Finite Element Modeling of Woven Fabric Composites

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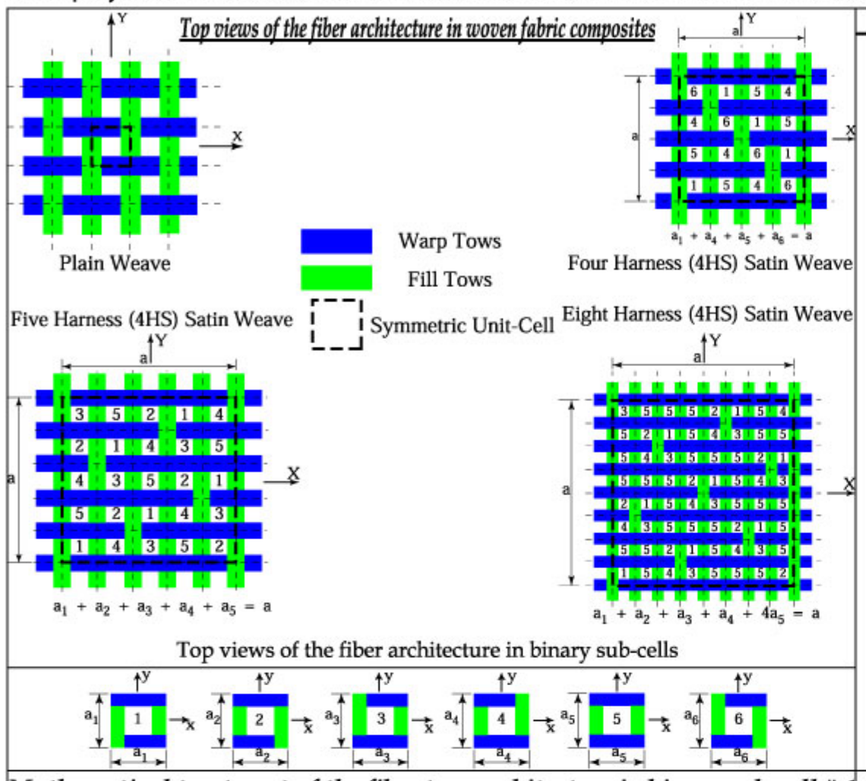
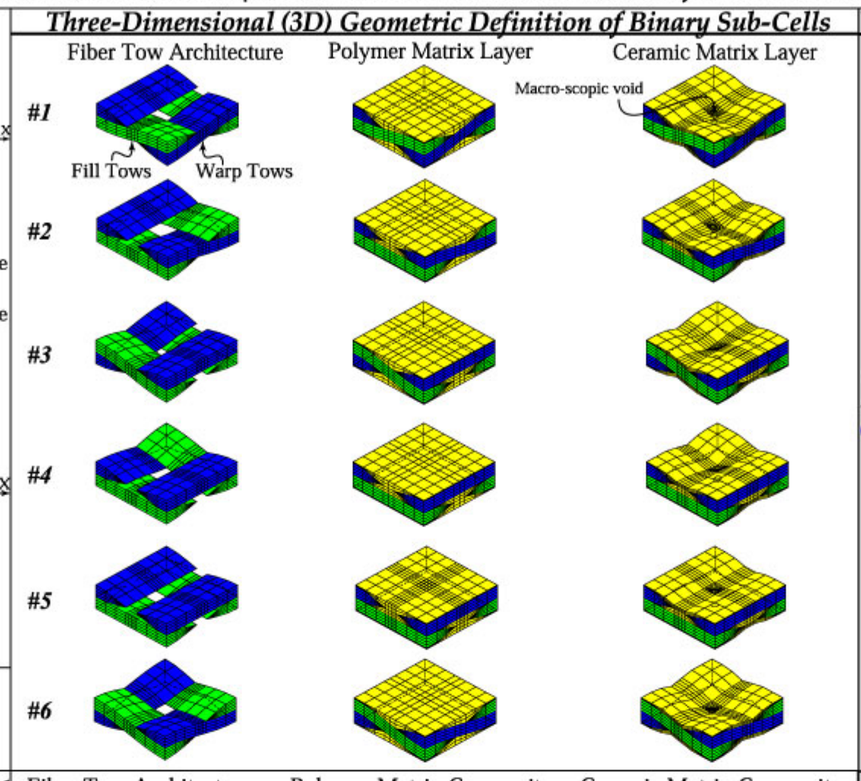
Woven fabric composites have emerged as promising alternative in frontier technology areas such as aerospace, defense and automotive applications. In particular, woven ceramic matrix composites exhibit superior strength at elevated temperatures while maintaining robust stiffness characteristics. Silicon Carbide (SiC) fiber reinforced Chemically Vapor Infiltrated (CVI) SiC matrix woven composites are being evaluated as candidate materials in the hot gas exhaust region of NASA's FasTrac engine which would provide the driving thrust to the future generation X-34 space vehicle. Woven polymer matrix composites are currently employed on the nose cone and wing leading edges of the Space Shuttle. Military striker aircraft such as the Northrup Grumman F/A-22, B-52 bomber and the USS Navy Sea Shadow employ polymer matrix composites toward savings in weight and enhancement of stealth capabilities.

