Design Curve Generation for 3D SiC Fiber Architecture

J. Lang and J. DiCarlo
NASA Glenn Research Center
Cleveland, Ohio

Research Supported by the
NASA Fundamental Aeronautics Program
Aero Sciences Project

Presented at 38th Annual Conference
on Composites, Materials, and Structures
Cape Canaveral, Florida, January 28, 2014
**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 provide composites with *improved delamination resistance, improved impact resistance, and improved thru-thickness strength and thermal conductivity*.

- It was also shown that if the matrix had reduced porosity, key structural and formation properties of advanced SiC/SiC composites are controlled and predictable from the *fiber tow geometric characteristics* and *volume fractions* within the fiber architecture.

- This important observation initiated in-house studies aimed at developing user-friendly software tools that can be used for designing virtual 3D-woven architectures that will best meet the key fiber-controlled multi-directional property requirements of specific CMC components.
Describe recent progress in the development of NASA’s 3D design tool:

- Development of preform design curves for designing and validating virtual SiC/SiC composite panels containing down-selected 3D modified layer-to-layer architectures of high-stiffness high-performance Hi-Nicalon Type S SiC fibers
- Design curves allow an understanding and prediction of the effects of fiber geometry on key properties of 3D preforms, such as fiber fractions in three directions, preform height, and minimum fiber bend radius to avoid fiber fracture
- Fabrication of the down-selected preforms and validation of the design curve predictions for the key process and geometric properties of the preforms.
- Initial approach for extending the design tool to predict the key multi-directional property of Matrix Cracking Strength (MCS) for SiC/SiC reinforced by these architectures.
### Key Tow Shapes and Dimensions in 2D and 3D Woven Architectures

Assumption: Tows are completely conformable while retaining 60% fiber packing

<table>
<thead>
<tr>
<th>Tow Shape</th>
<th>Rectangular (also square)</th>
<th>Elliptical (also circle)</th>
<th>Half Lenticular</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tow Schematics</strong></td>
<td><img src="image" alt="Tow Schematics" /></td>
<td><img src="image" alt="Elliptical Schematics" /></td>
<td><img src="image" alt="Half Lenticular Schematics" /></td>
<td><img src="image" alt="Diamond Schematics" /></td>
</tr>
<tr>
<td><strong>Typical Architectures where Tow Shape will appear</strong></td>
<td>3D orthogonal and angle interlock: stuffers and weavers</td>
<td>2D fabric: stuffers</td>
<td>3D orthogonal and angle interlock: surface stuffers</td>
<td>3D angle interlock: warp and fill stuffers</td>
</tr>
<tr>
<td><strong>Tow Height (h) x Tow Width (w) for (n) bundled tows (Total Tow Area = n A₀)</strong></td>
<td>hw = 1.0 (n A₀)</td>
<td>hw = 1.3 (n A₀)</td>
<td>hw ≥ 1.4 (n A₀)</td>
<td>hw = 2.0 (n A₀)</td>
</tr>
</tbody>
</table>
### 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 iBN)</th>
<th>HNS</th>
<th>HN</th>
<th>ZMI</th>
<th>Nicalon</th>
<th>Nextel 720</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Tow Fiber Count ( (N_f) )</td>
<td>800</td>
<td>500</td>
<td>500</td>
<td>800</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>Avg. Fiber Diameter ( (d) ), μm</td>
<td>9.7</td>
<td>12.6</td>
<td>13.7</td>
<td>11.0</td>
<td>14.1</td>
<td>12.5</td>
</tr>
<tr>
<td>~ Min. Bend Radius without fiber fracture</td>
<td>1.0 mm</td>
<td>1.0 mm</td>
<td>0.7 mm</td>
<td>0.3 mm</td>
<td>0.5 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>~ Fiber Area ( (A_f) ) in a Single tow, mm²</td>
<td>0.059 mm²</td>
<td>0.062</td>
<td>0.074</td>
<td>0.081 mm²</td>
<td>0.078 mm²</td>
<td>0.049 mm²</td>
</tr>
<tr>
<td>~ Min Area of Single Tow ( (A_0) ) assuming 0.60 packing factor</td>
<td>0.10 mm² ( (155 \text{ mil}²) )</td>
<td>0.103 mm² ( (160 \text{ mil}²) )</td>
<td>0.123 mm² ( (191 \text{ mil}²) )</td>
<td>0.135 mm² ( (210 \text{ mil}²) )</td>
<td>0.13 mm² ( (200 \text{ mil}²) )</td>
<td>0.08 mm² ( (125 \text{ mil}²) )</td>
</tr>
<tr>
<td>~ Natural Lay-Down Width ( (w^<em>) ) for ( (n) ) Bundled Tows: ( w^</em> = 4d \ (n \ N_f)^{0.5} )</td>
<td>1.10 ( (n)^{0.5} ) mm ( (43 \text{ n}^{0.5} \text{ mil}) )</td>
<td>1.12 ( n^{0.5} ) mm ( (44 \text{ n}^{0.5} \text{ mil}) )</td>
<td>1.22 ( n^{0.5} ) mm ( (48 \text{ n}^{0.5} \text{ mil}) )</td>
<td>1.25 ( (n)^{0.5} ) mm ( (50 \text{ n}^{0.5} \text{ mil}) )</td>
<td>1.26 ( (n)^{0.5} ) mm ( (50 \text{ n}^{0.5} \text{ mil}) )</td>
<td>1.00 ( (n)^{0.5} ) mm ( (39 \text{ n}^{0.5} \text{ mil}) )</td>
</tr>
</tbody>
</table>

