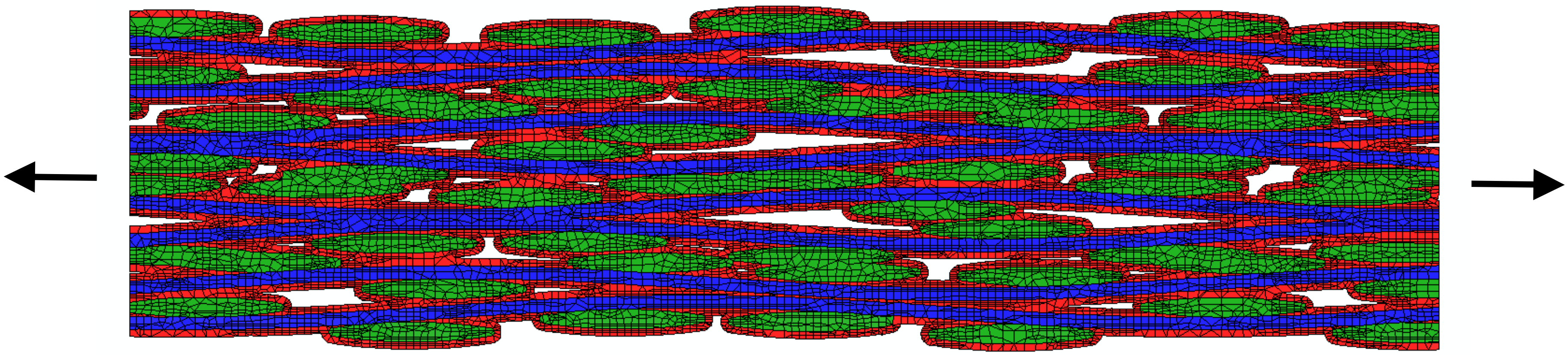


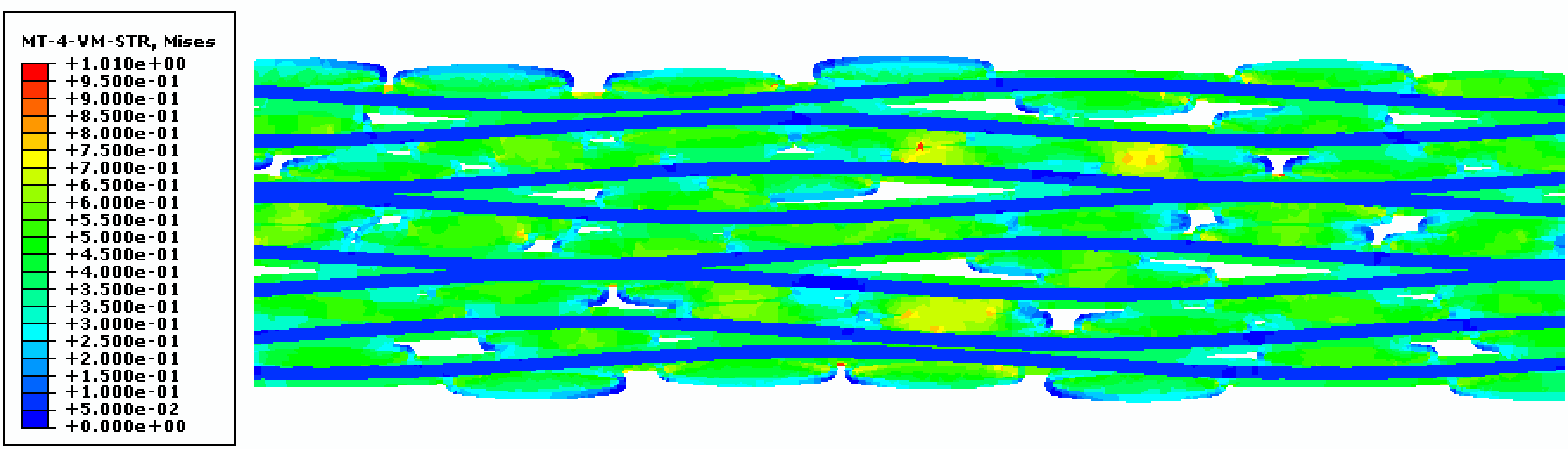
Section 10



Ideal 1

Simplified 2D Models Meshed with OOF2 and Load Cases Run with Abaqus FEA

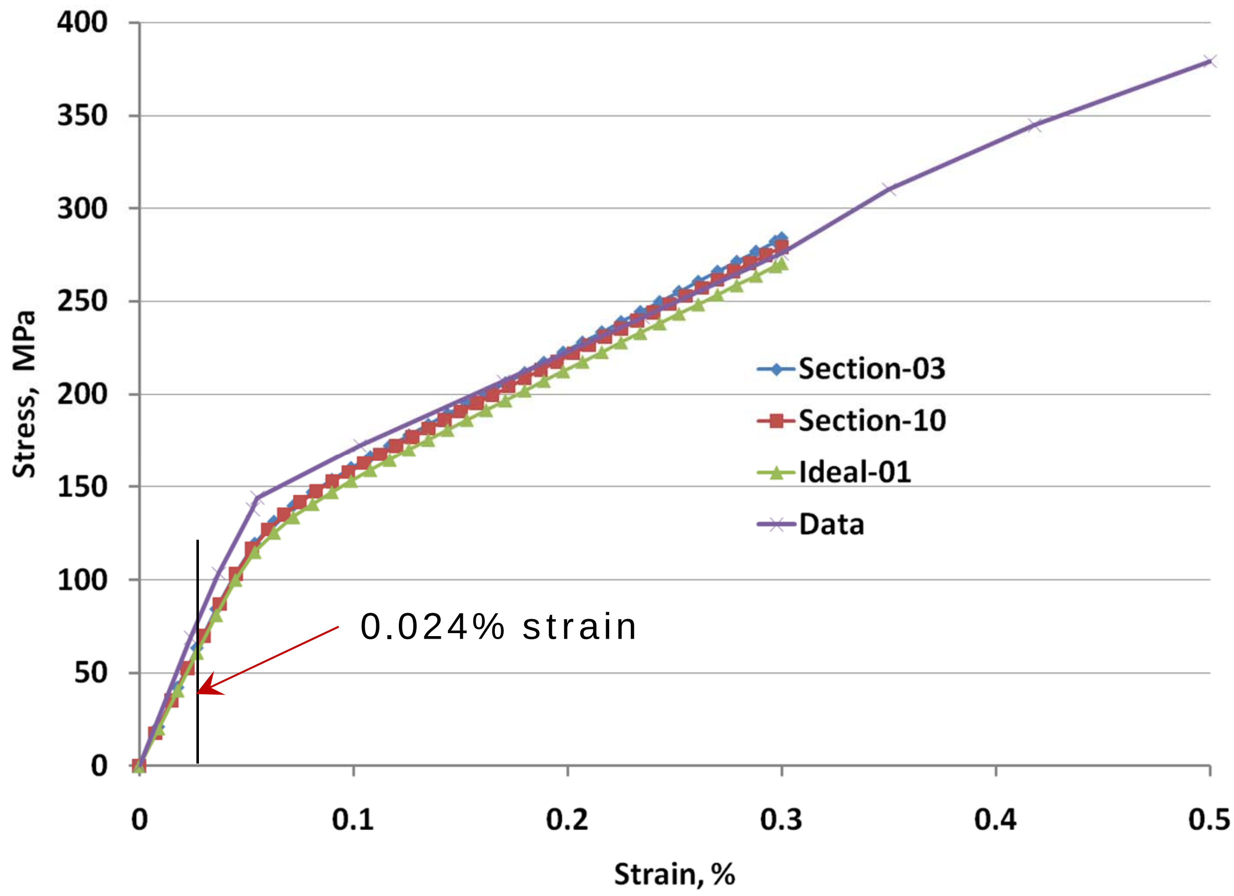




Cumulative Damage Modeling Approach

- As a first approximation, an elastic-perfectly plastic material model was used to analyze the initiation and progression of damage in the composite.
- A Mises yield surface that allows for isotropic yield was used for the constituents. Due to the unidirectionally applied load and two-dimensional geometry considered, an isotropic