Physics-Based Design Tools for Lightweight Ceramic Composite Turbine Components with Durable Microstructures

Under the Supersonics Project of the NASA Fundamental Aeronautics Program, modeling and experimental efforts are underway to develop generic physics-based tools to better implement lightweight ceramic matrix composites into supersonic engine components and to assure sufficient durability for these components in the engine environment. These activities, which have a cross-cutting aspect for other areas of the Fundamental Aero program, are focusing primarily on improving the multi-directional design strength and rupture strength of high-performance SiC/SiC composites by advanced fiber architecture design. This presentation discusses progress in tool development with particular focus on the use of 2.5D-woven architectures and state-of-the-art constituents for a generic un-cooled SiC/SiC low-pressure turbine blade.
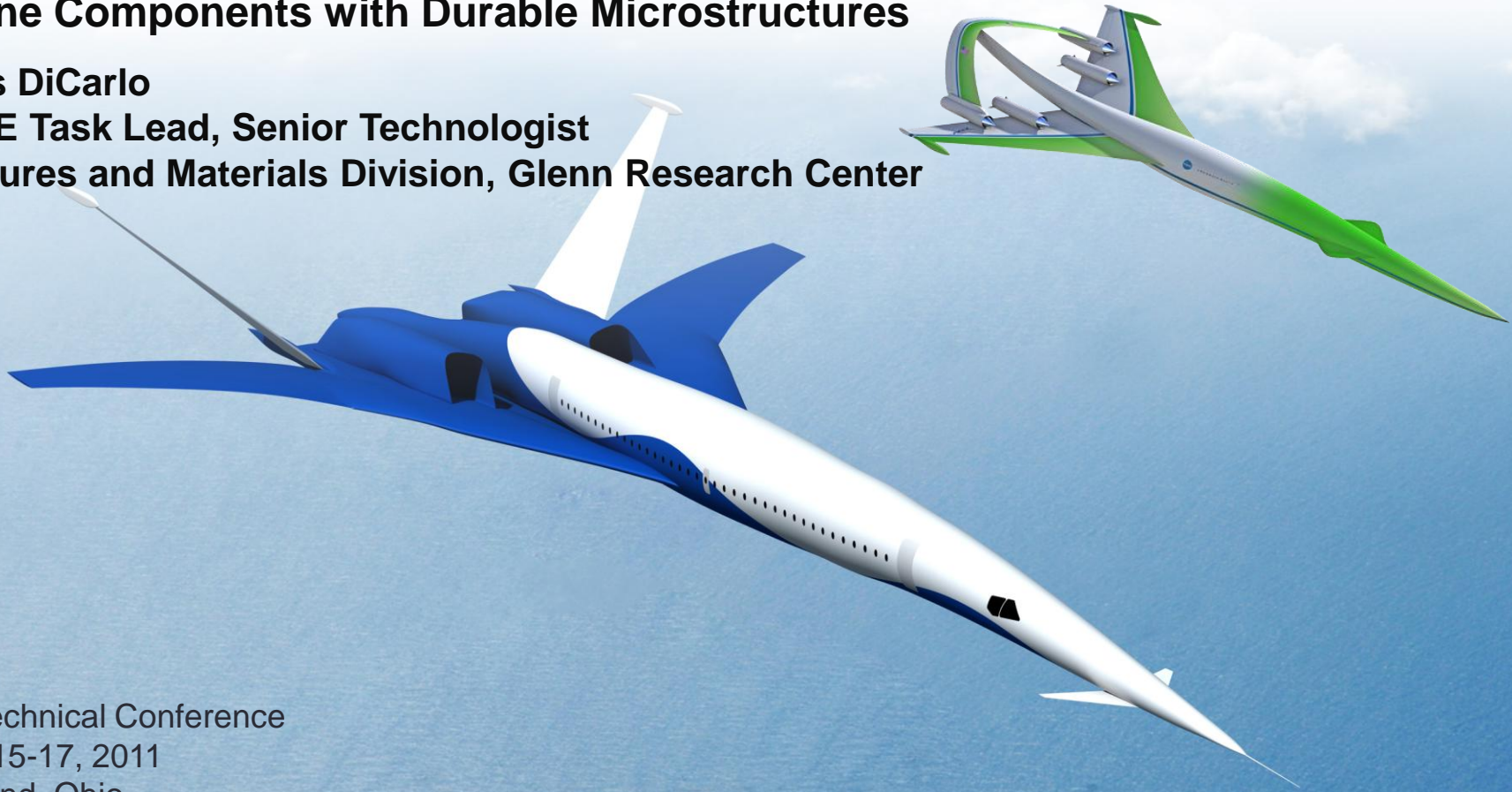
Fundamental Aeronautics Program
Supersonics Project

Physics-Based Design Tools for Lightweight Ceramic Composite Turbine Components with Durable Microstructures

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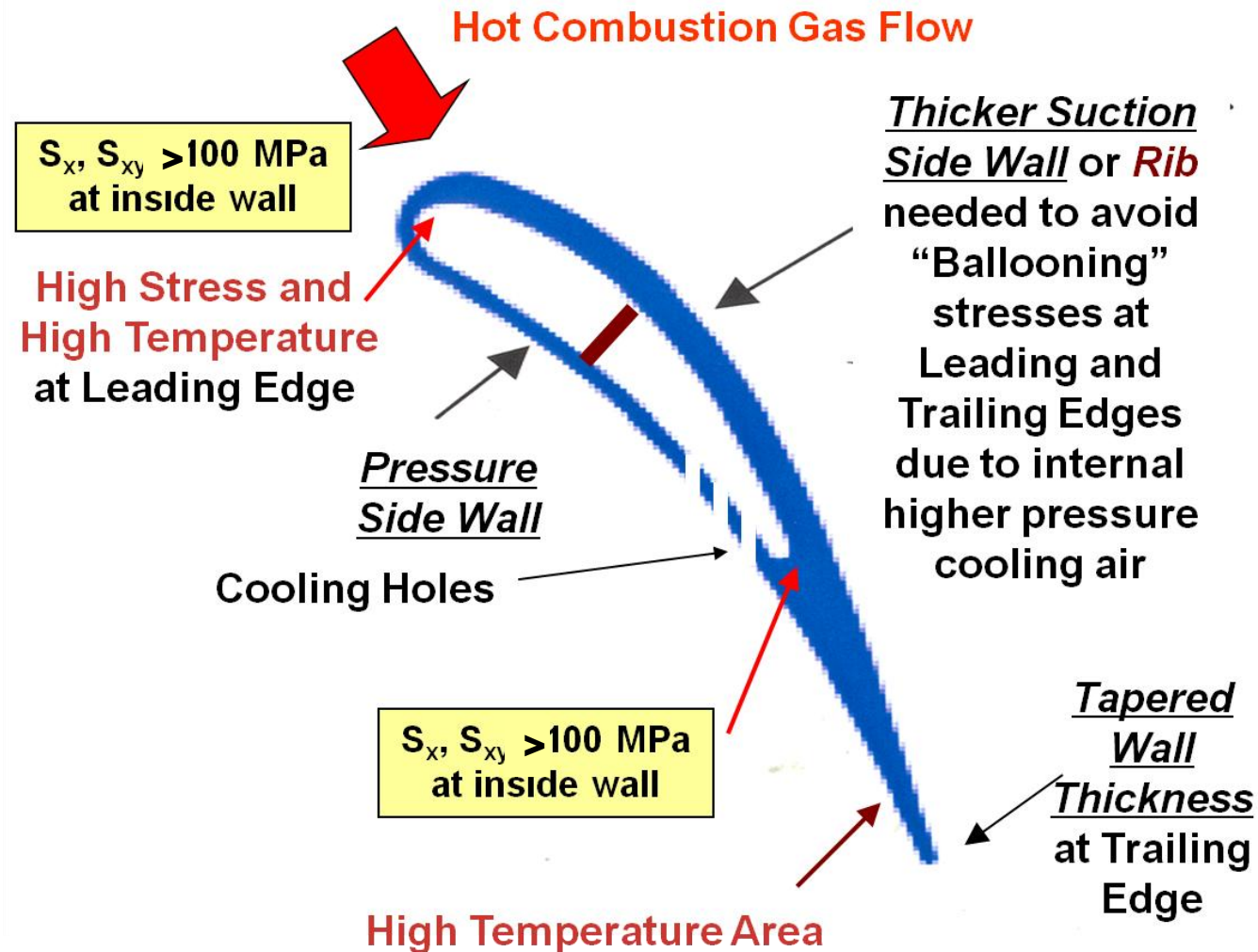# Light Weight, Durable Engines