The objective of the present study is to develop reliable analysis tools aimed at understanding the mechanical as well as thermal response of advanced plain and satin weave ceramic and polymer matrix fabric composites. The first step toward successfully characterizing the behavior of woven composites involves the mathematical description of the fiber tow architecture and matrix layer topology within the domain of the symmetric unit cells of these materials. As such, a new class of robust mathematical shape functions are developed and incorporated into the in-house finite element mesh generator DENDRO. The resulting three-dimensional (3D) finite element mesh is employed to conduct fundamental thermo-mechanical finite element studies as needed to capture the elastic micro-fields induced by the combined application of mechanical and processing thermal loads.

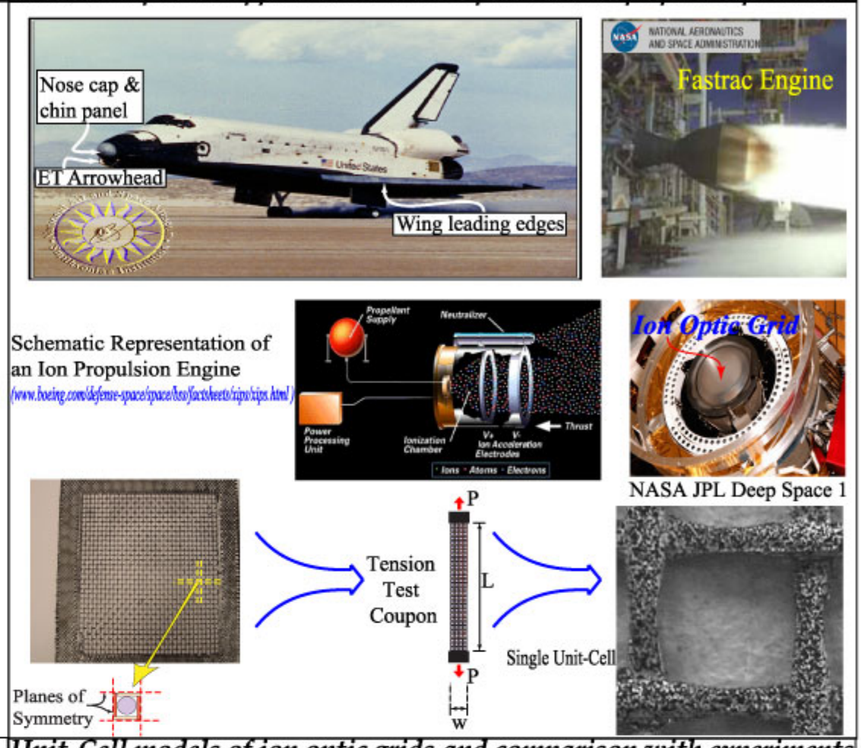
Top views of the fiber architecture in woven fabric composites



