Computation of fiber orientation in X-ray micro-tomography reconstructions

Presented by Federico Semeraro
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Technical Session #1: Micro-tomography based analysis

MOTIVATION & OBJECTIVES

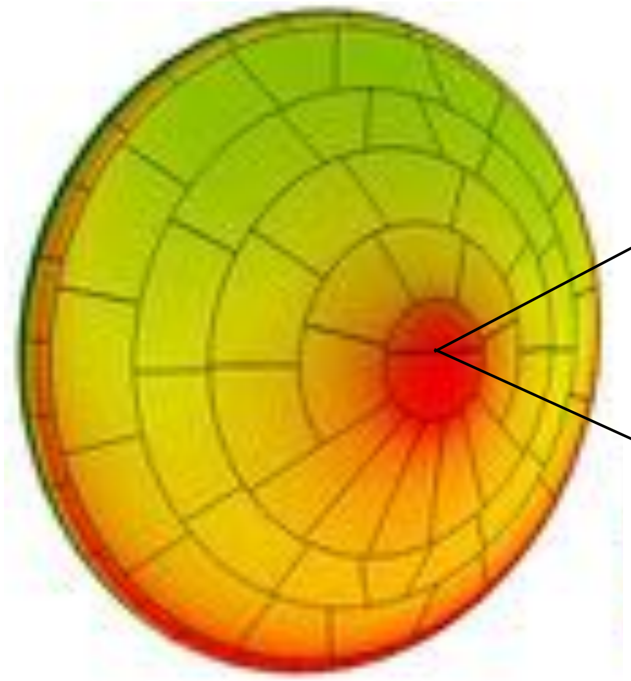
Modeling Thermal Protection Systems (TPS)

Macroscale Modeling

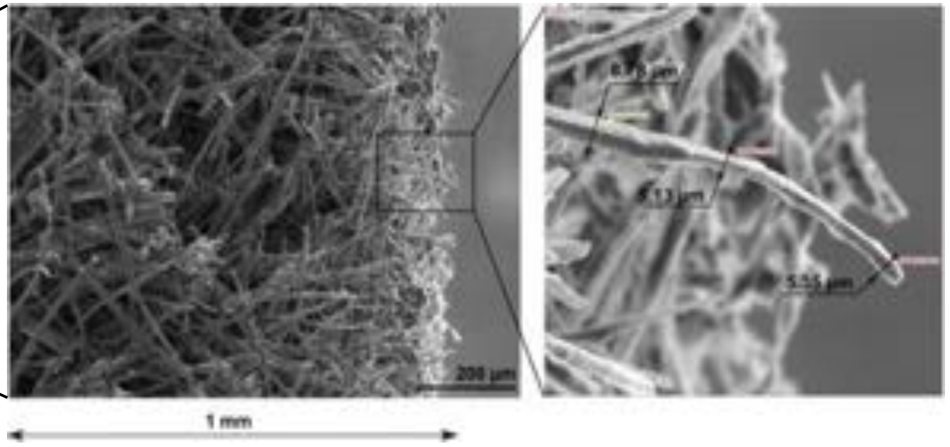
Full scale material response solvers, using volume-averaged techniques to solve conservation equations for ablation

Microscale Modeling

Used to inform material properties and material response parameters used in macro-scale modeling