Tech Challenge – Develop materials and validated modeling methods which can be incorporated into structural turbine engine components that need to withstand the service and environmental conditions of supersonic flight

Task Background

- Replacing metals in the hot-section components of supersonic engines with lightweight high-performance SiC fiber-reinforced SiC matrix **(SiC/SiC)** ceramic composites can offer multiple benefits:
  - Higher engine efficiency and thrust
  - Reduced weight and emissions
  - Longer and more reliable component life
- However, technical challenges exist today not only in the fabrication of complex-shaped turbine components, but also in assuring the SiC/SiC component remains durable under supersonic service conditions

Task Objective - Address these challenges in a generic manner by developing and validating physics-based concepts, tools, and process/property models for the design and lifing of SiC/SiC turbine components in general and turbine blades in particular

# Multiple Fabrication and Thermo-Structural Challenges for Cooled SiC/SiC Airfoil Component

**Hot Combustion Gas Flow**

S_x, S_{xy} >100 MPa at inside wall

High Stress and High Temperature at Leading Edge

Thicker Suction Side Wall or *Rib* needed to avoid "Ballooning" stresses at Leading and Trailing Edges due to internal higher pressure cooling air

Pressure Side Wall

Cooling Holes

S_x, S_{xy} >100 MPa at inside wall

Tapered Wall Thickness at Trailing Edge

High Temperature Area

Task Approach

- Without afterburner, last stage turbine temperatures in commercial supersonic engine will be hotter, and thus will need SiC/SiC with capability to at least 2400°F.

- Select last stage *Low Pressure Turbine (LPT) SiC/SiC turbine blade* for <u>tool and model development</u>, not only because it is large enough to offer weight-savings, but also it can be *uncooled* to reduce cooling air requirements

- Uncooled concept has multiple advantages:
  - Eliminates stress risers due to cooling holes
  - Minimizes thermal and pressure stresses thru airfoil wall
  - Eliminates complexity, weight, and cost issues with internal cooling schemes

- Select hollow airfoil for ease of matrix infiltration, reduced thermal shock concerns, and prototype for eventual cooling schemes

- Select *NASA Type-1SiC/SiC CMC* based on 2400°F capability, high structural performance, high thermal conductivity, capability for complex fiber architectures, and extensive property database

# Key SiC/SiC Property Requirements for Durable Turbine Components
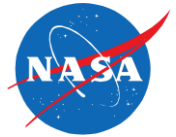
- **Multi-Directional Tensile Strength and Damage Tolerance**

Stress

Ultimate

Matrix Cracking
Strength or Design Limit
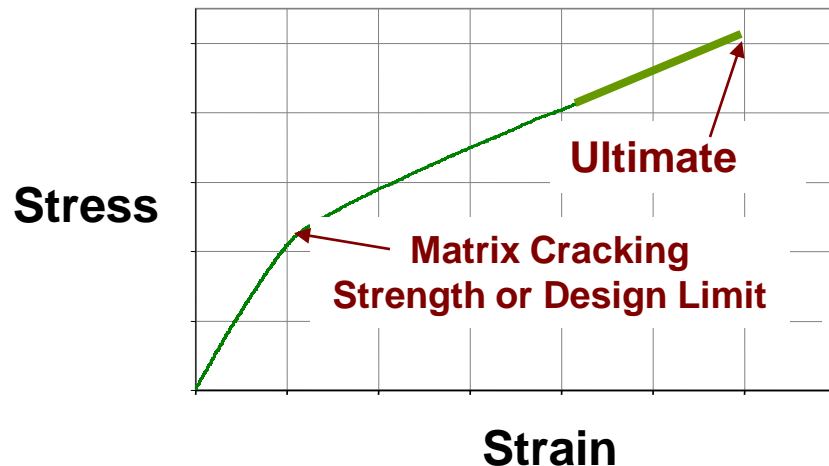
Strain

- **High Matrix Cracking Strength** *(MCS)* **and Strain**

- **High Ultimate Strength/Strain**

- **UTS > MCS in all directions**

- **Intrinsic Time/Temperature Structural Capability**
  - **Constituent microstructural stability**
  - **High Tensile Creep and Rupture Strength** *(RS)*
- **High Thermal Conductivity** (minimize thermal stress)
- **Environmental Durability** (oxygen, water vapor)

