An Update on Design Tools for Optimization of CMC 3D Fiber Architectures

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Background

• In recent studies, NASA has shown that there are multiple performance advantages in using 3D architectures for advanced SiC/SiC composites. These advantages primarily arise from the use of thru-thickness fibers that allow composites with improved delamination resistance, improved impact resistance, and improved thru-thickness strength and thermal conductivity.

• Another potential advantage for 3D architectures is improved matrix infiltration down the weaver fibers. Furthermore, the use of 3D automation can possibly reduce manufacturing costs and scatter in composite properties due to the elimination of the human element that is typically involved in 2D tape and fabric lay-up techniques.

• However, for the most advanced SiC/SiC composites, the SiC fibers are stoichiometric in composition resulting in high bending stiffness. They also possess large nano-grains and associated rough fiber surfaces leading to poor abrasion resistance. These issues can enhance the probability of fiber fracture during 3D preforming and thus limit the available 3D architectural designs and thru-thickness fiber fractions.

Presentation

Objective: Describe and up-date progress for NASA's efforts to develop 3D architectural design tools for CMC in general and for SiC/SiC composites in particular.

Approach/Outline

Describe past and current sequential work efforts aimed at:

• Understanding key fiber and tow physical characteristics in conventional 2D and 3D woven architectures as revealed by microstructures in the literature

• Developing an Excel program for down-selecting and predicting key geometric properties and resulting key fiber-controlled properties for various conventional 3D architectures

• Developing a software tool for accurately visualizing all the key geometric details of conventional 3D architectures

• Validating tools by visualizing and predicting the internal geometry and key mechanical properties of a NASA SiC/SiC panel with a 3D orthogonal architecture

• Applying the predictive and visualization tools toward advanced 3D orthogonal SiC/SiC composites, and combining them into a user-friendly software program
Key Architecture Factors Controlling Multi-Directional MCS:

- Effective fiber volume fraction in test direction:
  \[ f_0 = f(0) \text{ or } f(\pm 60\text{° weavers}) \cdot \cos(\theta) \text{, whichever largest} \]

- Maximum height of tows perpendicular to lost direction:
  \[ h = h_{\text{Max}} \]

Key Tow Shapes and Dimensions in 2D and 3D Woven Architectures

- Rectangular (also square)
- Elliptical (also circle)
- Half Lenticular
- Half Diamond

Tow Height \( h \) x Tow Width \( w \) for \( n \) bundled tows:

- Typical Schematics
- Architectures where Tow Shape will appear:
  - 3D orthogonal and angle interlock: stuffers and weavers
  - 2D fabric stuffers
  - 3D orthogonal and angle interlock: surface stuffers
  - 3D angle interlock: warp and fill stuffers

Key Fiber and Tow Modeling Parameters as Measured from 2D and 3D-Woven CMC Micrographs in the Literature

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Sylramic (also SiC)</th>
<th>ZMI</th>
<th>Nextel</th>
<th>Nextel 720</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Tow-Fiber Count (( f ))</td>
<td>800</td>
<td>500</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>Avg. Fiber Diameter (( d ), ( \mu ))</td>
<td>9.7</td>
<td>11.0</td>
<td>14.1</td>
<td>12.5</td>
</tr>
<tr>
<td>- Fiber Area in Single Tow (( A_0 ), mm(^2))</td>
<td>0.056 mm(^2)</td>
<td>0.061 mm(^2)</td>
<td>0.078 mm(^2)</td>
<td>0.049 mm(^2)</td>
</tr>
<tr>
<td>- Min. Area of Single Tow (( A_0 ) assuming 6.60 packing factor)</td>
<td>1.00 in ( w` ) mm</td>
<td>0.105 in ( w` ) mm</td>
<td>0.135 in ( w` ) mm</td>
<td>0.065 in ( w` ) mm</td>
</tr>
<tr>
<td>- Natural Lay-Down Width (( w<code> \)) for (n) Bundled Tows: \( w</code> = 4d(n A_0) )</td>
<td>1.10 in ( w` ) mm</td>
<td>1.25 in ( w` ) mm</td>
<td>1.26 in ( w` ) mm</td>
<td>1.00 in ( w` ) mm</td>
</tr>
</tbody>
</table>

Note: Lay-down width (\( w` \)) only applies when the tow ends per/inch allow a tow spacing larger than \( w` \)
NASA Computer-Based Visualization Tool for Basic 3D Architecture Types

- Through Thick Angle Interlock w/o Warp Stuffer
- Through Thick Angle Interlock w/ Warp Stuffer
- Ply-on-Ply Angle Interlock
- 3D Orthogonal

Current Architectural Approach and Rationale

- There are multiple ways one can design a 3D fiber architecture. To assure accuracy in the design tools while at the same time achieving some practical results, our initial approach has been to focus on simple 3D orthogonal architectures.
- On the practical side, these architectures best allow us to keep the in-plane warp and fill stuffer tows to be straight, while allowing control of the thru-thickness weaver fiber volume fraction and reinforcement angle in the center of a CMC component wall where interlaminar stresses are envisioned to be maximum due to thermal gradients.
- Design and visualization tools were recently validated using a CVI-MI SiC/SiC panel with this 3D Orthogonal architecture:

Key Design-Tool Predictions for NASA 3D-Orthogonal CVI-MI SiC/SiC Microstructure with Syrlamic Stuffers and 2M Fiber Weavers

<table>
<thead>
<tr>
<th>Property</th>
<th>Predicted</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fiber Volume, %</td>
<td>32.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Warp Weave</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Largest Perpendicular Torus Height, mm</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Thru-Thickness Cracking Strength, MPa</td>
<td>126</td>
<td>126</td>
</tr>
</tbody>
</table>
Current and Future Activities

- Employ our design tools to seek and demonstrate 3D architectures for SiC/SiC turbine vanes with high total fiber fraction and with directional fractions dictated by the vane service requirements.

- One key goal is to determine architectural design and preforming approaches that will allow successful replacement of ZMI warp weaver tows with the stronger and more thermally conductive Sylramic-iBN fiber.

- Continue to upgrade our design tools by creating a user-friendly "ComoGen" software package that incorporates all of our 3D design, prediction, and visualization programs.