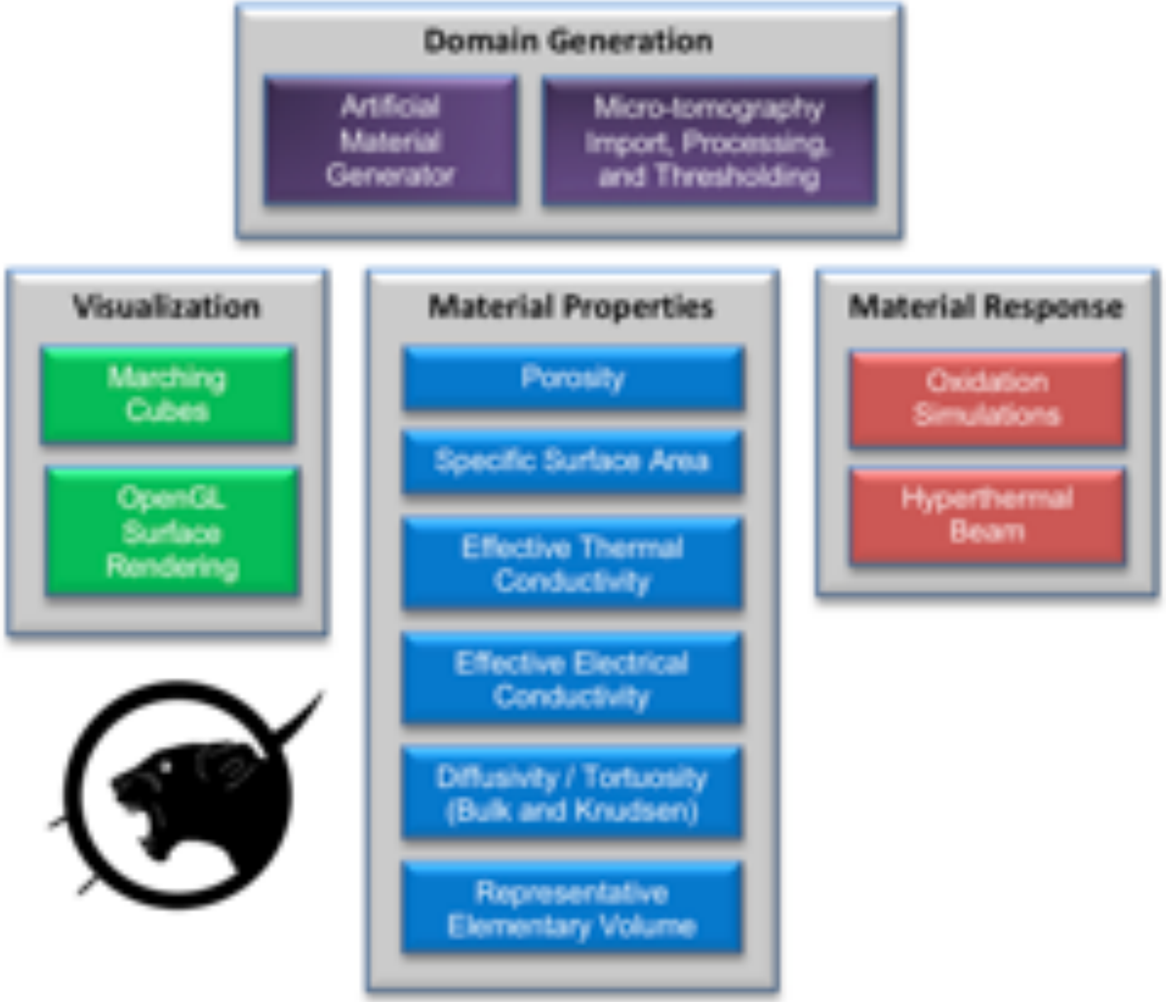
Simulation of surface temperature for MSL heatshield*[1]