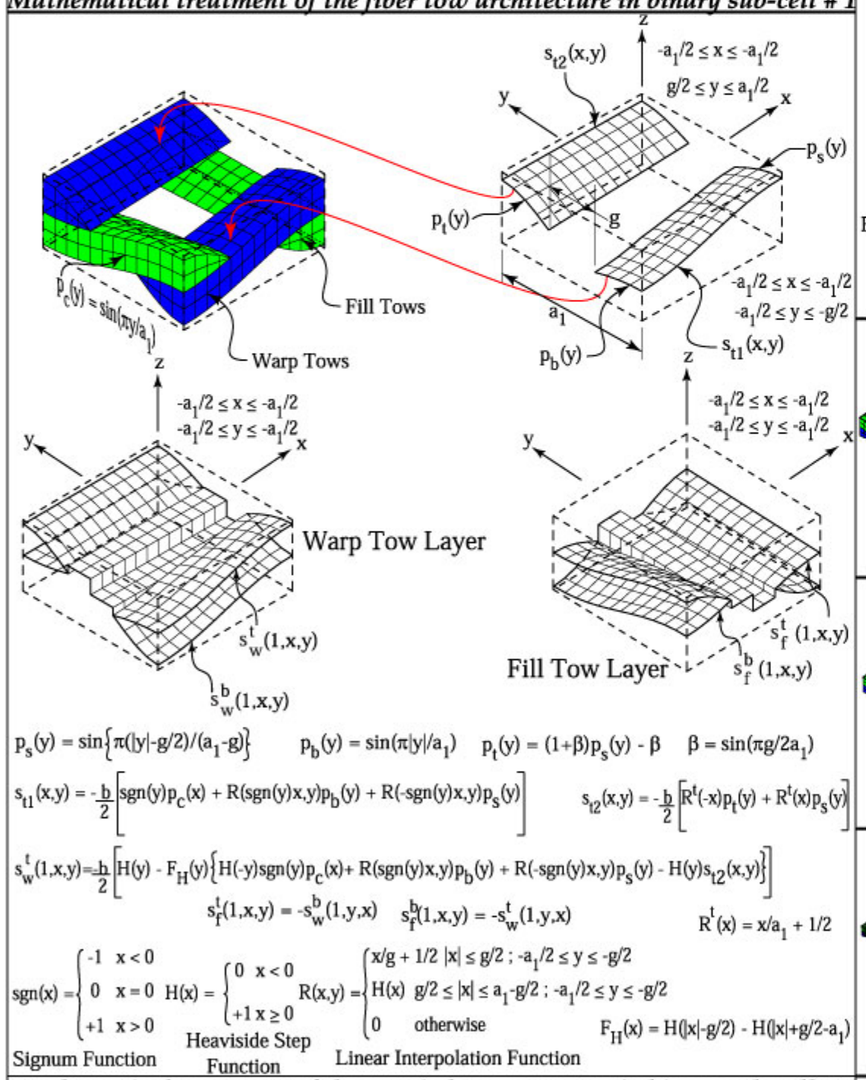
Three-Dimensional (3D) Geometric Definition of Binary Sub-Cells



Woven composites applications in Aerospace and Deep Space exploration



Mathematical treatment of the fiber tow architecture in binary sub-cell # 1



$$p_s(y) = \sin\left\{\pi(|y|-g/2)/(a_1-g)\right\} \qquad p_b(y) = \sin(\pi|y|/a_1) \qquad p_t(y) = (1+\beta)p_s(y) - \beta \qquad \beta = \sin(\pi g/2a_1)$$

$$s_{t1}(x,y) = -\frac{b}{2}\left[\mathrm{sgn}(y)p_c(x) + R(\mathrm{sgn}(y)x,y)p_b(y) + R(-\mathrm{sgn}(y)x,y)p_s(y)\right] \qquad s_{t2}(x,y) = -\frac{b}{2}\left[R^t(-x)p_t(y) + R^t(x)p_s(y)\right]$$

$$s_w^t(1,x,y) = -\frac{h}{2}\left[H(y) - F_H(y)\left\{H(-y)\mathrm{sgn}(y)p_c(x) + R(\mathrm{sgn}(y)x,y)p_b(y) + R(-\mathrm{sgn}(y)x,y)p_s(y) - H(y)s_{t2}(x,y)\right\}\right]$$