plasticity model was considered to be acceptable. It is recognized that a maximum principal stress criterion is more appropriate.
- Longitudinal tows and transverse tows were treated as homogenized materials in this model, even though the tow consisted of fiber, interfacial coating, matrix and intra-tow porosity.

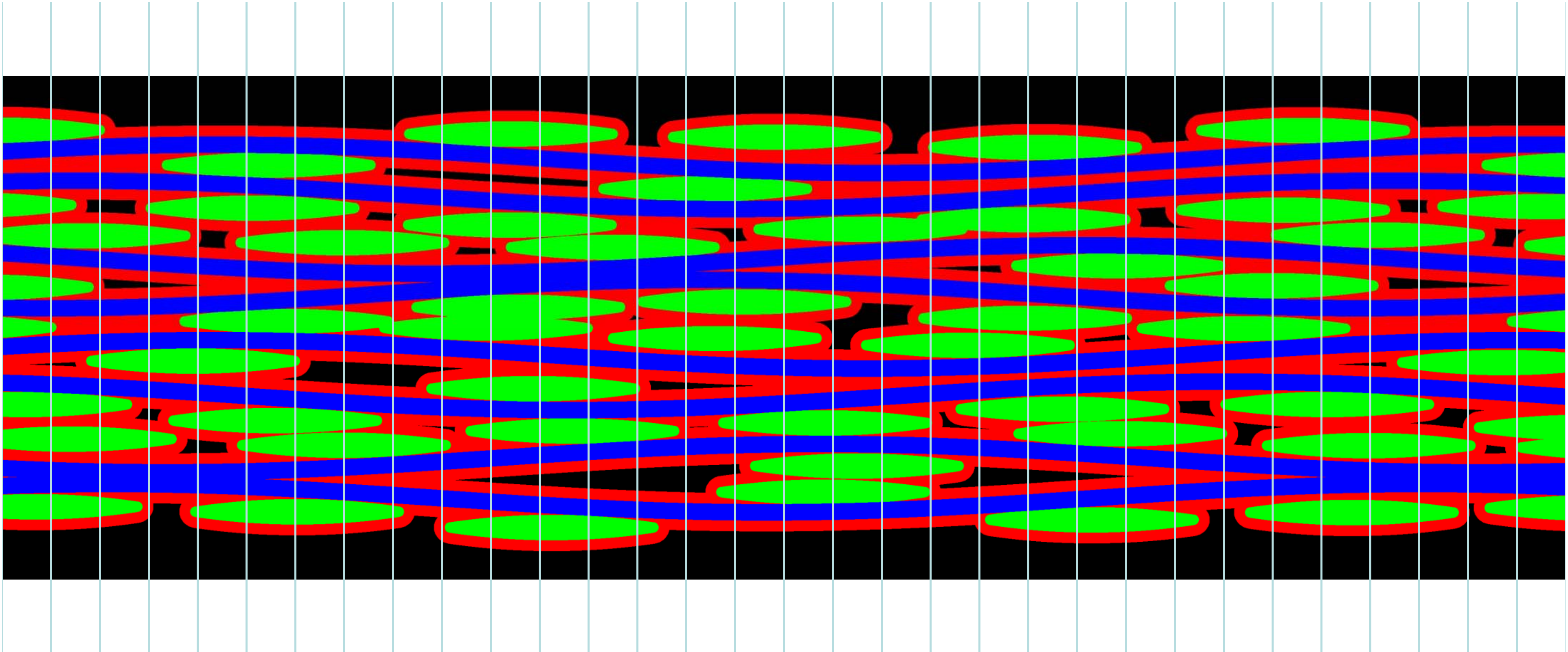
Stress-Strain Response



Hypothesis:

Do the local volume fractions of the constituents correlate with the local stresses?

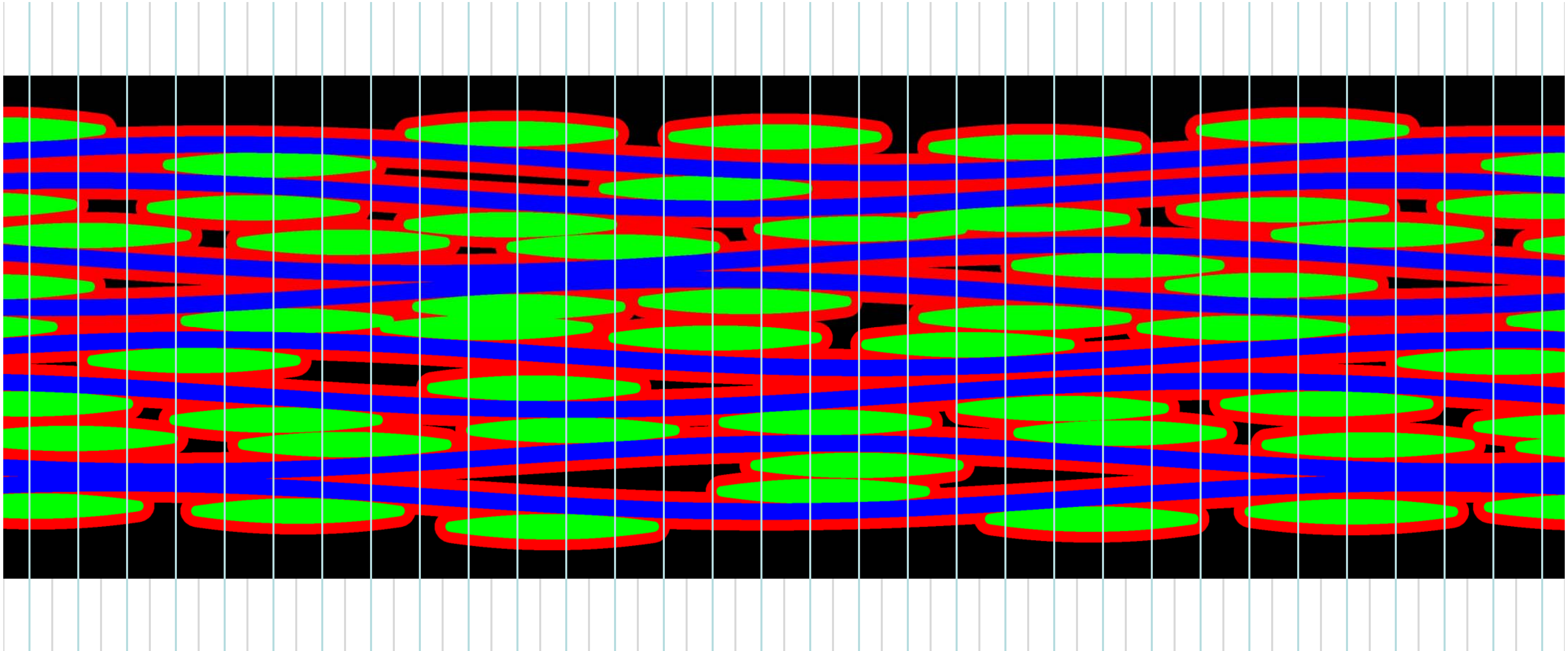
Local Volume Fractions



Within each slice measure the volume fractions of:

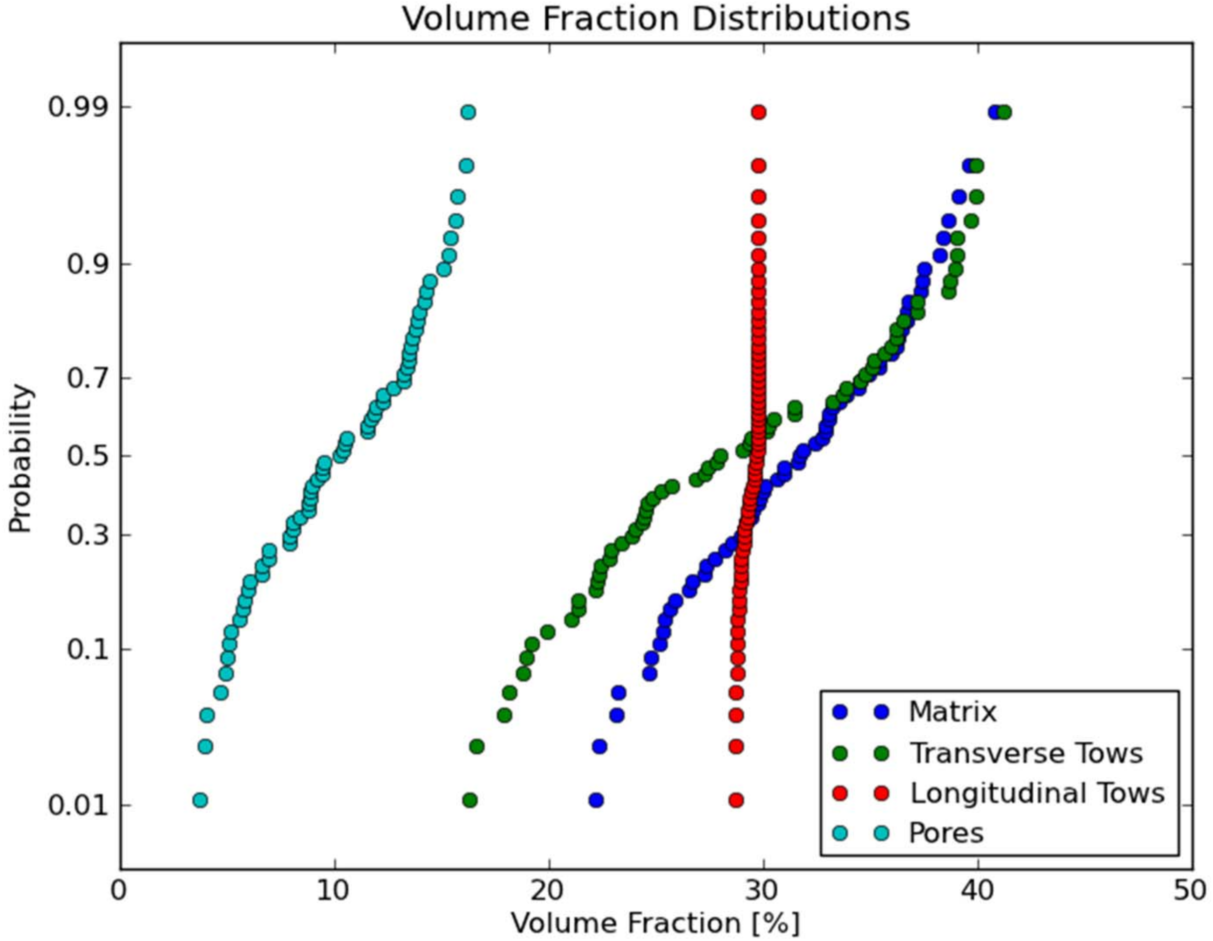
- Matrix
- Transverse Tow
- Longitudinal Tow
- Porosity

Local Volume Fractions



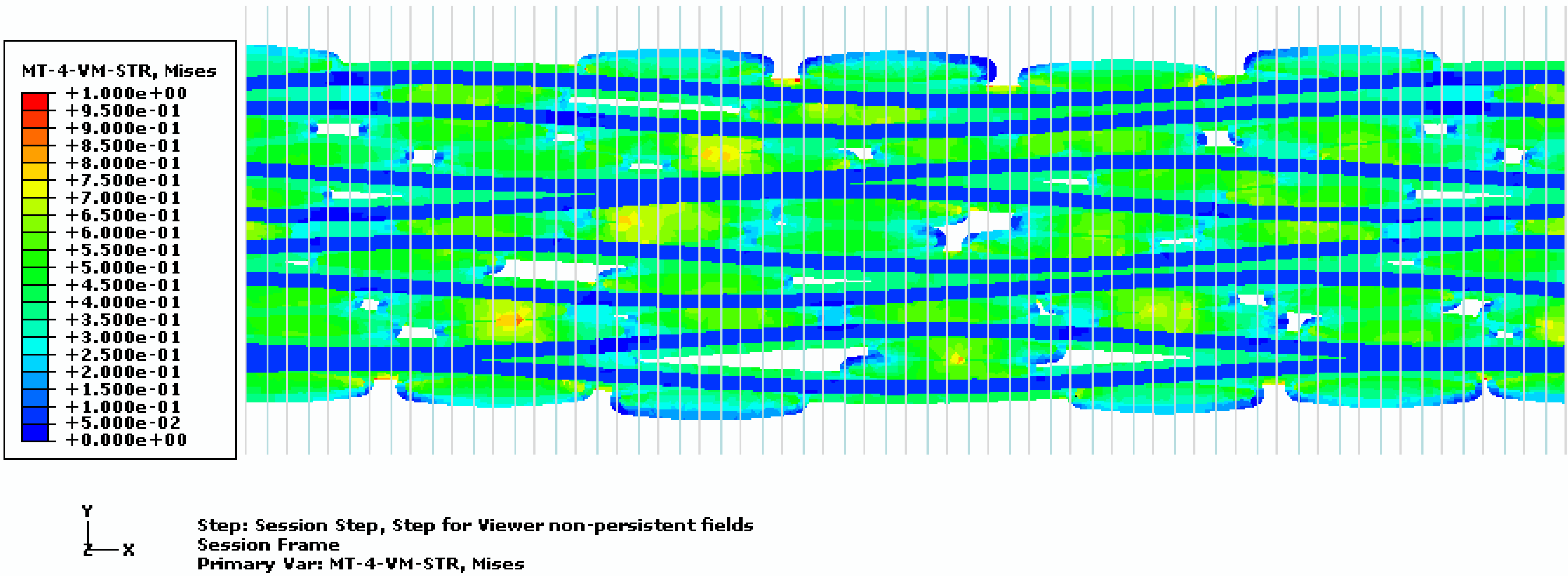
To help ensure that the slicing doesn't cause selection bias, the process is repeated on overlapping sections.
32 slices + 31 overlapping slices = 63 measurements

Section 03



Note: There is significant variability in the local constituent volume fractions.