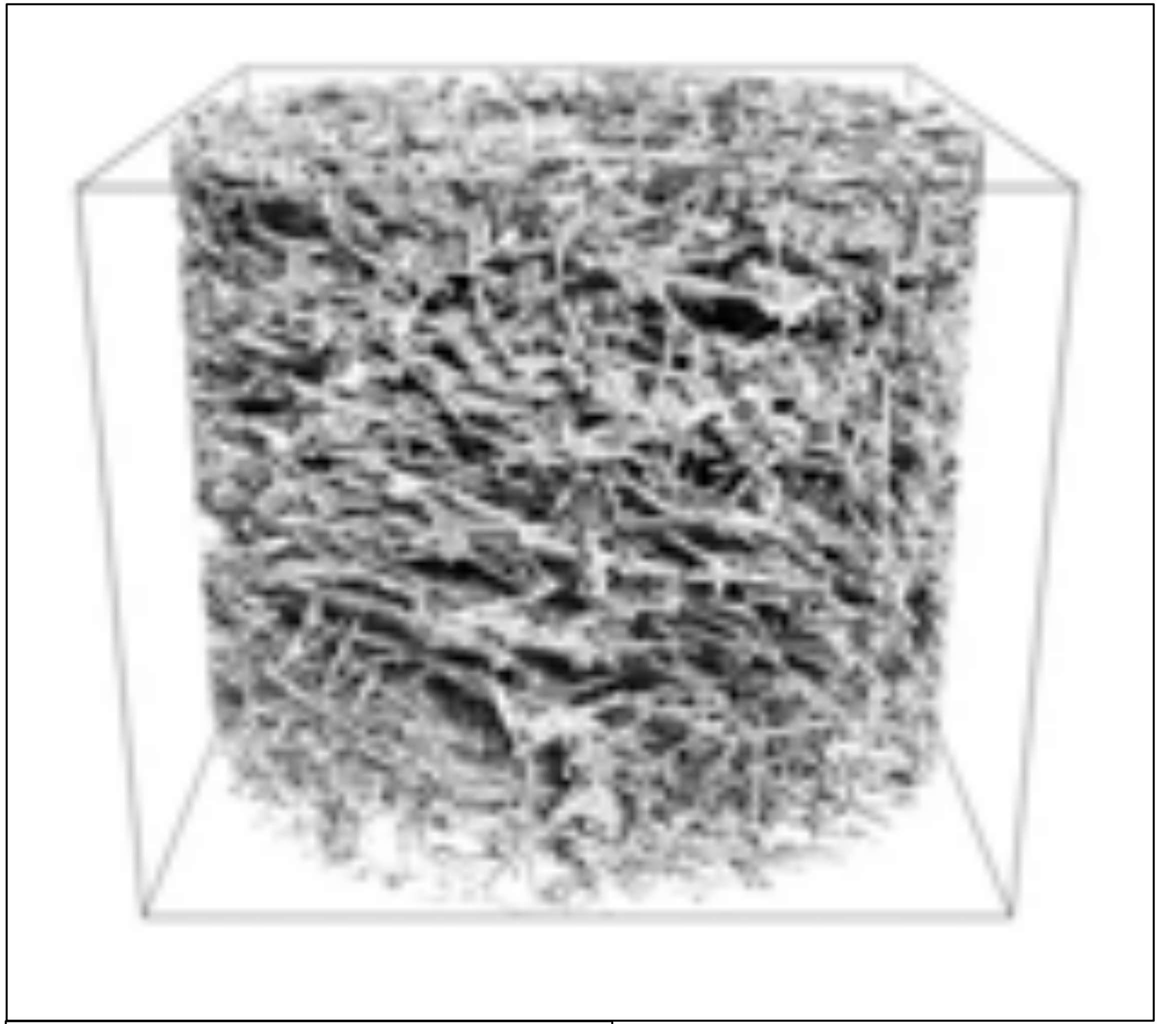


Lachaud and Mansour, *JTHT* 2013

*[1] Meurisse, Jeremie BE, et al. "Multidimensional material response simulations of a full-scale tiled ablative heatshield." *Aerospace Science and Technology 76 (2018)*: 497-511.

Porous Microstructure Analysis (PuMA)