NASA Approach for High-Performance SiC/SiC Composites

Partial CVI SiC Matrix

Stoichiometric SiC Fiber

CVI BN Fiber Coating
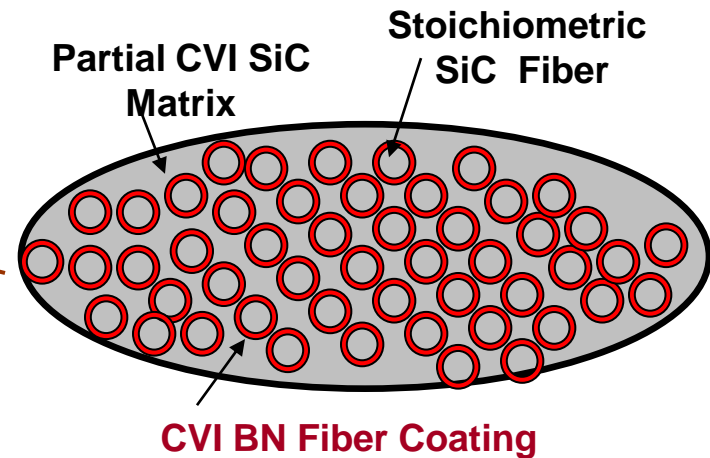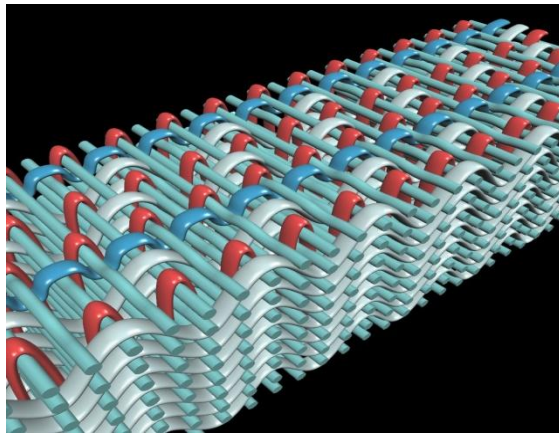
• Textile-form 2D, 2.5D, and 3D fiber preforms consisting primarily of multi-fiber tows of small-diameter, high-strength, near-stoichiometric SiC fibers, such as the NASA-developed Sylramic-iBN fiber

• Use chemical vapor infiltration (CVI) to form a BN-based interface coating on SiC fibers

• Partially infiltrate a protective CVI SiC matrix within and around tows

• Depending on the application, infiltrate remaining preform porosity with SiC-based matrices using one of many approaches such as CVI, PIP, Slurry, etc, and their hybrid combinations

• *NASA Type 1 Matrix*: CVI SiC + SiC slurry + Melt-Infiltrated (MI) silicon
   • Advantages: large database, high density for high conductivity, low permeability, and MCS controlled only by fiber architecture

Task Activities and Progress

Structural Blade Analyses:

Analytical and FE modeling of Type-1 SiC/SiC material in a generic LPT blade with a design and FE analyses provided, respectively, by Rolls Royce Liberty Works and Diversitech under AF SAA.

Minimum MCS allowables at Blade Root:

σ_x **(radial) > 180 MPa**

σ_y **(chord) > 100 MPa**

σ_z **(axial) > 50 MPa**

Minimum RS allowable at Mid-Span

σ_x **(radial) > 100 MPa**

SiC/SiC Fiber Architectural Studies:

Experimental and physics-based modeling studies aimed at understanding and designing *optimum fiber architectures* to meet LPT blade key thermo-structural requirements

SiC/SiC Blade 3D and 2.5D Fabrication Studies:

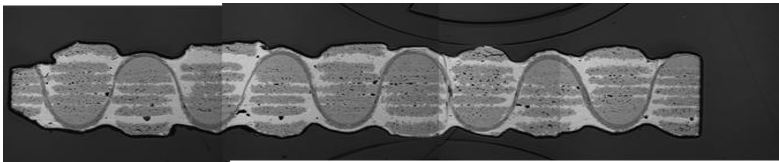NASA NRA Contracts: 3TEX, Teledyne Scientific; Initiation of in-house formability studies

Radial (x)

Thru-Wall (z)

(y)