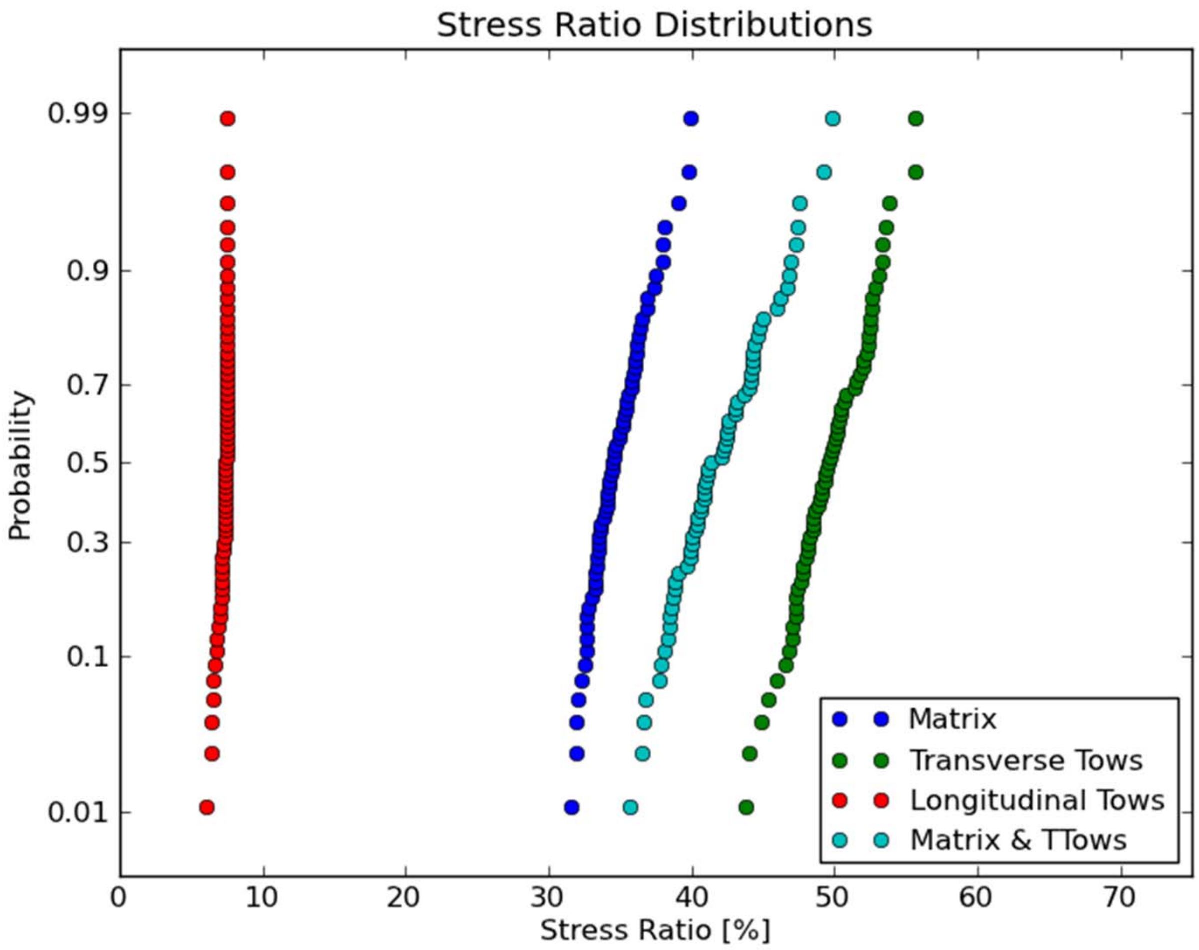
Section 03 at 0.024% Strain



Within each slice measure the average stress ratio in:

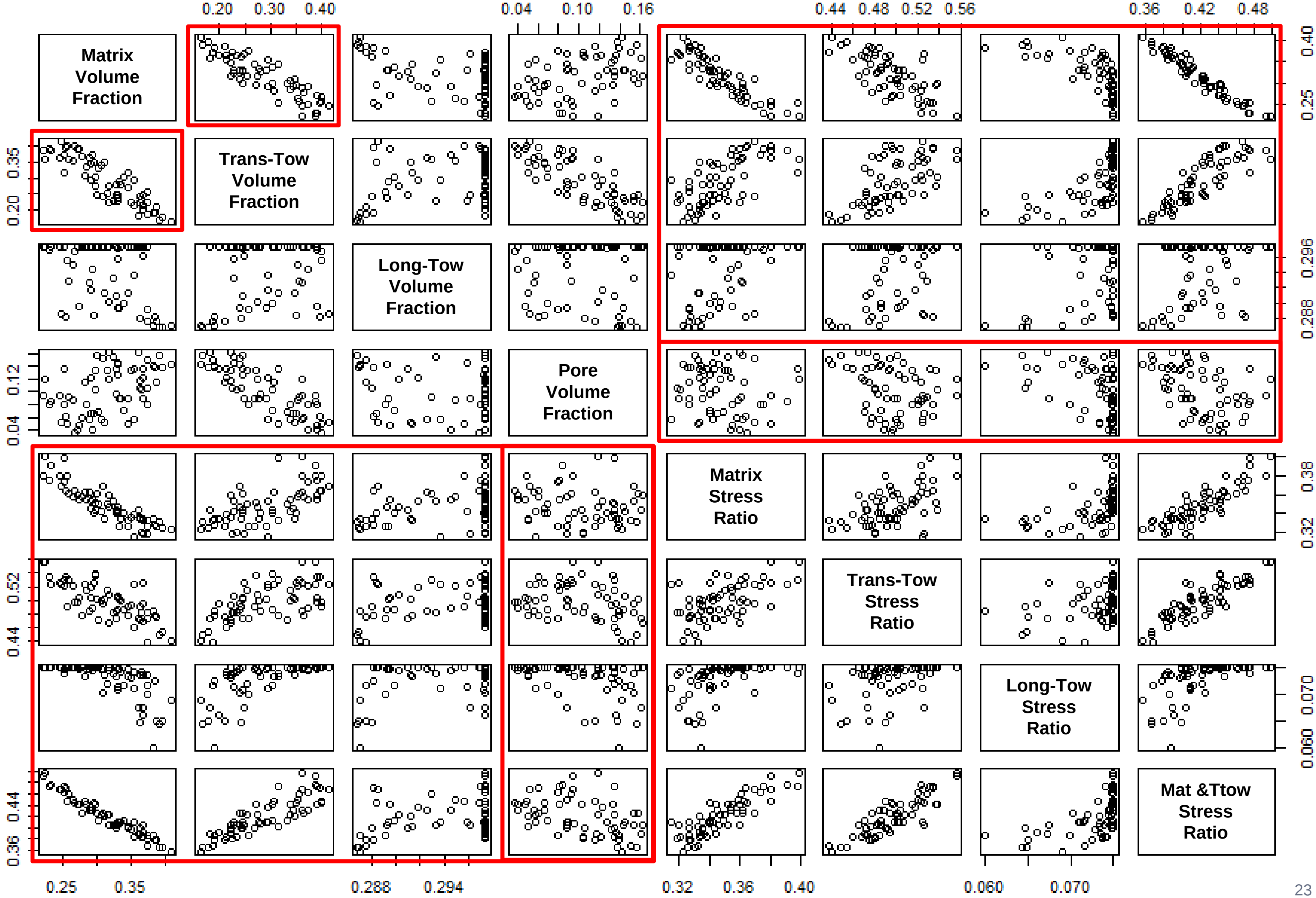
- Matrix
- Transverse Tows
- Longitudinal Tows
- Combined Matrix and Transverse Tows