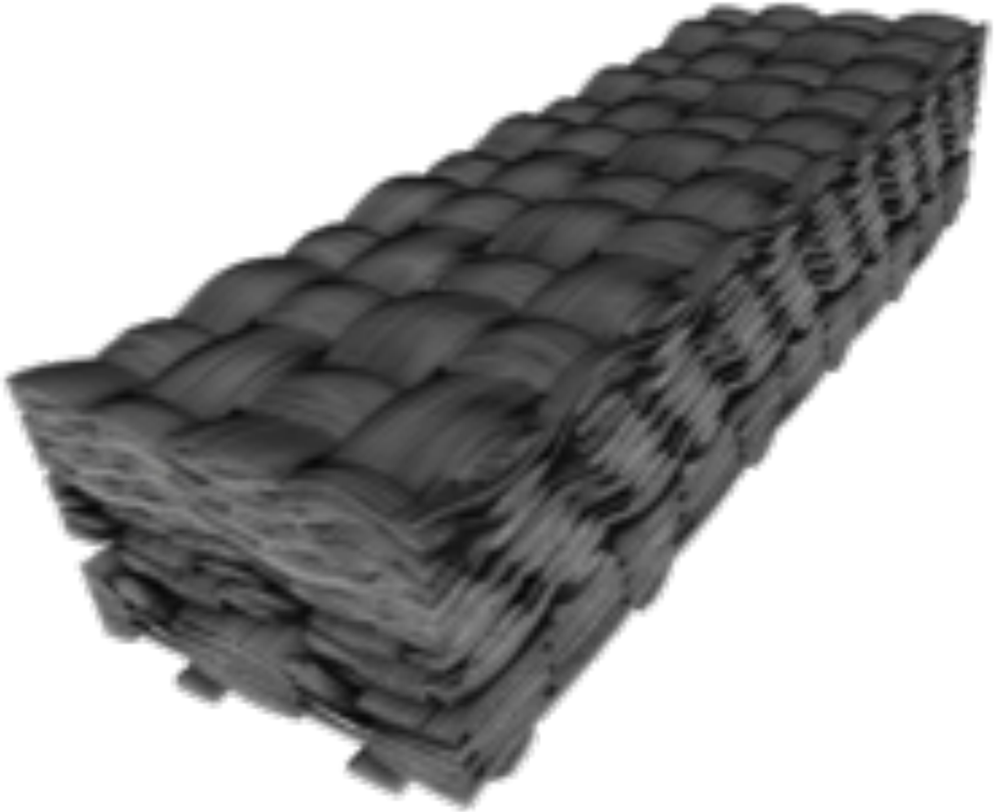


CT Reconstruction of FiberForm

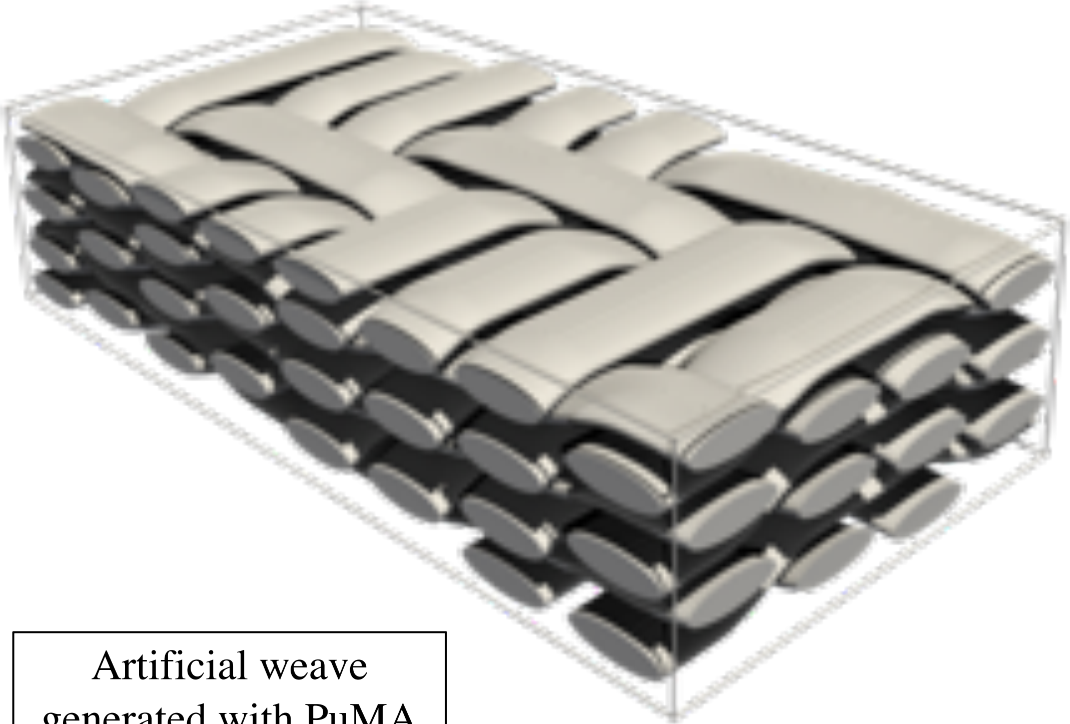
Ferguson, J. C., Panerai, F., Borner, A., & Mansour, N. N. (2018). PuMA: the Porous Microstructure Analysis software. *SoftwareX*, *7*, 81-87. https://software.nasa.gov/software/ARC-17920-1