Blade Wall at Root

H

Attachment

Hollow Cavity
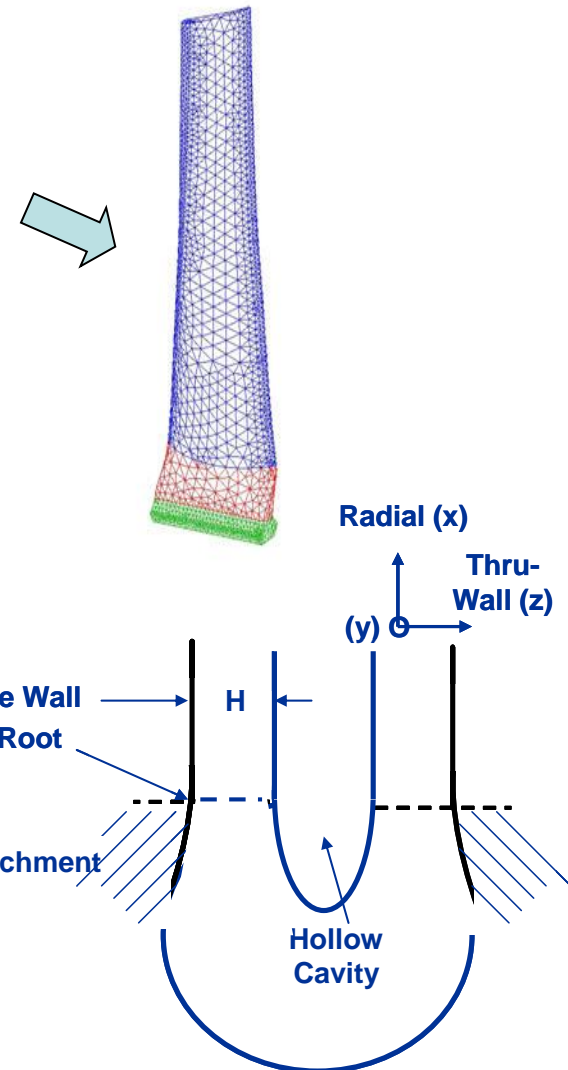
Acoustic Emission Used to Study Architecture Effects on In-Plane Matrix Cracking Strength (MCS) of Type-1 SiC/SiC
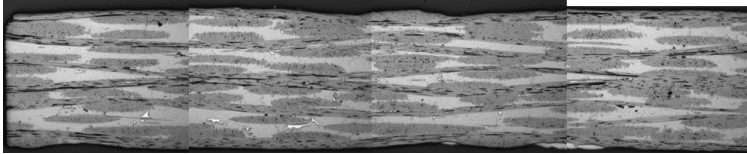
2D Five-harness Satin
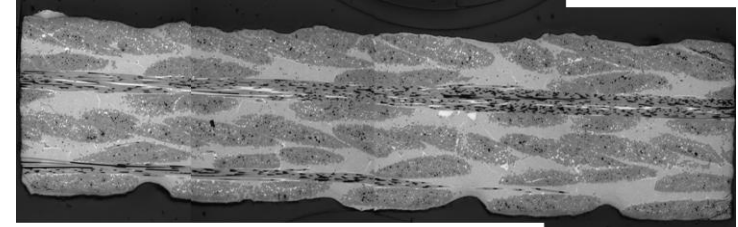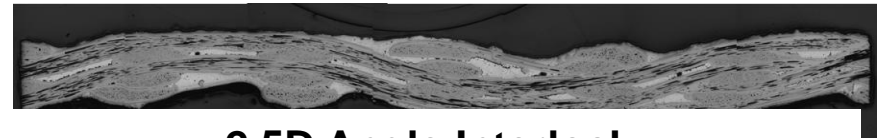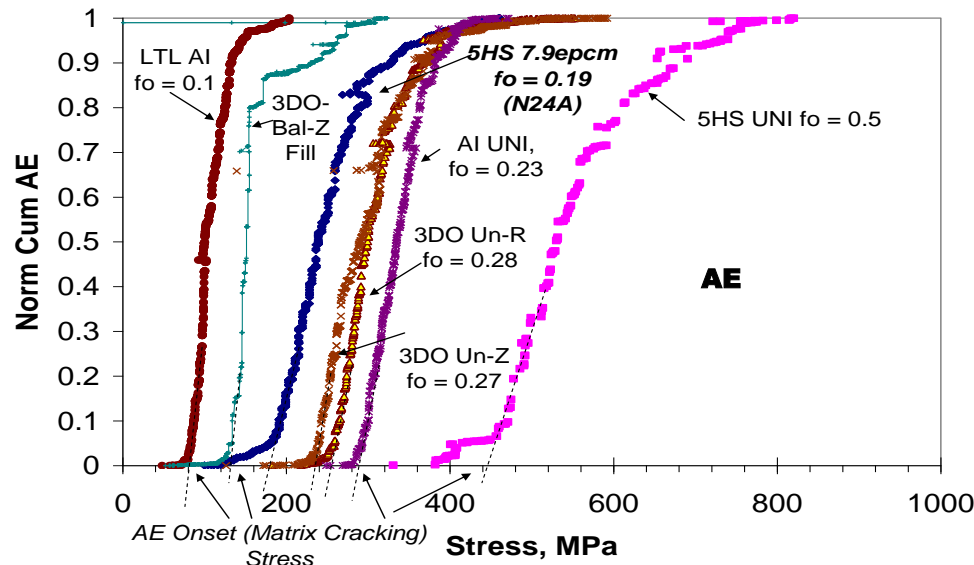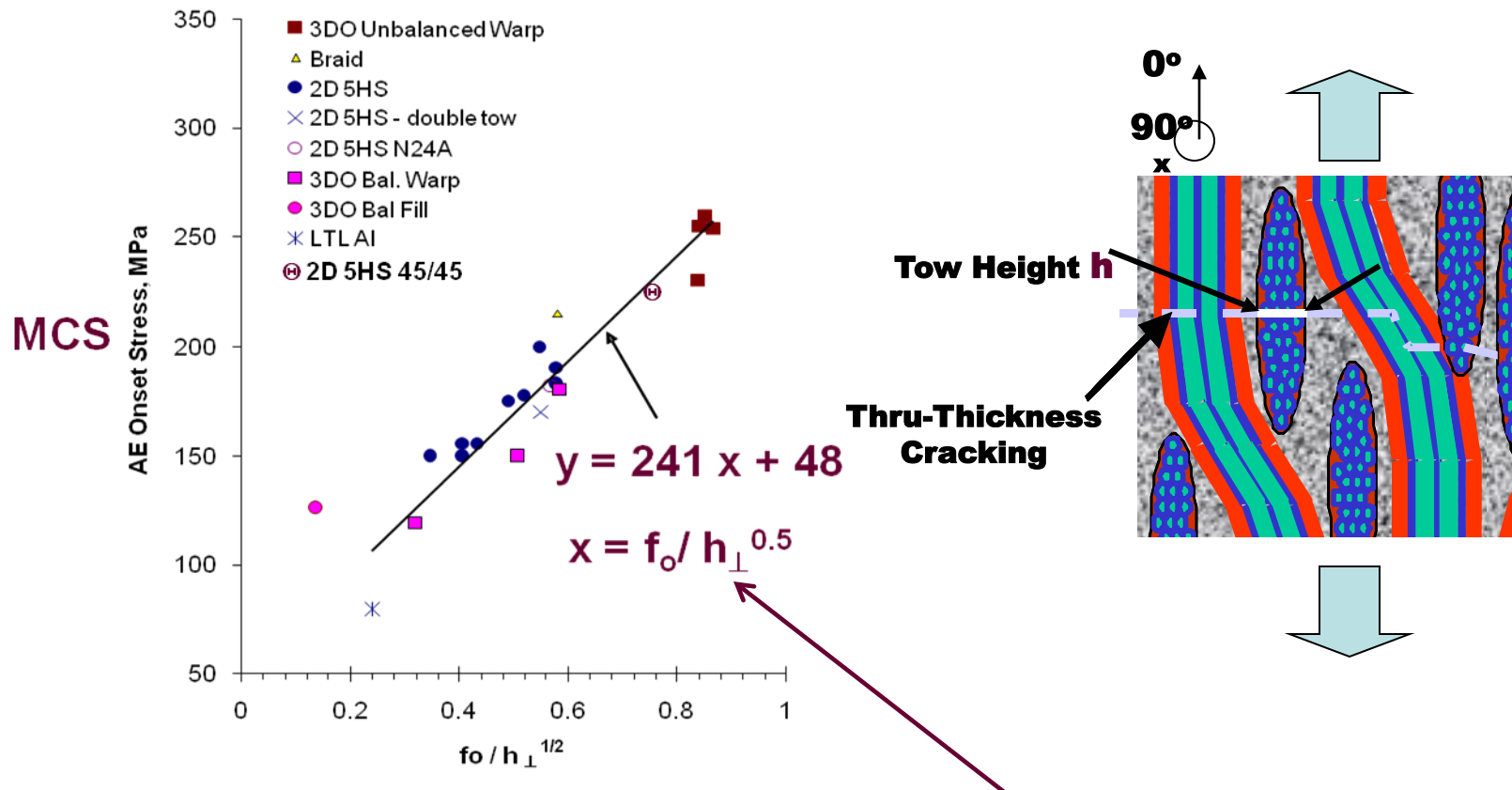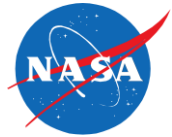

2D Braid

3D Orthogonal

2.5D Angle Interlock

Task has demonstrated that In-plane onset stress for thru-thickness matrix cracking can be increased from 100 to ~300 MPa by __proper architecture selection__

(Key for SiC/SiC blades)

Physics-Based Design Tool Developed for Predicting Architecture Effects on In-Plane MCS for Type-1 SiC/SiC