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

Through Thick Angle Interlock w/o Warp Stuffers

Through Thick Angle Interlock w/ Warp Stuffers

Ply-to-Ply Angle Interlock, TEAM Inc recommendation

Warp Weaver

Fill Stuffer

Warp Stuffer

3D Orthogonal -1 float
3D Architecture Design Activities and Process Constraints

**Objective:** Generate design curves for the key process, geometric, and mechanical properties of 3D architectures for virtual composites based on the following constraints that are applicable to SiC/SiC CMC reinforced by high-performance high-stiffness SiC fibers:

- Keep fibers as **straight** as possible in-plane for highest in-plane MCS and rupture strength
- Avoid fiber fracture caused by bending and abrasion of the best stoichiometric SiC fibers:
  - Warp weaver bend radius > fiber fracture radius
- Maximize total fiber volume fraction for sufficient multi-directional reinforcement
- Assure sufficient fiber content in the x, y, z directions to meet typical component multi-directional structural requirements.

**Key:** high effective z fiber fraction for thru-thickness properties
Current Down-selected 3D Architectures for SiC/SiC Composites

• Based on performance characteristics desired such as total volume content, panel height, tow float, tow bundle, directional fiber volume content, and ease of fabrication, a design tool was used to down-select three types of 3D modified layer-to-layer architectures of high-stiffness high-performance Hi-Nicalon Type S SiC fibers.
• Preforms of these architectures were fabricated by TEAM and will eventually be used to fabricate SiC/SiC panels for property evaluation.
• Design tool predictions were compared to those measured on the final preforms.
Process Property Curves for Modified 3D Layer-to-Layer Angle Interlock

Curves for Layer-to-Layer Angle Interlock
Without Warp Stuffers and Four Warp Weavers per Column
2-end fill stuffer, no served tow, (warp weaver = 26 epi)

- Height and Bend Radius (mil)
- Weave Angle (degrees)
- Fill Ends per Inch

HNS Limit

Symbols:
- ■ Angle
- ▲ BendRadius
- × Height

www.nasa.gov
Fiber Volume Curves for Modified 3D Layer-to-Layer Angle Interlock

Fiber Volume Content Curve for Layer-to-Layer Angle Interlock
Without Warp Stuffers and Four Warp Weavers per Column
2-end fill stuffer, no served tow, (warp weaver = 26 epi)

Fiber Volume Fraction (%)