Challenges in Micro-scale modeling

As NASA moves towards woven TPS materials, our modeling must adapt



12-ply real TPS weave



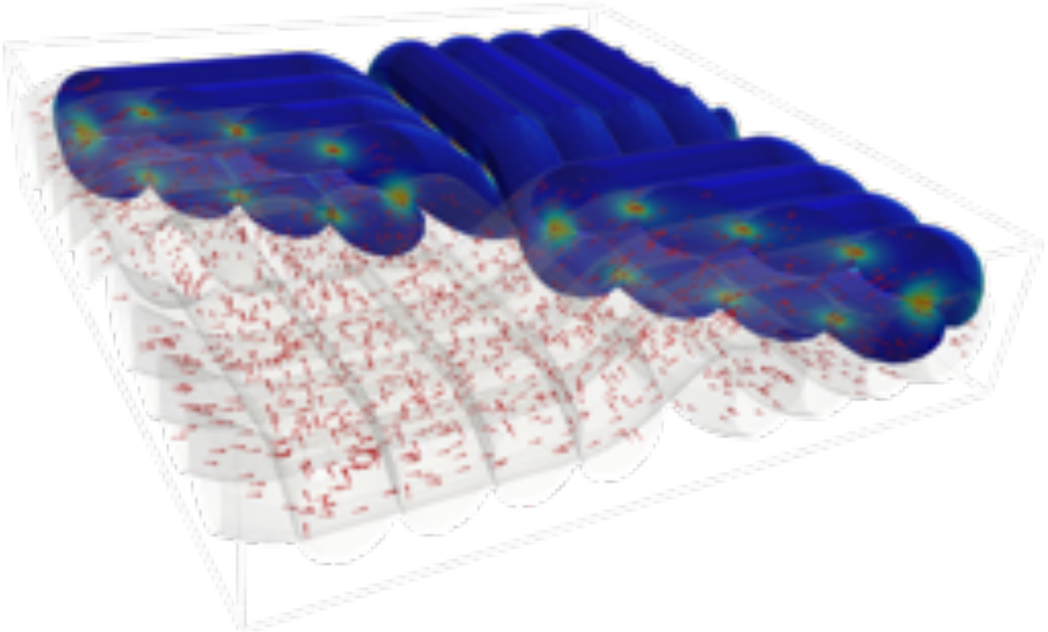
Artificial weave generated with PuMA

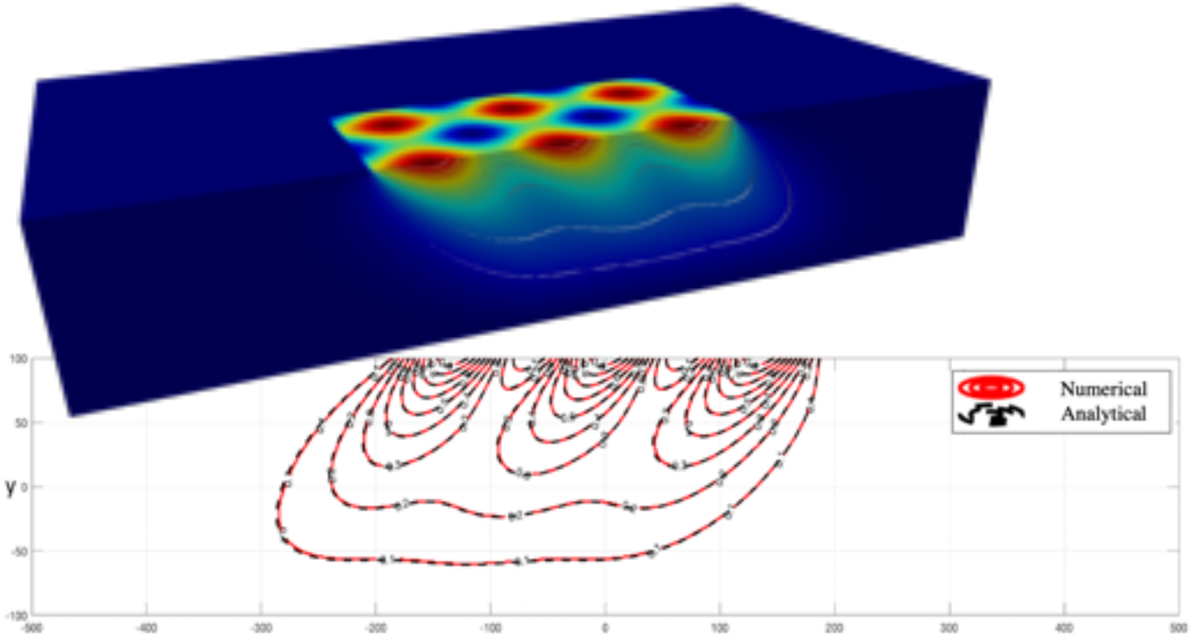
Objectives

Computation of Effective Material Properties

Fiber Orientation Estimation*[1]

Physical and Numerical Model*[2]