MCS

Legend:
- ■ 3DO Unbalanced Warp
- △ Braid
- ● 2D 5HS
- ✕ 2D 5HS - double tow
- ○ 2D 5HS N24A
- ■ 3DO Bal. Warp
- ● 3DO Bal Fill
- ✳ LTL Al
- ⊕ 2D 5HS 45/45

$$y = 241\,x + 48$$

$$x = f_o / h_\perp^{0.5}$$

Axis labels: AE Onset Stress, MPa (y-axis); $f_o / h_\perp^{1/2}$ (x-axis)

0°, **90°**, **x**

Tow Height h

Thru-Thickness Cracking

Key Architecture Factors Controlling Multi-Directional MCS:

f_0 = effective fiber volume fraction in test direction

= f (0° stuffers) **OR** = [f (+/-θ weavers)][cos (θ)], whichever largest

$h_\perp$ (mm) = maximum height of tows perpendicular to test direction

Larson-Miller Design Tool Developed for Predicting Architecture Effects on In-Plane RS for Type-1 SiC/SiC
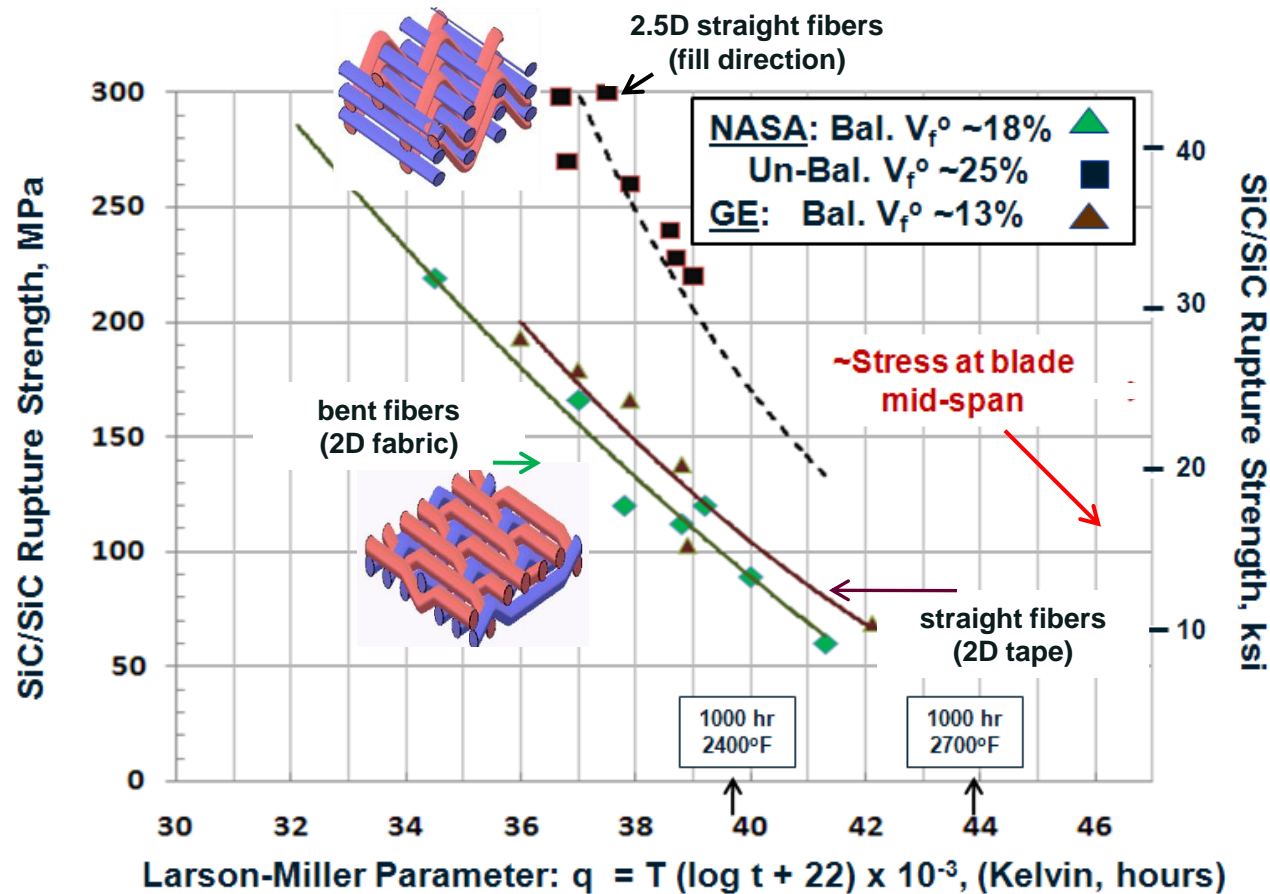

- *Increasing fiber volume fraction in loading direction not only improves SiC/SiC cracking strength, but also SiC/SiC rupture strength*
- *For hundreds of hours at ~2400°F and below, unbalanced 2.5D fiber architectures <u>with straight fibers</u> in radial direction can significantly improve high-temperature SiC/SiC blade durability in comparison to 2D architectures*

2.5D Sylramic-iBN Fiber Architectures offer Other Important Benefits for SiC/SiC Components
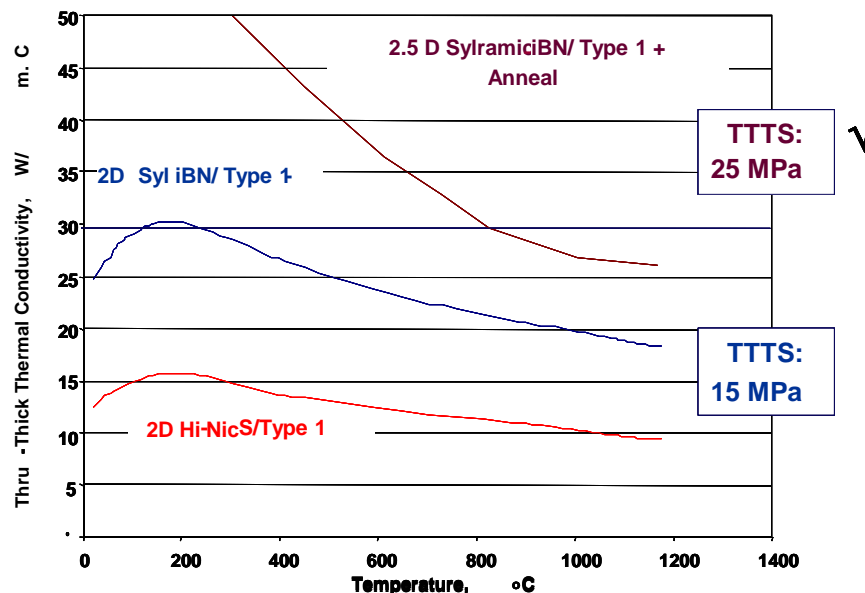

