Modeling the Stress Strain Behavior of Woven Ceramic Matrix Composites

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Abstract

Woven SiC fiber reinforced SiC matrix composites represent one of the most mature composite systems to date. Future components fabricated out of these woven ceramic matrix composites are expected to vary in shape, curvature, architecture, and thickness. The design of future components using woven ceramic matrix composites necessitates a modeling approach that can account for these variations which are physically controlled by local constituent contents and architecture. Research over the years supported primarily by NASA Glenn Research Center has led to the development of simple mechanistic-based models that can describe the entire stress-strain curve for composite systems fabricated with chemical vapor infiltrated matrices and melt-infiltrated matrices for a wide range of constituent content and architecture. Several examples will be presented that demonstrate the approach to modeling which incorporates a thorough understanding of the stress-dependent matrix cracking properties of the composite system.
SiC/SiC Ceramic Matrix Composite Development at NASA Glenn (Lewis)

- **1990’s = Enabling Propulsion Materials (EPM) Program with GE and P&W:** High Speed Civil Transport Combustor Liner (1200°C, > 10,000 hours)
  - Highest temperature fiber
  - BN interphase
  - Melt (Si) infiltrated SiC matrix
- **2000’s = Ultra Efficient Engine Technology (UEET) Program:** 1315°C application temperature, e.g., turbine vane
  - Further improvements to fiber, interphase, and matrix
- **Future? = Space Propulsion:** 1450°C+ application temperatures, e.g., thin cooled structures, turbine blades…
  - Non-Si containing matrices: CVI SiC, PIP SiC
Objective: Model $\sigma/\varepsilon$ Behavior of CMC’s

- Constituent (fib., mat., int.) composition
- Constituent fractions
- Architecture
- Elastic Properties
- Non-Linear Stress-Strain Response
- Matrix cracking
- Ultimate Properties

Graph showing stress (MPa) on the y-axis and strain (%) on the x-axis, with different colored lines and areas indicating different properties and behaviors.
However, composites will vary throughout a component…

- Constituent contents
- Number of plies
- Local architectures
- Thickness
- Processing uniformity
- Curvature

For example, Sylramic fiber-reinforced melt-infiltrated composites (2D 5 harness satin) that vary in:

- Number of plies by factor of 2
- Thickness by factor of 2
- Tow ends per cm in weave
- Matrix content
- Fiber content
- Size of tow
- Debonding interface
Typical approaches to modeling mechanical properties involve making many panels of the “same thing” in order to get statistical variations.

There is a greater need to model composite behavior as a function of constituent and architecture variation for design of components and predicting use-life.
Outline

Composite processing

Use of Modal Acoustic Emission

3 Examples of Non-linear $\sigma/\varepsilon$ Behavior (orthogonal direction)
  – 2D Melt-infiltrated system
  – 3D Melt-infiltrated system
  – 2D CVI SiC System
Standard Slurry Cast Melt-Infiltrated (MI) 2D & 3D Woven Composites

- Sylramic Fiber
- Weaving
- Fabric
- Low Temp CVI Si-BN Interphase Infiltration
- For Syl-iBN, special treatment prior to CVI Si-BN
- CVI SiC Matrix Infiltration
- Reactor
- SiC/SiC preform
- Slurry Cast SiC Matrix
- Silicon Melt Infiltration
- Furnace
- MI SiC/SiC

For Syl-iBN, special treatment prior to CVI Si-BN.
Modal Acoustic Emission of CMCs

- Locate damage events and failure events → $\Delta t$
- Monitor stress(or time)-dependent matrix cracking → Cumulative AE Energy
- Identify damage sources, e.g. matrix cracks, fiber breaks → Frequency
- Measure stress(or time) dependent Elastic Modulus → Speed of sound
An Example: Hi-Nicalon/CVI SiC

Normally, using a threshold voltage technique for location gives $\pm$ 2mm accuracy. For 3D composites, each event was examined "by hand" to determine 1st peak ($\pm$ 0.25 mm)!
Relationship Between AE and Matrix Cracking

0° fiber, BN, CVI SiC Minicomposite
90° fiber, BN, CVI SiC Minicomposite
MI (Si + SiC) matrix

See Evans et al., Cox and Marshall, Chou et al, Lamon et al., etc…
Example #1: 2D Woven Melt-Infiltrated Systems When Stressed in Orthogonal Direction

HN and Sylramic (iBN) Fiber-types
Stress-Strain and AE for Different Composite Panels

- Acoustic Emission used to monitor matrix crack density and derive a matrix crack distribution
- Applied to Sylramic-based and Hi-Nicalon-based composite systems that vary by a factor of two in number of plies, thickness, tow ends per cm, and number of fibers per woven tow
For Orthogonal Composites, the 90° Fiber-Tows are the Source for Matrix Crack Formation

- The stress that acts on the 90° fiber-tows is the stress in the composite “outside” of the load-bearing fiber, BN, CVI SiC minicomposite, i.e., the “mini-matrix” stress:

\[
\sigma_{\text{min matrix}} = \left( \sigma_c + \sigma_{th} \right) \left( \frac{E_c - f_{\text{min i}} E_{\text{min i}}}{1 - f_{\text{min i}}} \right)
\]