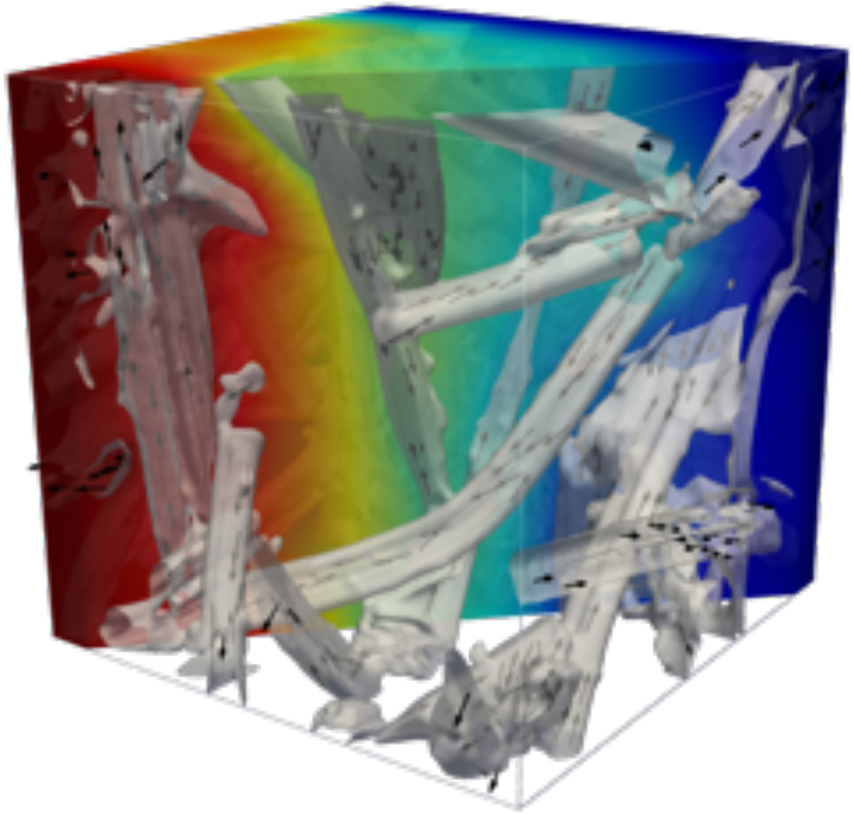


*[1] Federico Semeraro, Joseph C. Ferguson, Francesco Panerai, Robert J. King, Nagi N. Mansour. Anisotropic Analysis of Fibrous and Woven Porous Media, Part I: Estimation of Local Material Orientation. *Journal of Computational Physics [to appear]*

*[2] Federico Semeraro, Joseph C. Ferguson, Francesco Panerai, Nagi N. Mansour. Anisotropic Analysis of Fibrous and Woven Porous Media, Part II: Computation of Effective Conductivity. *Journal of Computational Physics [to appear]*