2400F Impact
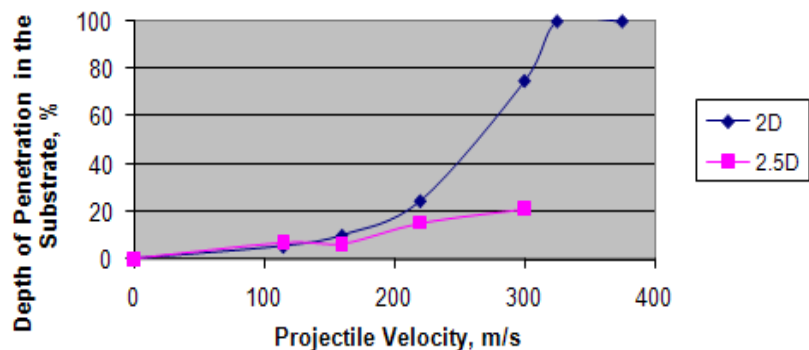
Task has demonstrated unbalanced 2.5D textile-formed architectures offer not only improved matrix cracking strength, creep-rupture resistance, thru-thickness damage tolerance and tensile strength, but also improved thermal conductivity and reduced in-service thermal stresses provided the constituents are highly conductive, such as Sylramic-iBN fiber + CVI-SiC matrix

Analytical Modeling of Integral 2.5D Angle-Interlock Preforms for LPT Blade
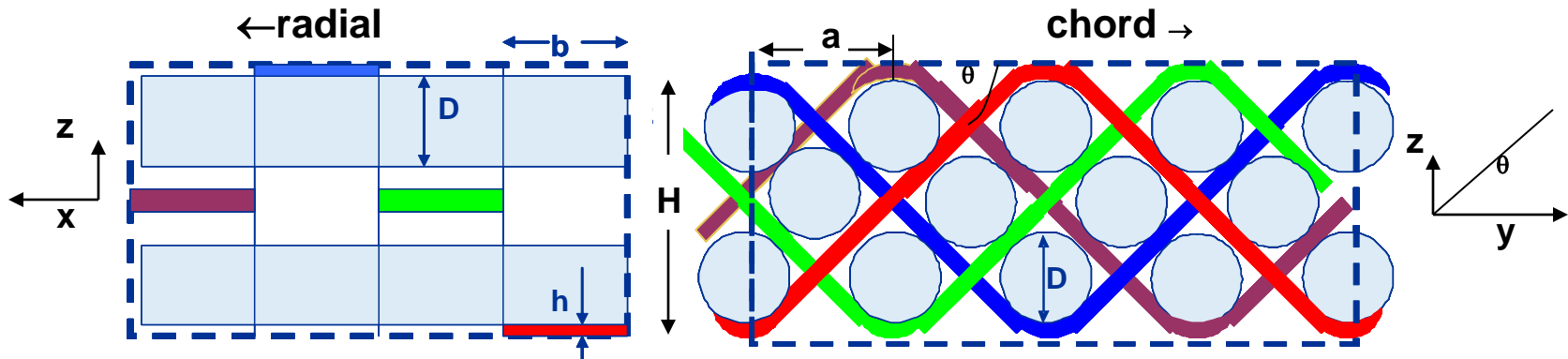
- Only Warp stuffers ⬭ of bundled single tows in radial (x) direction
- Only Through-Thickness Angle-Lock Fill Weavers ▬ of bundled single tows to achieve reinforcement in both chord (y) and wall (z) directions

Key Factors to be modeled for blade wall in root area

- *Optimum Warp Stuffer size, shape, and volume fraction:*
    - to provide σ_x (MCS) > 180 MPa,
    - to not severely degrade σ_y (MCS) and σ_z (MCS) due to tunnel cracking,
    - to allow sufficient CVI SiC infiltration, and
    - to avoid excessive bend fracture of fill Sylramic fibers during preforming
- *Optimum Fill Weaver size, volume fraction, and angle θ to provide σ_x (MCS)* requirement and highest possible values for σ_y (MCS) and σ_z (MCS)
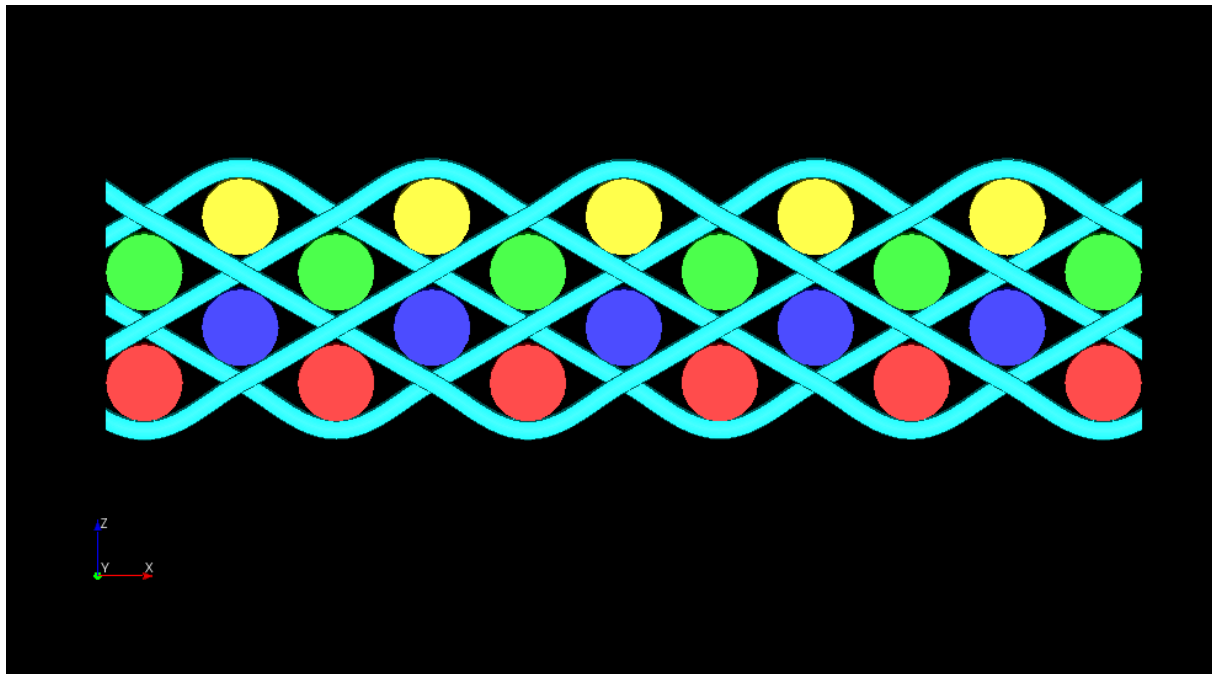
Software Graphics Program Developed for 3D Visualization of SiC/SiC Preforms with 2.5D Fiber Architectures