Fill Ends per Inch
## Design Tool Prediction of T.E.A.M., Inc Preforms

<table>
<thead>
<tr>
<th>Style Number</th>
<th>Design Number</th>
<th>Weave</th>
<th>Panel ID</th>
<th>Warp per column</th>
<th>Warp columns per Inch</th>
<th>Fills per column</th>
<th>Fill columns per Inch</th>
<th>Panel thickness</th>
<th>Fiber volume by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0039-01-01</td>
<td>4</td>
<td>26</td>
<td>4.5</td>
<td>19.0</td>
<td>0.059</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0039-01-02</td>
<td>4</td>
<td>26</td>
<td>4.5</td>
<td>19.0</td>
<td>0.060</td>
<td>32%</td>
</tr>
<tr>
<td>0039-01</td>
<td>1A</td>
<td>Mod L-L</td>
<td>0039-01-03</td>
<td>4</td>
<td>26</td>
<td>4.5</td>
<td>20.0</td>
<td>0.062</td>
<td>33%</td>
</tr>
</tbody>
</table>

### Visualization Tool Results (CompGen)

| Mod L-L | 4 | 26 | 4.5 | 20.0 | 0.060 | 34% |

### Visualization Tool Design Property Results

<table>
<thead>
<tr>
<th>Weaver Angle</th>
<th>Vfx</th>
<th>Vfy</th>
<th>Vfz</th>
<th>Bend Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.03°</td>
<td>22.4%</td>
<td>11.5%</td>
<td>2.0%</td>
<td>405.1 mils</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Style Number</th>
<th>Design Number</th>
<th>Weave</th>
<th>Panel ID</th>
<th>Warp per column</th>
<th>Warp columns per Inch</th>
<th>Fills per column</th>
<th>Fill columns per Inch</th>
<th>Panel thickness</th>
<th>Fiber volume by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0039-02-01</td>
<td>4</td>
<td>26</td>
<td>4.5</td>
<td>35.0</td>
<td>0.059</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0039-02-02</td>
<td>4</td>
<td>26</td>
<td>4.5</td>
<td>35.0</td>
<td>0.060</td>
<td>47%</td>
</tr>
<tr>
<td>0039-02</td>
<td>1B</td>
<td>Mod L-L</td>
<td>0039-02-03</td>
<td>4</td>
<td>26</td>
<td>4.5</td>
<td>35.0</td>
<td>0.062</td>
<td>46%</td>
</tr>
</tbody>
</table>

### Visualization Tool Results (CompGen)

| Mod L-L | 4 | 26 | 4.5 | 36.8 | 0.063 | 42% |

### Visualization Tool Design Property Results

<table>
<thead>
<tr>
<th>Weaver Angle</th>
<th>Vfx</th>
<th>Vfy</th>
<th>Vfz</th>
<th>Bend Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.28°</td>
<td>16.0%</td>
<td>25.2%</td>
<td>3.5%</td>
<td>104.3 mils</td>
</tr>
</tbody>
</table>

www.nasa.gov
**Design Tool** for Predicting and Optimizing Architecture Effects on Matrix Cracking Strength for Dense SiC/SiC

**Key Architecture Factors Controlling Multi-Directional MCS:**
- $f_0 = \text{effective fiber volume fraction in test direction (needs to be maximized)}$
- $h_\perp (\text{mm}) = \text{maximum height of tows perpendicular to test direction (needs to be minimized)}$

MCS Prediction for Modified 3D Layer-to-Layer Angle Interlock

Predicted MCS for Layer-to-Layer Angle Interlock
Without Warp Stuffers and Four Warp Weavers per Column
2-end fill stuffer, no served tow, (warp weaver = 26 epi)

Minimum bend radius
Limit - 40 mils

Desired bend radius
Limit - 60 mils

- MCSX
- MCSY
- MCSZ

Fill Ends per Inch
Summary and Future Directions

- The design tool provides design curves that allow a simple and quick way to examine multiple factors that can influence the processing and key properties of the preforms and their final SiC-reinforced ceramic composites without over obligating financial capital for the fabricating of materials.
- Tool predictions for process and fiber fraction properties have been validated for a HNS 3D preform.
- The virtualization aspect of the tool will be used to provide a quick generation of solid models with actual fiber paths for finite element evaluation to predict mechanical and thermal properties of proposed composites as well as mechanical displacement behavior due to creep and stress relaxation to study load sharing characteristic between constitutes for better performance.
- Tool predictions for the fiber controlled properties of the SiC/SiC CMC fabricated from the HNS preforms will be valuated and up-graded from the measurements on these CMC.