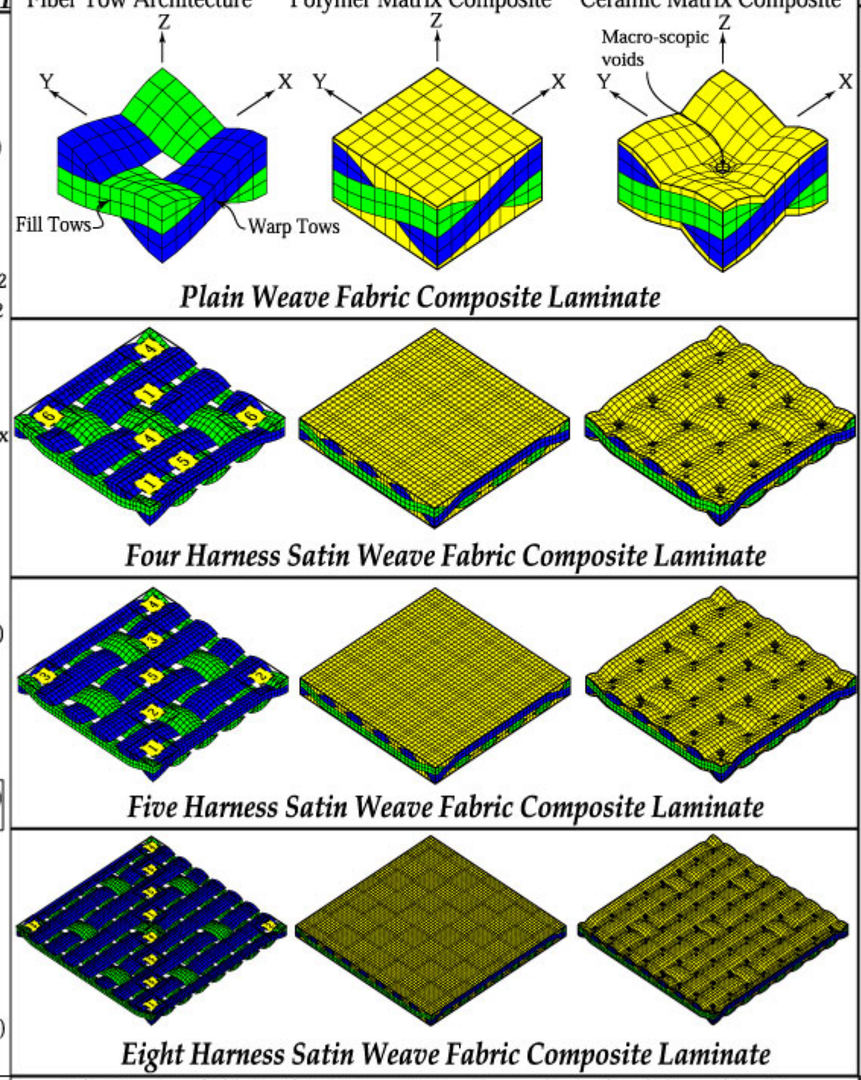
$$s_f^t(1,x,y) = -s_w^b(1,y,x) \qquad s_f^b(1,x,y) = -s_w^t(1,y,x) \qquad R^t(x) = x/a_1 + 1/2$$

$$\mathrm{sgn}(x) = \begin{cases} -1 & x<0 \\ 0 & x=0 \\ +1 & x>0 \end{cases} \quad \text{Signum Function} \qquad H(x) = \begin{cases} 0 & x<0 \\ +1 & x\geq 0 \end{cases} \quad \text{Heaviside Step Function}$$