Single Tow Area = 1; Fiber Packing = 65 %
Warp Stuffers: **N_w = 4, circular shape, 4 plies**, max tow fraction
Fill Weavers: **N_F = 1**, rectangular shape, angle = 30°, gaps = 0


- *Initial 2.5D architecture has been optimized and practiced at a commercial preformer, but due to low tension in fill weaver tows and high fiber stiffness, final preform ballooned to 3 times the desired thickness*
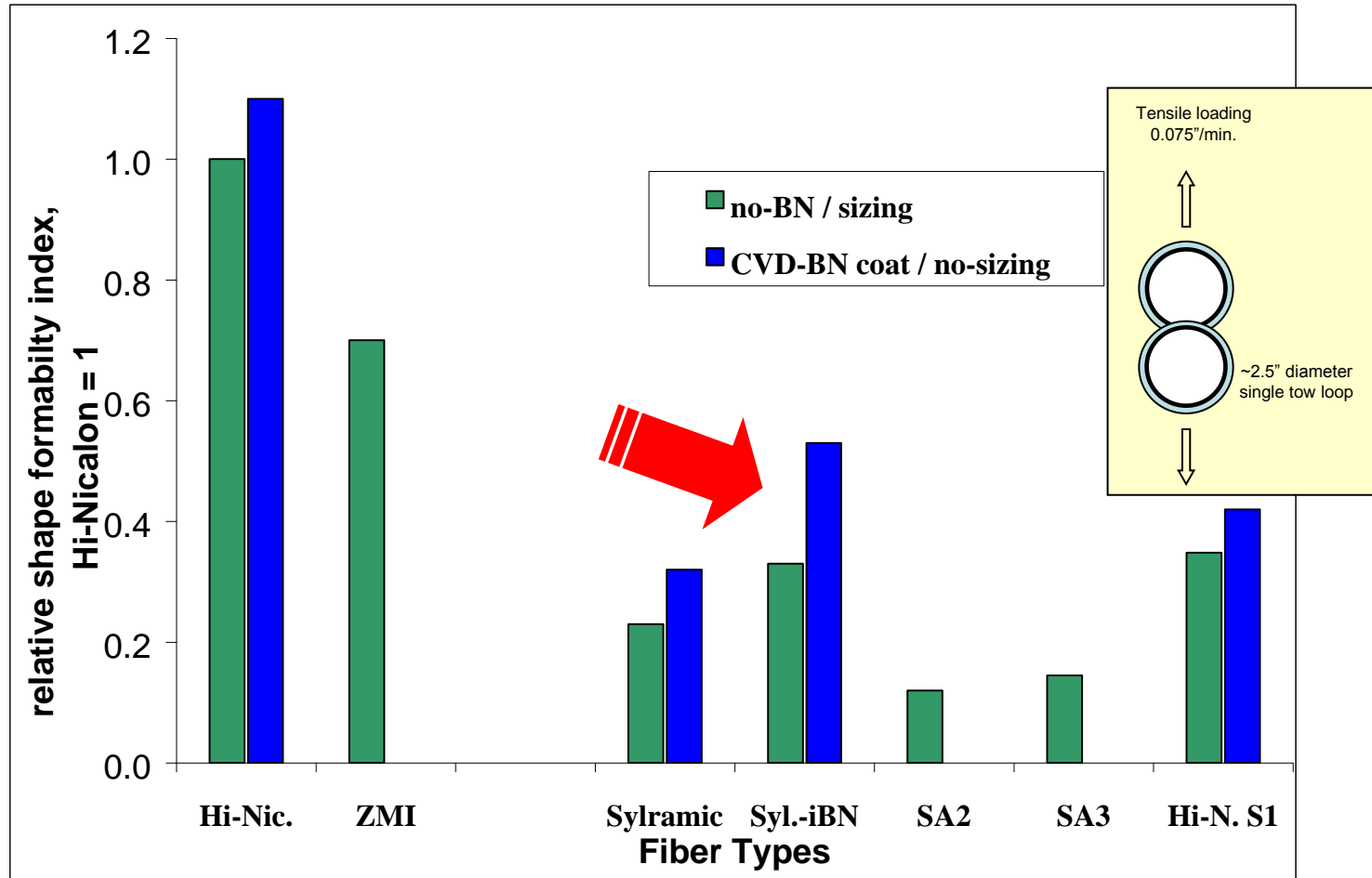
Visualization Software Tool Being Developed for User-Friendly SiC/SiC Architecture Design