Section 03 at 0.024% Strain



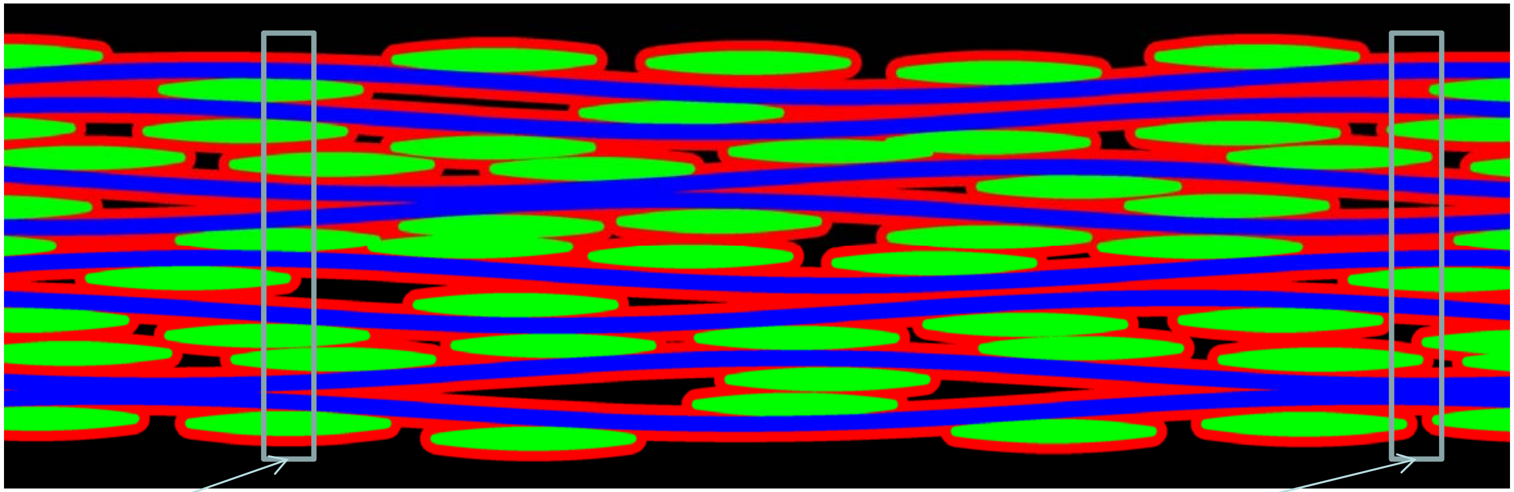
Note: There is also significant variability in the local constituent stress ratios.

Section 03

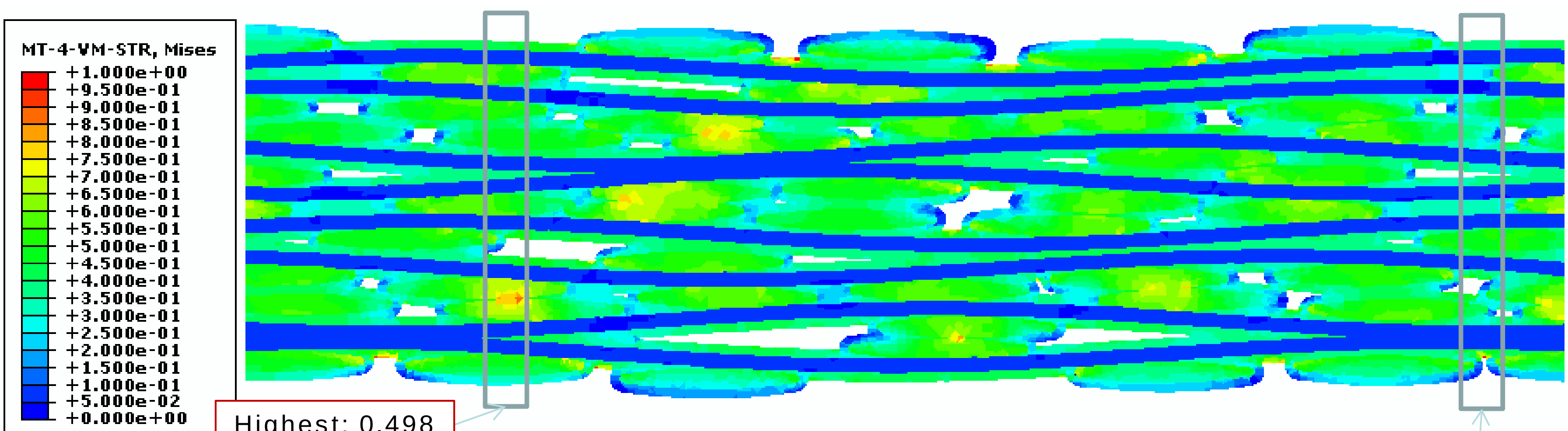


Matrix Volume Fraction
Trans-Tow Volume Fraction
Long-Tow Volume Fraction
Pore Volume Fraction
Matrix Stress Ratio
Trans-Tow Stress Ratio
Long-Tow Stress Ratio
Mat &Ttow Stress Ratio
0.20 0.30 0.40
0.04 0.10 0.16
0.44 0.48 0.52 0.56
0.36 0.42 0.48
0.40 0.25
0.296 0.288
0.38 0.32
0.070 0.060
0.35 0.20
0.12 0.04
0.52 0.44
0.44 0.36
0.25 0.35
0.288 0.294
0.32 0.36 0.40
0.060 0.070