All the information required is obtained from RT stress-strain test (or sound techniques) and processing data sheet.
A very simple relationship for matrix cracking in 2D MI SiC/SiC Composites

\[ \rho_c = \text{final crack density} \]
\[ \sim 2.5/\text{mm for Hi-Nicalon} \]
\[ \sim 10/\text{mm for Sylramic} \]
\[ \sigma_o = 150 \text{ MPa}; \ m = 5 \]

\[ \rho_c \left( \sigma_{\text{min matrix}} \right) = \rho_c \left[ 1 - \exp \left( -\left( \frac{\sigma_{\text{min matrix}}}{\sigma_o} \right)^m \right) \right] \]
Can Then Use to Model $\sigma/\varepsilon$

Determine $\rho_c(\sigma_c)$ from $\rho_c(\sigma_{\text{minimatrix}})$ relationship:

$$\varepsilon = \frac{\sigma}{E_c} + \alpha \delta(\sigma) \frac{\rho_c}{E_f} (\sigma + \sigma_{\text{th}})$$

Where

$$\delta = \alpha r \frac{(\sigma + \sigma_{\text{th}})}{2\tau}$$

$$\alpha = (1-f) E_m / f E_c$$

* After Curtin and Pryce and Smith

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**Starting point for life-degradation models**
Example #2: 3D-Orthogonal Composites With Different Z-Fiber Types

X- and Y-direction Fibers = Sylramic or Syl-iBN
MI Composites
Woven 3D-Orthogonal Composites with **Different** Z-Fiber Types

**X-Direction:**
Two Sylramic Tows (1600 fibers)
10 epi
7 plies

**Y-Direction:**
One Sylramic Tow (800 fibers)
18 or 20 epi
8 plies

**Z-Direction:**
- **ZMI** (800 fiber/tow)
- **T300** (1000 fiber/tow)
- **Rayon** (400 fiber/tow)
3D Orthogonal $\sigma/\varepsilon$ Behavior

- **Y-direction**
  - Rayon
  - T300
  - ZMI

- **ZMI (X-direction)**
Loading in the Y-Direction

cross-sectional views

~1.5mm

~1.5mm
(1) Matrix micro-cracks originate in the UNI sections (low energy AE)

(2) Large matrix cracks form in the UNI sections (High energy AE)

(3) Matrix cracks form in XPLY regions
Stress Distributions For Three Y-Direction Oriented 3D Composites and Standard 2D Composite

- Wide range of matrix cracking stress-distributions
- XPLY cracking stresses always higher than UNI cracking stresses
- Rayon > T300 > ZMI

![Graph showing stress and strain distributions](image-url)
Minimatrix Stress Dependence for Matrix Cracking in 3D Composites

- Good correlation for XPLY regions
- UNI regions unaffected

Convert to $\sigma_{\text{minimatrix}}$
UNI Regions Dependent on Height of Z-Tow: Griffith-type Relationship

Onset Composite Stress
Slope = 2.17 MPa m$^{1/2}$

Onset Minimatrix Stress
Slope = 1.07 MPa m$^{1/2}$

* Tow height measured 0.5 mm from surface
Example #3: 2D CVI SiC Composites

Variation in orthogonal fiber-loading in order to raise matrix cracking stresses.
Syl-iBN, BN interphase, CVI SiC Matrix Composites

- Balanced weave = 7.9 tow ends per cm
- Unbalanced weave = 9.4 x 5.5 tow ends per cm
Matrix Cracking Dependent on Stress in CVI SiC and “Bridging Condition”

Stress in load-bearing CVI SiC: \( \sigma_{\text{SiC}} = \left( \frac{\sigma}{E_c} \right) E_{\text{SiC}} \)

Low fiber volume fraction

High fiber volume fraction

Convert to \( \sigma_{\text{CVI SiC}} \)
Good Prediction of $\sigma/\varepsilon$ Behavior

- CVI; 7.9 epcm
  - $f=0.12$ (002)
  - $E=293$ GPa
- CVI; 5.5 epcm
  - $f=0.12$ (002)
  - $E=261$ GPa
- 8 ply (002)
  - $f=0.21$
  - $E=293$ GPa
- C-interphase
  - $f=0.17$
  - $E=230$ GPa
- $E = 253$ GPa

Circles correspond to model.
Conclusions

• Robust relationships have been determined to describe matrix cracking in a wide range of “dense-matrix” SiC/SiC composites when stressed in orthogonal directions.
• These can be implemented in design of components with variation in constituent content, architecture, and shape (for orthogonal directions).
• The matrix cracking behavior serves as the “starting point” for life-modeling at stresses above matrix cracking limits.
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Effect of Tow Size and Shape: Single-Tow vs. Double-Tow Woven Composites

- Identical fiber volume fraction; Both five-harness satin

Comparison of composite stress vs. strain for single-tow and double-tow woven composites:
- **Single-tow woven**: 
  - Stress: 7.8 epcm
  - Fiber volume fraction: \( f_0 = 0.19 \)
- **Double-tow woven**: 
  - Stress: 3.9 epcm
  - Fiber volume fraction: \( f_0 = 0.19 \)

Additional notation:
- \( h_d = h_s \)
- \( w_d = 2w_s \)