FIBER ORIENTATION METHODS

Overview

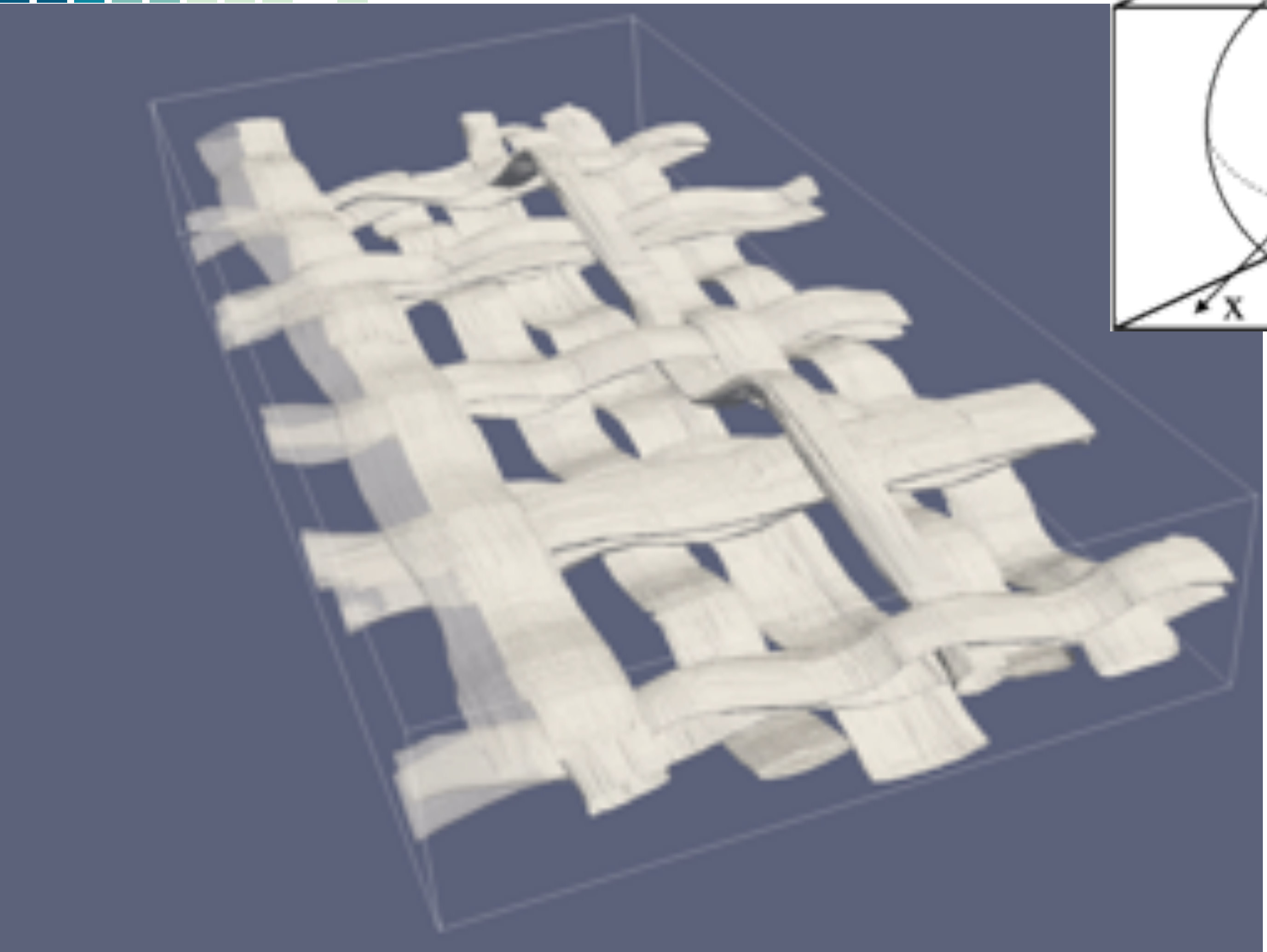


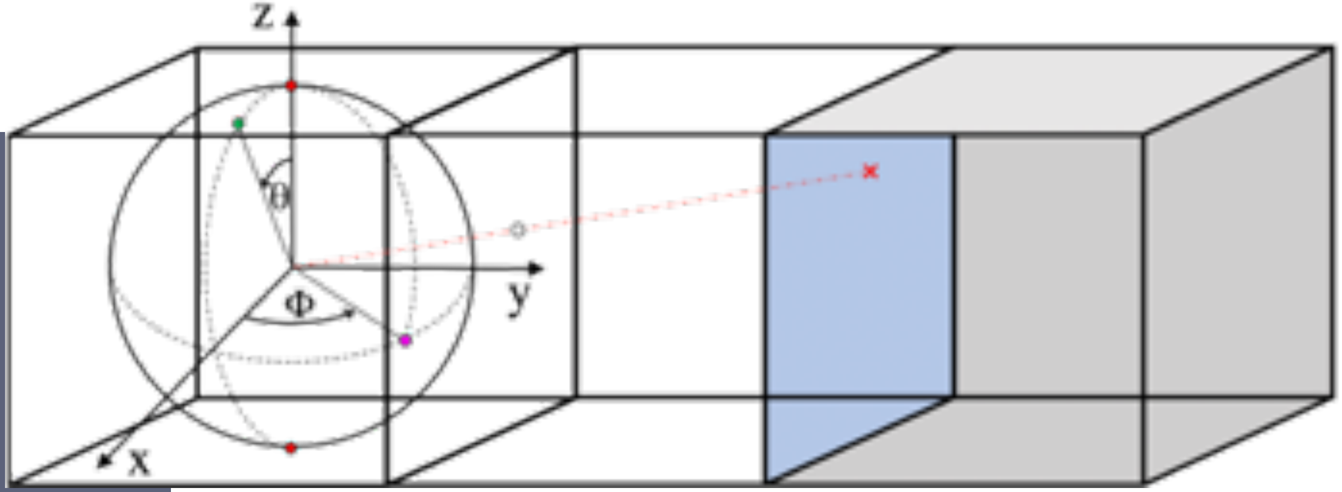
- Ray Casting (novel)
- Artificial Flux*[1]
- Structure Tensor*[2]

*[1] Matti Schneider, Matthias Kabel, Heiko Andrä, et al. Thermal fiber orientation tensors for digital paper physics. *International Journal of Solids and Structures 2016*; 100-101 234

*[2] Krause M, Hausherr JM, Burgeth B, Herrmann C, Krenkel W. Determination of the fibre orientation in composites using the structure tensor and local x-ray transform. *J Mater Sci 2010*; 45(4):888–96.