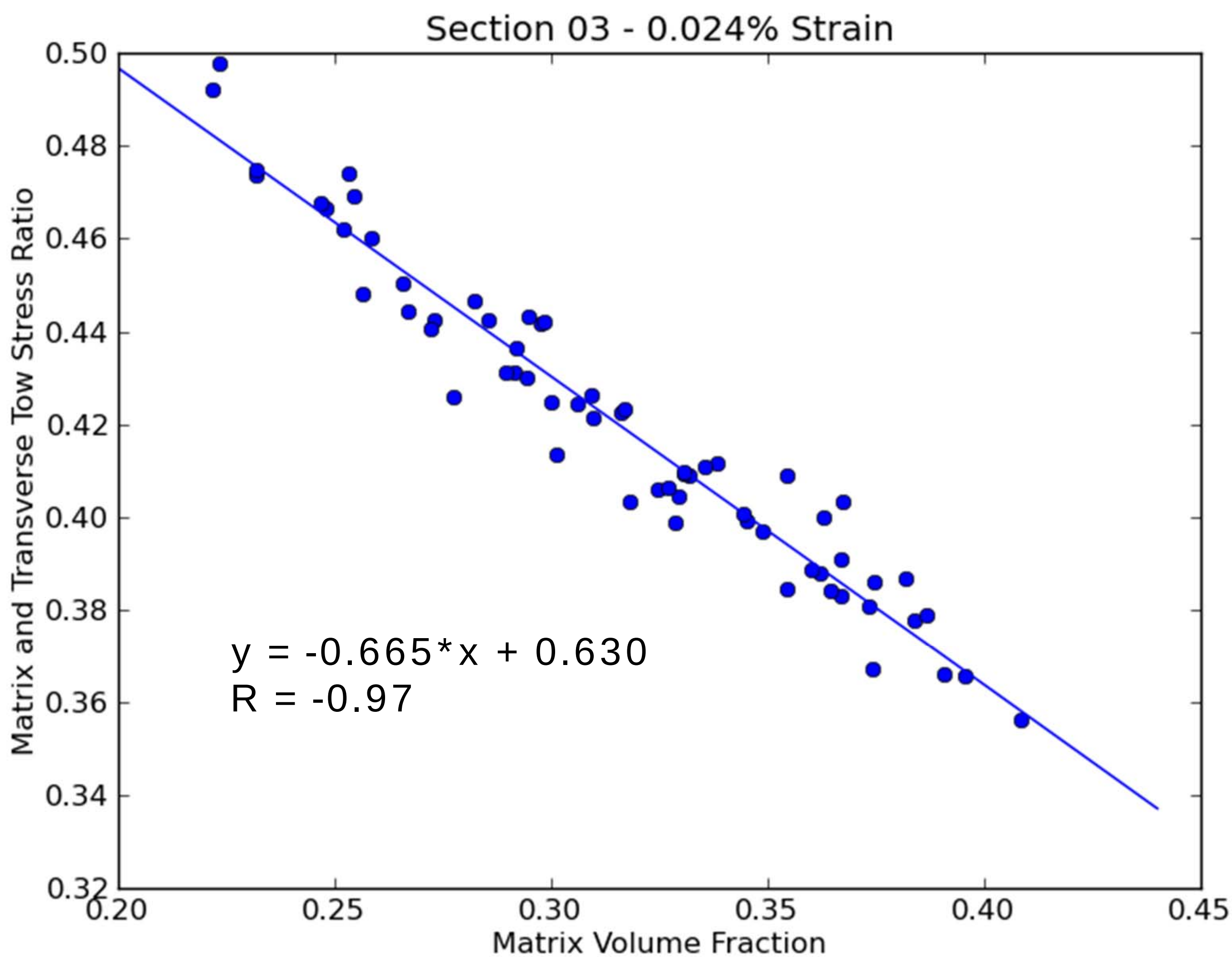
Section 03



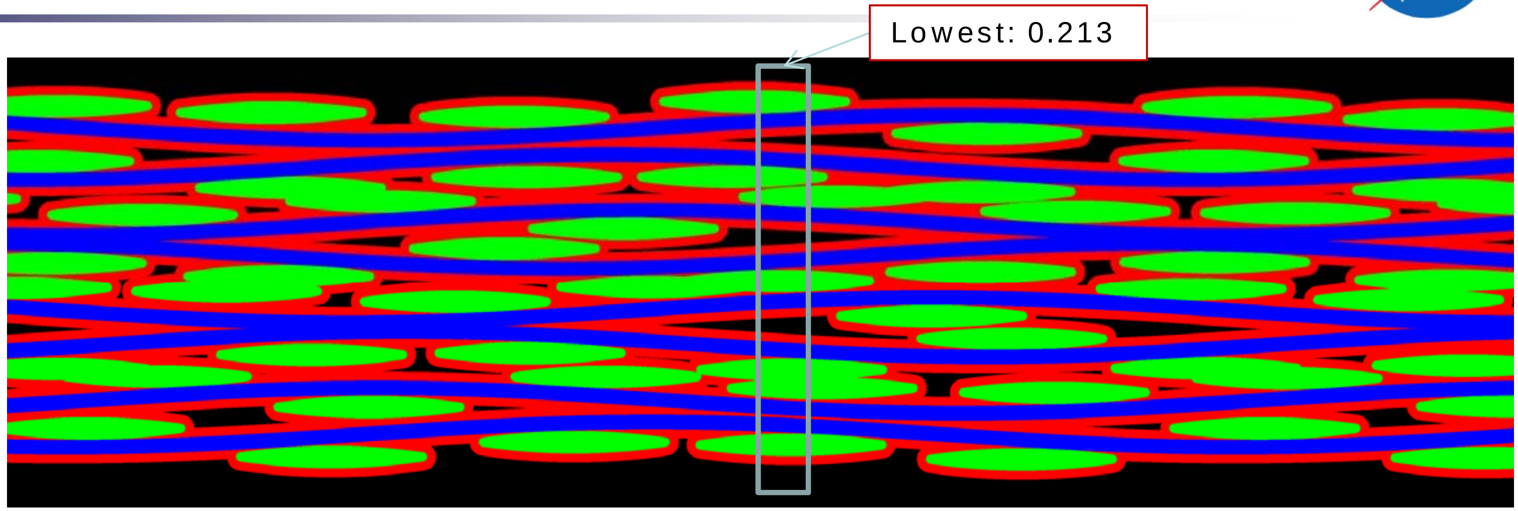
Matrix Volume Fraction



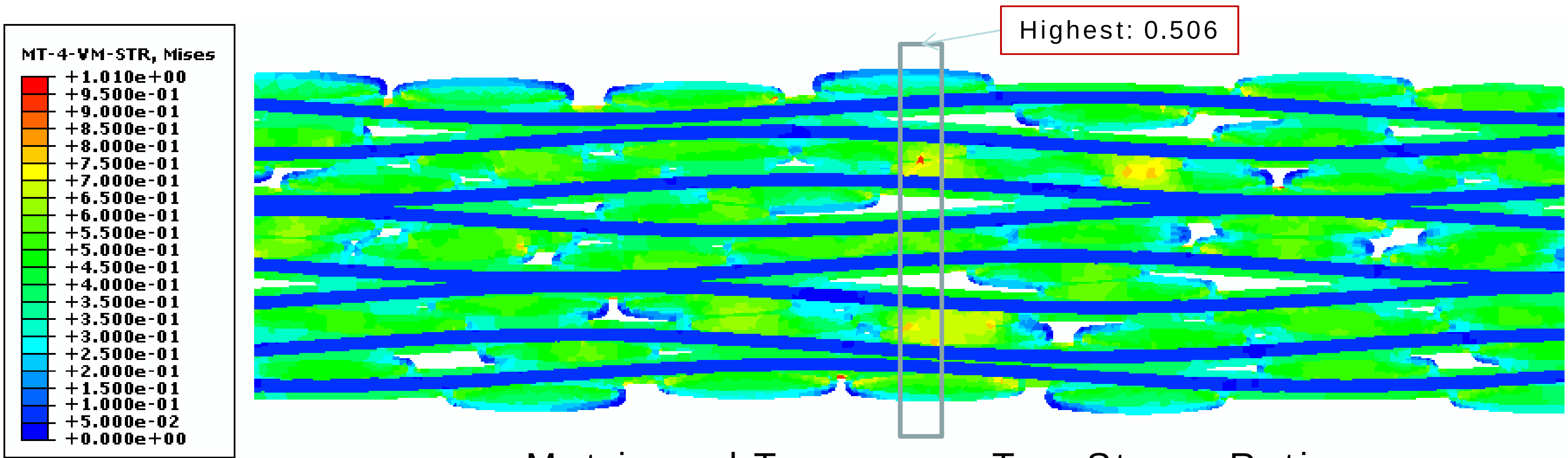
Matrix and Transverse Tow Stress Ratio


Section 03 - 0.024% Strain
Matrix and Transverse Tow Stress Ratio
Matrix Volume Fraction
0.50
0.48
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
0.20
0.25
0.30
0.35
0.40
0.45
y = -0.665*x + 0.630
R = -0.97

