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

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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*

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
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

0.024% strain
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
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
$y = -0.665 \times x + 0.630$

$R = -0.97$
Section 10

Matrix Volume Fraction

Lowest: 0.213

Highest: 0.506

Matrix and Transverse Tow Stress Ratio

Highest: 0.506

Lowest: 0.213
Ideal 1

Matrix Volume Fraction

Lowest: 0.179

Matrix and Transverse Tow Stress Ratio

Highest: 0.442
Ideal 1 - 0.024% Strain

\[ y = -0.537 \times x + 0.518 \]

\[ R = -0.99 \]
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.