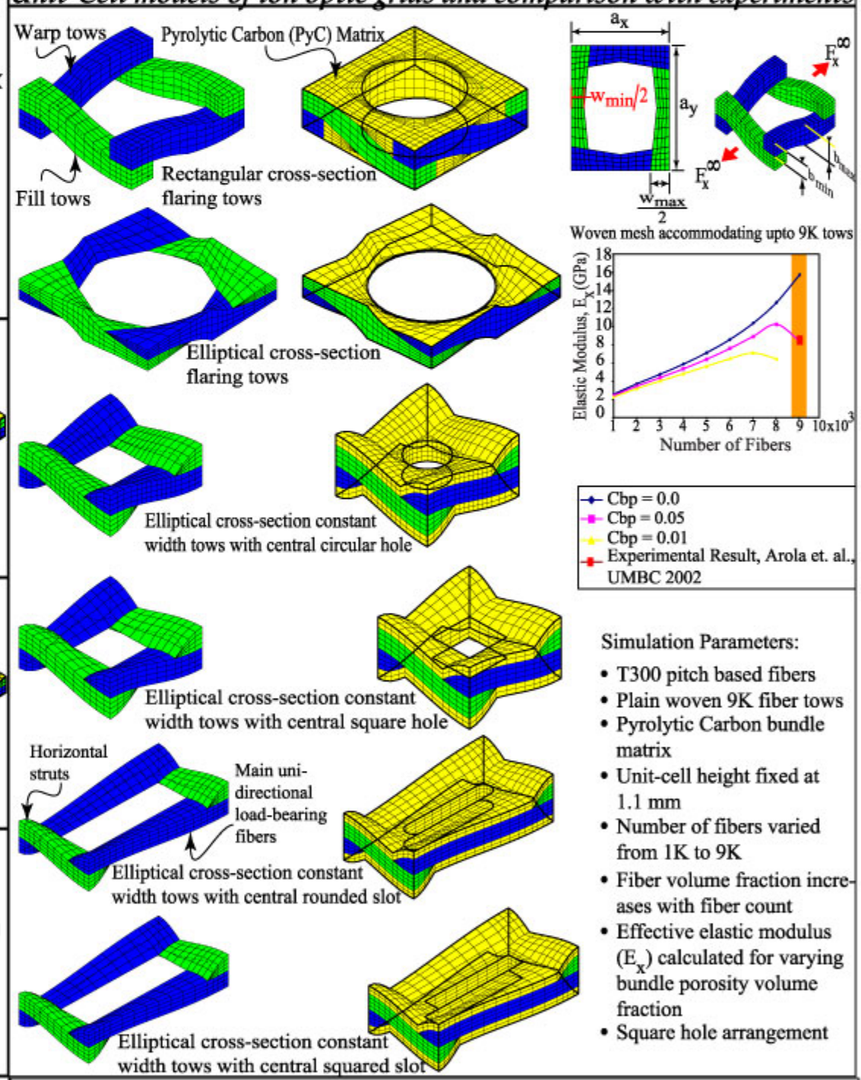
$$R(x,y) = \begin{cases} x/g + 1/2 & |x| \leq g/2 \;;\; -a_1/2 \leq y \leq -g/2 \\ H(x) & g/2 \leq |x| \leq a_1 - g/2 \;;\; -a_1/2 \leq y \leq -g/2 \\ 0 & \text{otherwise} \end{cases} \quad \text{Linear Interpolation Function}$$

$$F_H(x) = H(|x|-g/2) - H(|x|+g/2-a_1)$$

Fiber Tow Architecture / Polymer Matrix Composite / Ceramic Matrix Composite



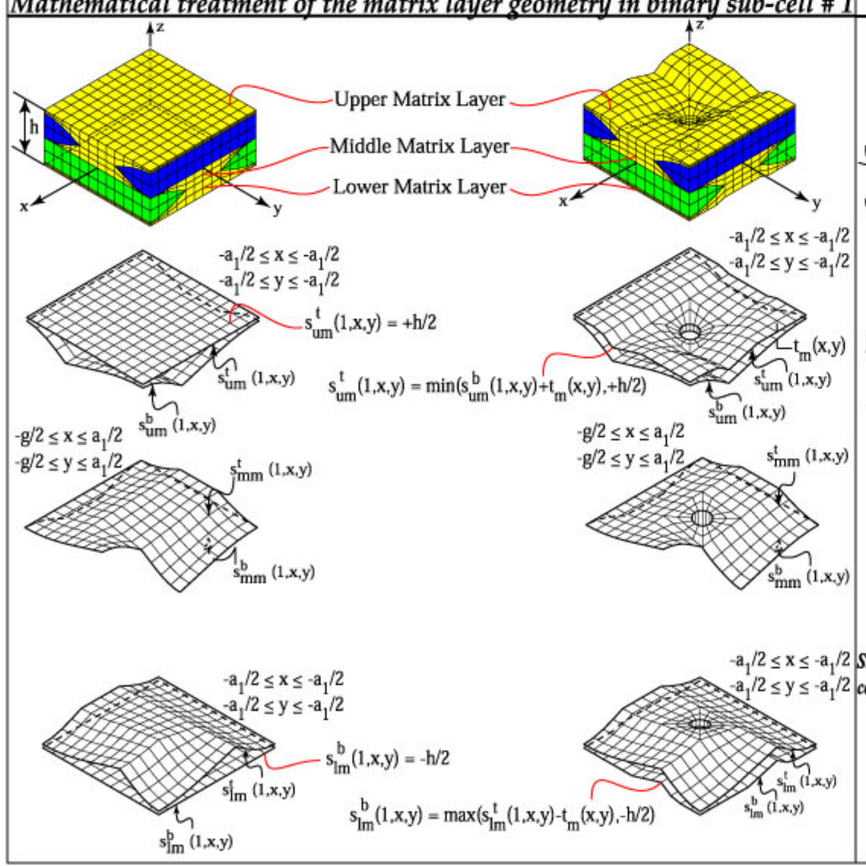
Unit-Cell models of ion optic grids and comparison with experiments