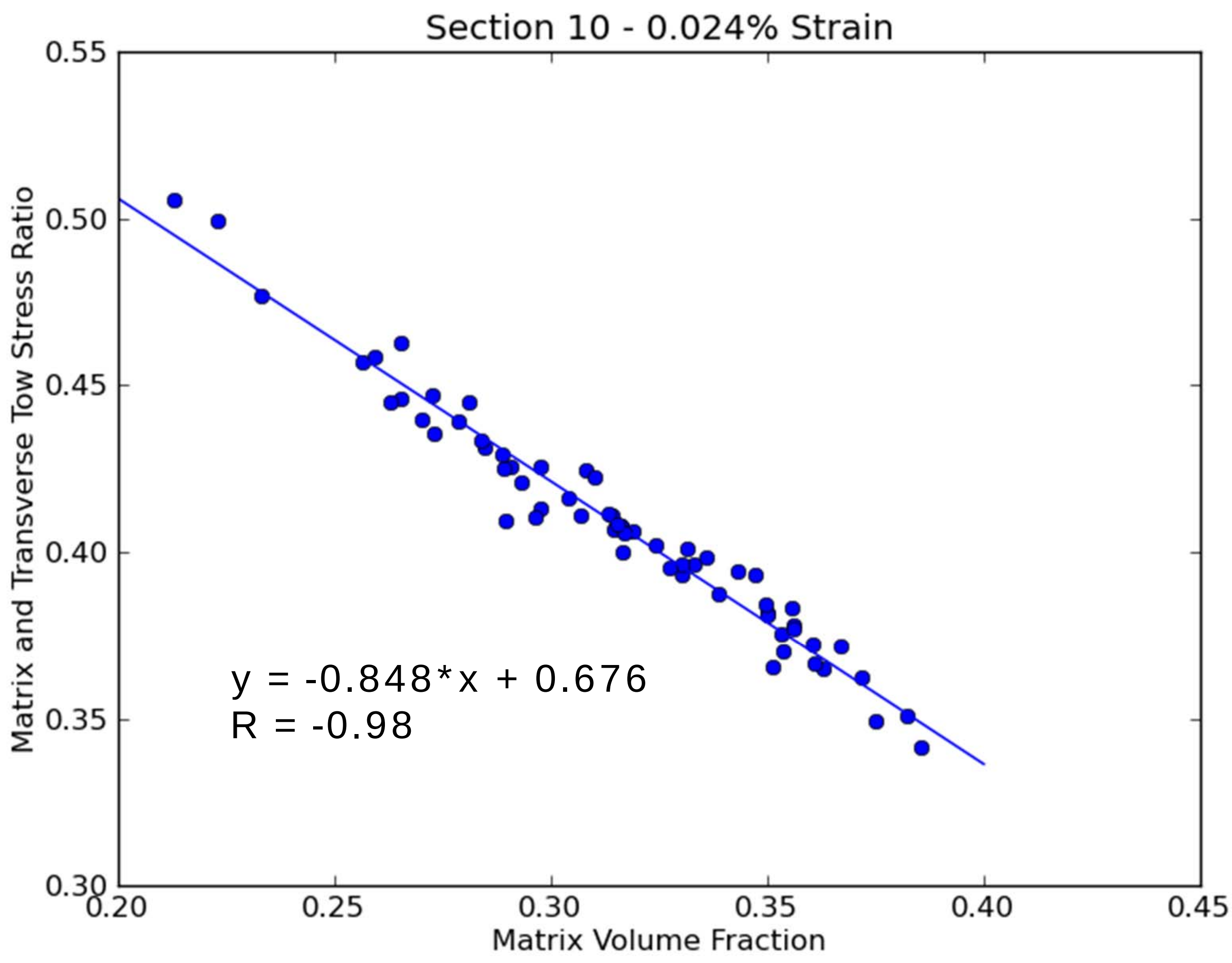
Section 10



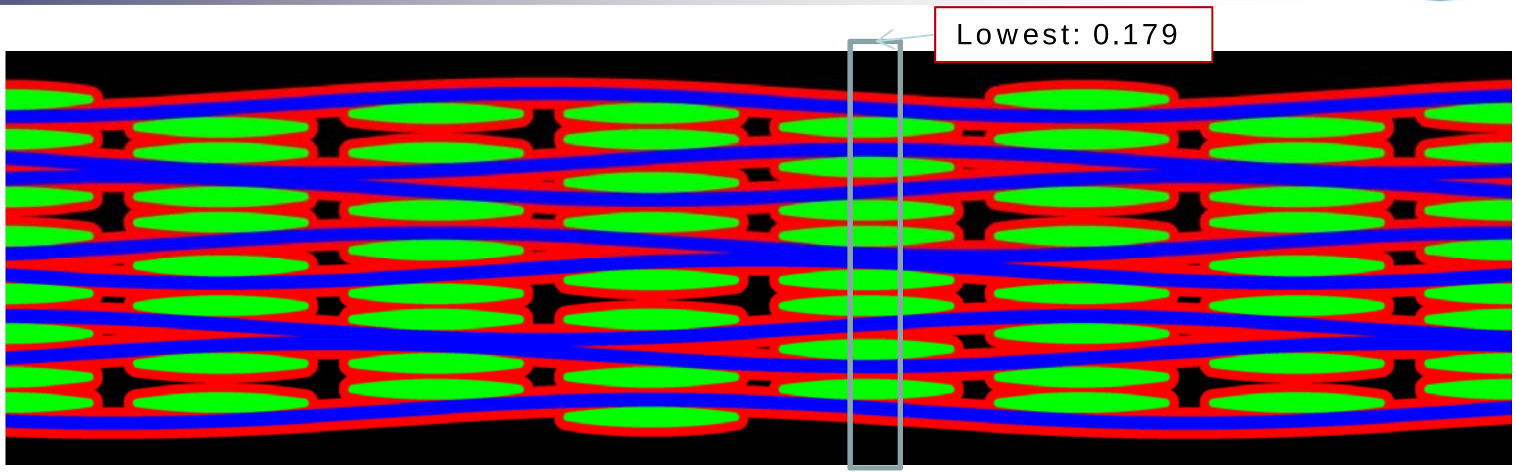
Matrix Volume Fraction



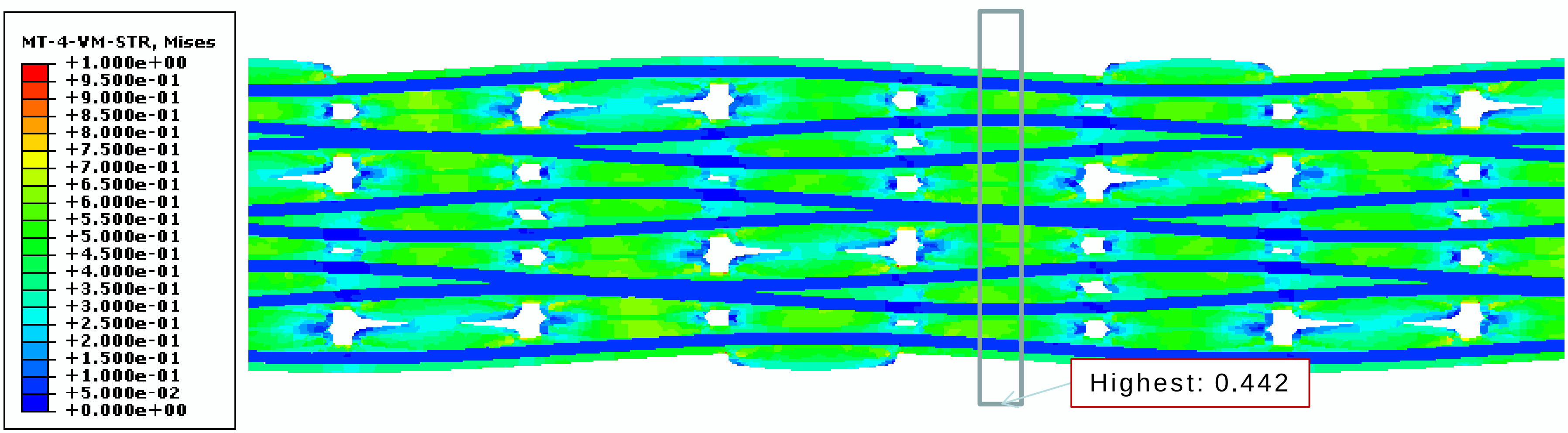
Matrix and Transverse Tow Stress Ratio


Section 10 - 0.024% Strain
0.55
0.50
0.45
0.40
0.35
0.30
0.20
0.25
0.30
0.35
0.40
0.45
Matrix and Transverse Tow Stress Ratio
Matrix Volume Fraction
y = -0.848*x + 0.676
R = -0.98

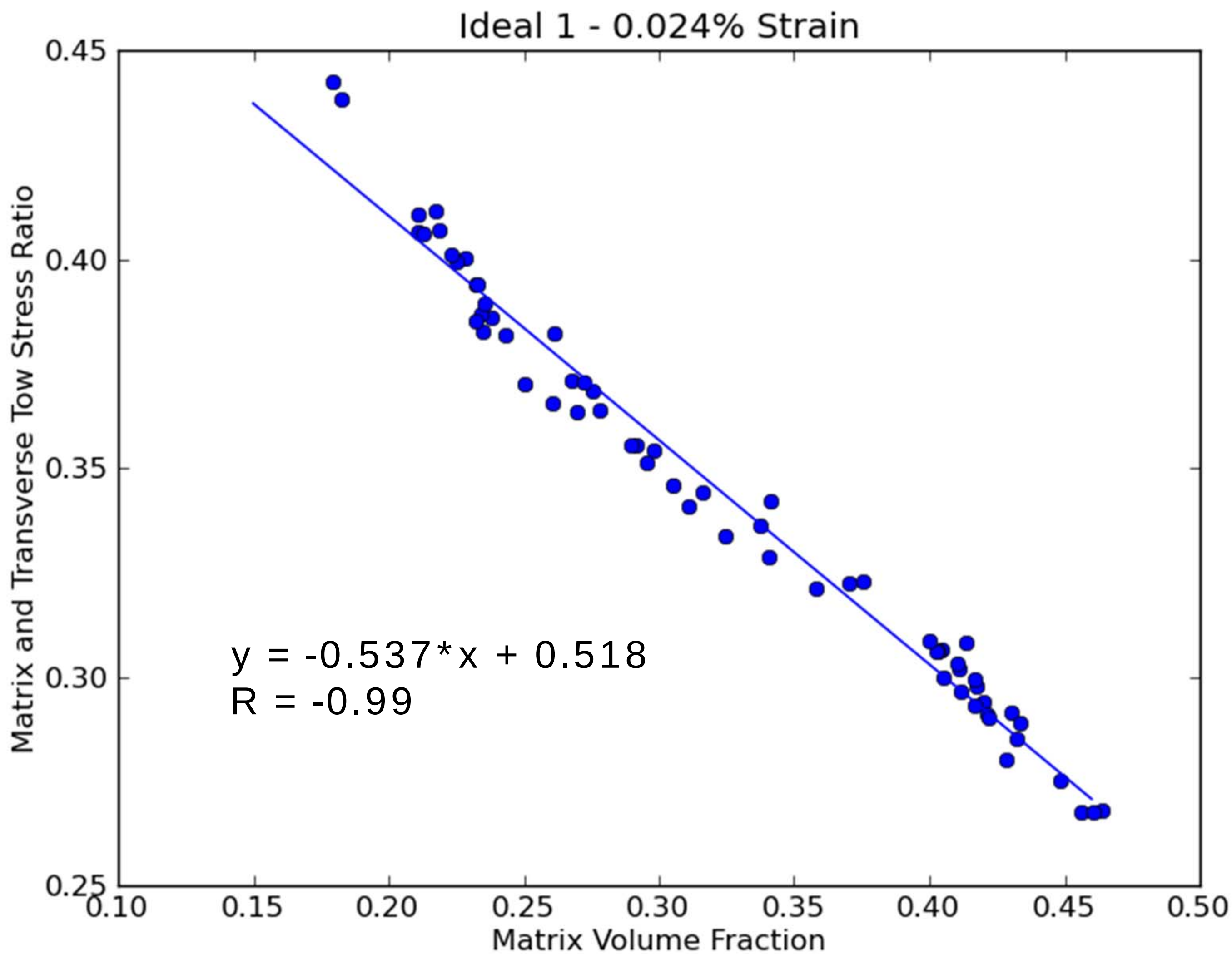
Ideal 1



Matrix Volume Fraction



Matrix and Transverse Tow Stress Ratio



Ideal 1 - 0.024% Strain
Matrix and Transverse Tow Stress Ratio
Matrix Volume Fraction
y = -0.537*x + 0.518
R = -0.99
0.45
0.40
0.35
0.30
0.25
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50

Findings

- The local average matrix stress in simplified CMC 2D models is highly correlated with the local matrix volume fraction.
- The weighted average of the normalized matrix and transverse sectioned tow stress had a higher correlation with the local matrix volume fraction than the matrix stress, alone.
- The local matrix volume fraction is inversely correlated with the local tow volume fraction.
- In this CVI system, porosity is poorly correlated with local matrix stress.

Conclusions

- Because the matrix can carry a significant fraction of the imposed stress in this composite system, locations with low local matrix volume fraction (because of stacked transverse tows) tended to be locally weaker.
- Although microstructural variability does not have a large effect on some tensile properties (elastic modulus and proportional limit strength), it does significantly influence local stress and therefore first matrix cracking events.
- If the matrix must be intact, to reduce the impact of environmental attack, the effect of microstructural variability must be understood and accounted for.

NASA