Benefits: local directional fiber content, preform permeability for matrix infiltration
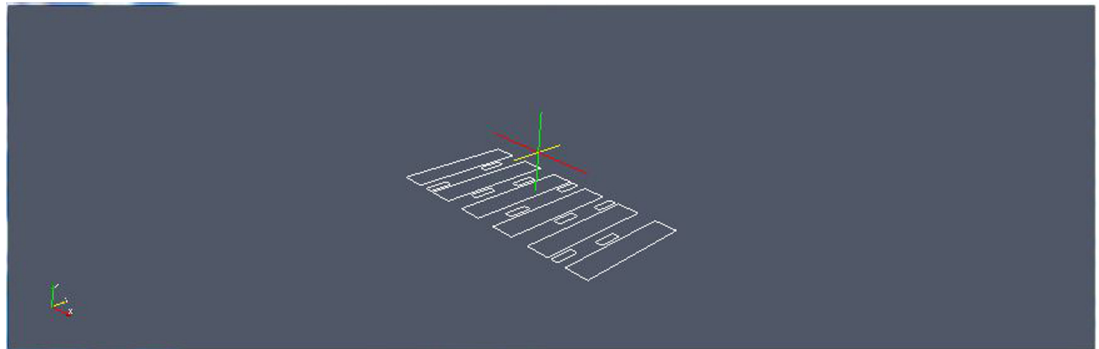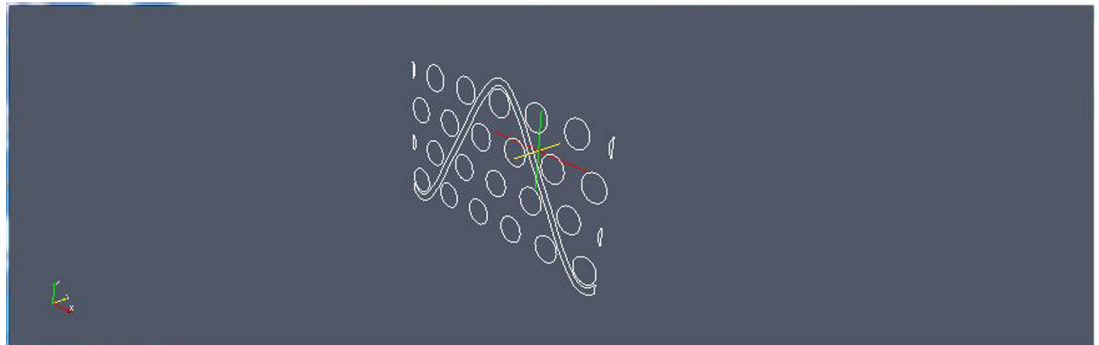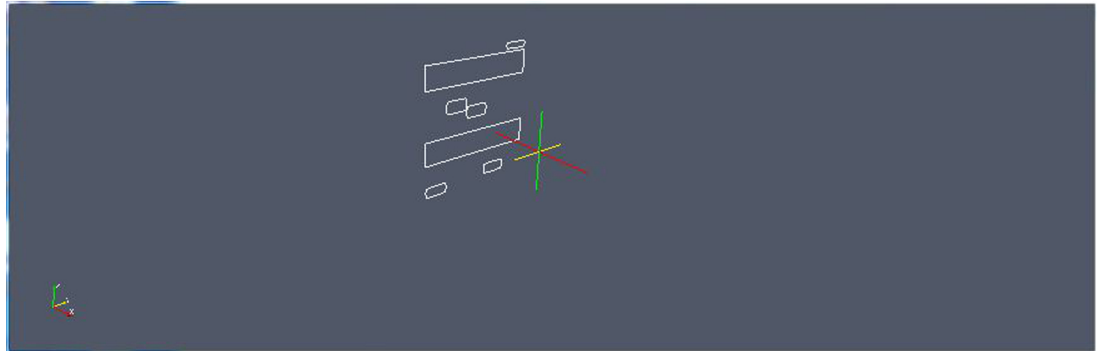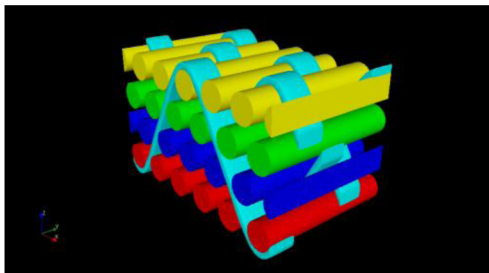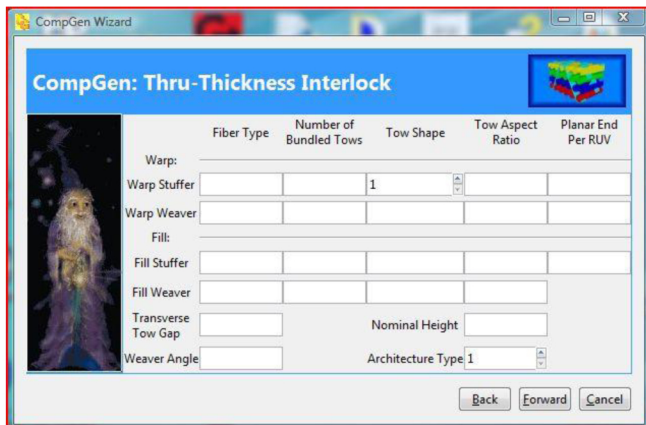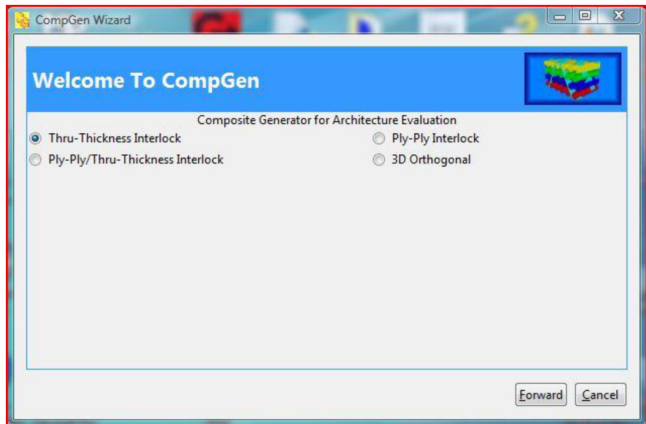
Tests and Remedies Being Developed for Formability Challenges with High-Modulus SiC Fibers

To aid in complex architecture design, NASA GRC has developed shape formability test for SiC tows

Two NRA Contracts for Design and Demo of SiC/SiC Airfoils with 3D Architectures of High-Modulus SiC Fibers
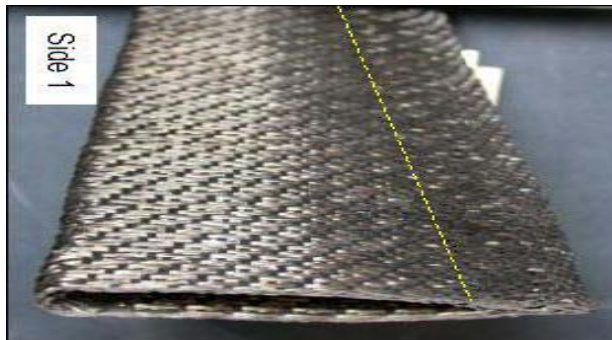
3TEX has used *3D braiding* for airfoil fabrication:
   particular concerns: thin trailing edge formation, sufficient thru-thickness fiber content, and low chord fiber content in airfoil walls due to need for high braid angle

On the other hand, **Teledyne Scientific** has successfully used *2.5D weaving* for fabrication of a complex-shaped preform for a LPT airfoil:

Task Summary

- Implementation of high-performance SiC/SiC ceramic composites into supersonic gas turbine components, like LPT blades, will require complex fiber architecture designs and innovative formation processes. With focus on NASA Type-1 SiC/SiC composites reinforced by 2.5D architectures, this FA Supersonics Task is currently examining these challenges and attempting to overcome them with various innovative modeling and process tools.

- Initial design and commercial manufacturing tools have been developed for formation of SiC/SiC LPT blade airfoils reinforced by architectures with thru-thickness high-modulus SiC fibers. The design tools are based on experimental results that show these architectures, in comparison to conventional 2D architectures, can provide more structurally durable microstructures and enhanced thermo-structural properties, such as, greater matrix-cracking strength and rupture strength, which are particularly important for the highly stressed radial direction of a turbine blade.

- Studies are continuing by developing software tools and in-house process and test facilities to down-select and demonstrate generic design approaches for the optimum fiber architectures and preforming methods, not only for the LPT blade airfoil, but also for the blade dovetail. Concerns with fiber formability are also being addressed.

Team Contributors

- **Process/Property Modeling**:

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  Greg Morscher (Univ. Akron)

- **Mechanical Modeling**: **Jerry Lang**

- **Testing**: **Ron Phillips**

- **Software Development**: **Jerry Lang**