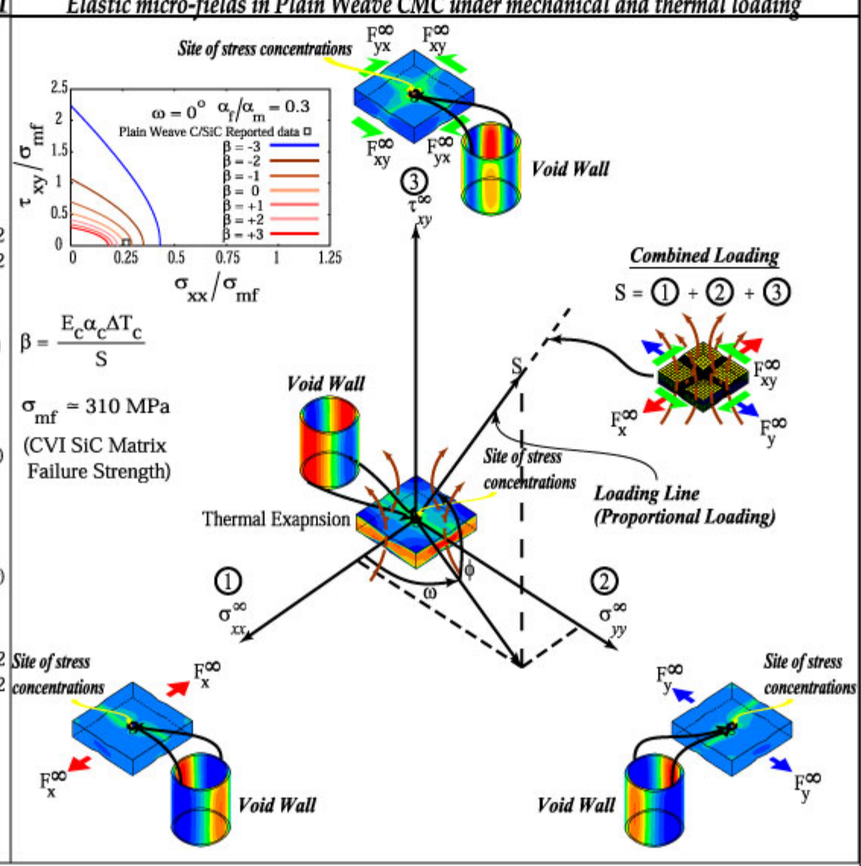
Simulation Parameters:

- T300 pitch based fibers
- Plain woven 9K fiber tows
- Pyrolytic Carbon bundle matrix
- Unit-cell height fixed at 1.1 mm
- Number of fibers varied from 1K to 9K
- Fiber volume fraction increases with fiber count
- Effective elastic modulus (E_x) calculated for varying bundle porosity volume fraction
- Square hole arrangement

Mathematical treatment of the matrix layer geometry in binary sub-cell # 1



Elastic micro-fields in Plain Weave CMC under mechanical and thermal loading



Conclusions

- Robust computational models of complex woven fabric composites have been developed with aid of generalized mathematical surface functions.
- The models are inherently capable of accounting for the intricate fiber tow architecture as well as the spatially varying matrix layer topology characteristic of woven composites fabricated via the Chemical Vapor Infiltration (CVI) technique.
- Failure loci based on the Maximum Normal Stress criterion have been established for the Plain Weave (PW) CVI SiC/SiC composite.
- The predicted Proportional Limit strength for the PW CVI SiC/SiC composite was shown to be in excellent agreement with experimental data.
- Simulations performed for the PW ion optic grid produced an envelope of effective elastic moduli predictions which was shown to be in excellent agreement with experimental studies.

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Selected References

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3) S. I. Haan. "Modeling of the Mechanical Response of Plain Weave Composites". Ph.D. Thesis, The University of Maryland, 2000.