Ray Casting

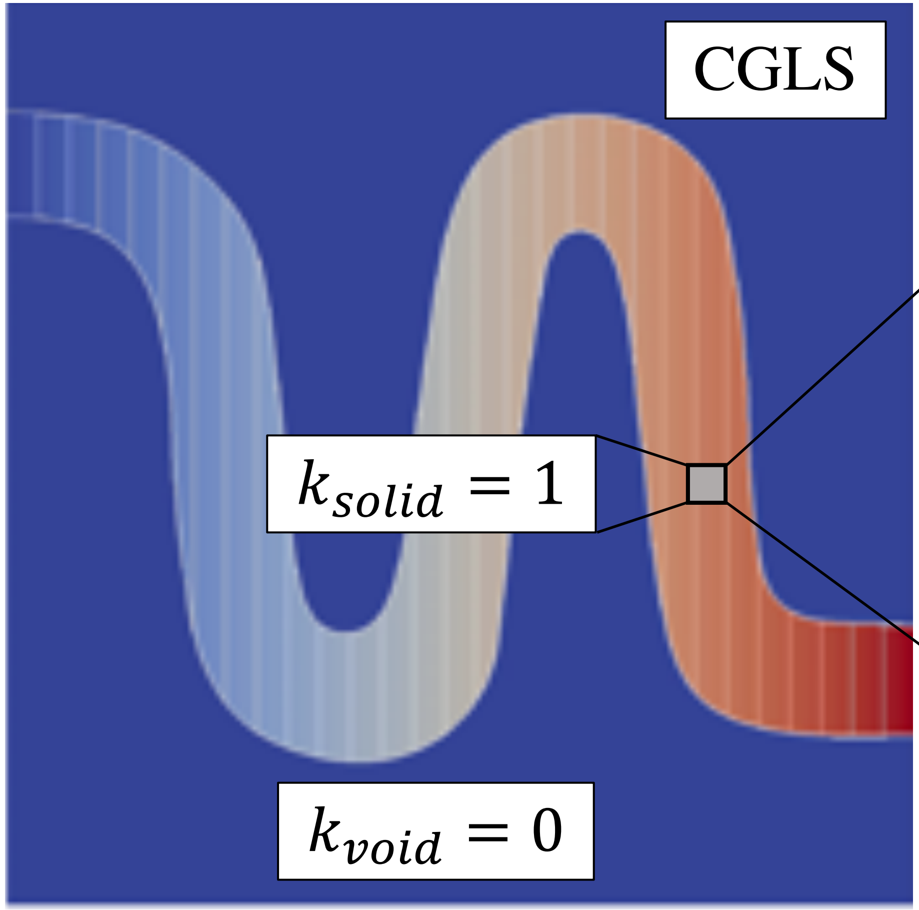


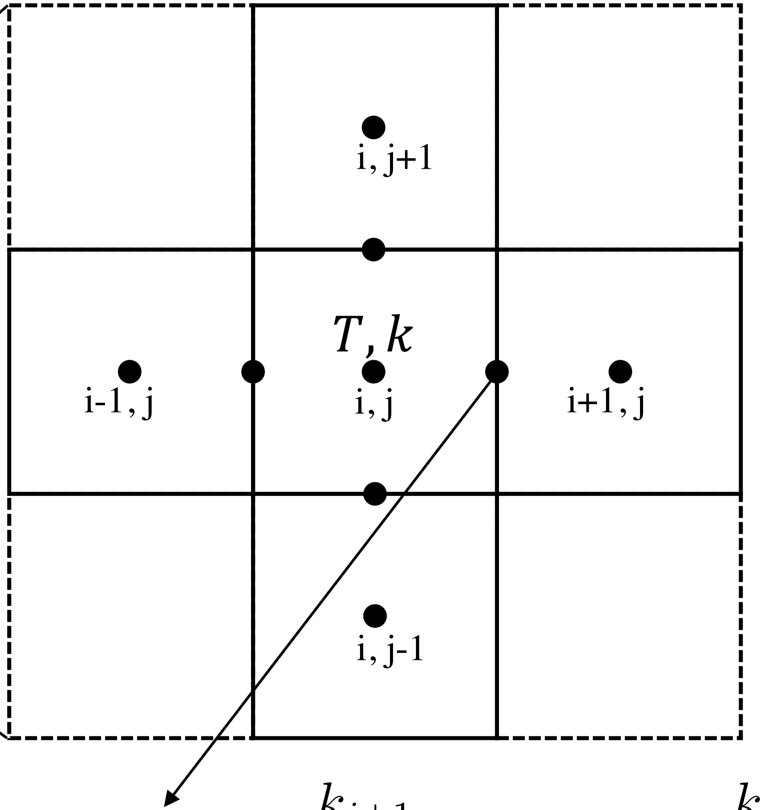


$$\theta \in [0, 180^\circ) \qquad \phi \in [0, 360^\circ)$$

$$N = \left(\frac{180^\circ}{d\psi} - 1\right)\left(\frac{360^\circ}{d\psi}\right) + 2$$

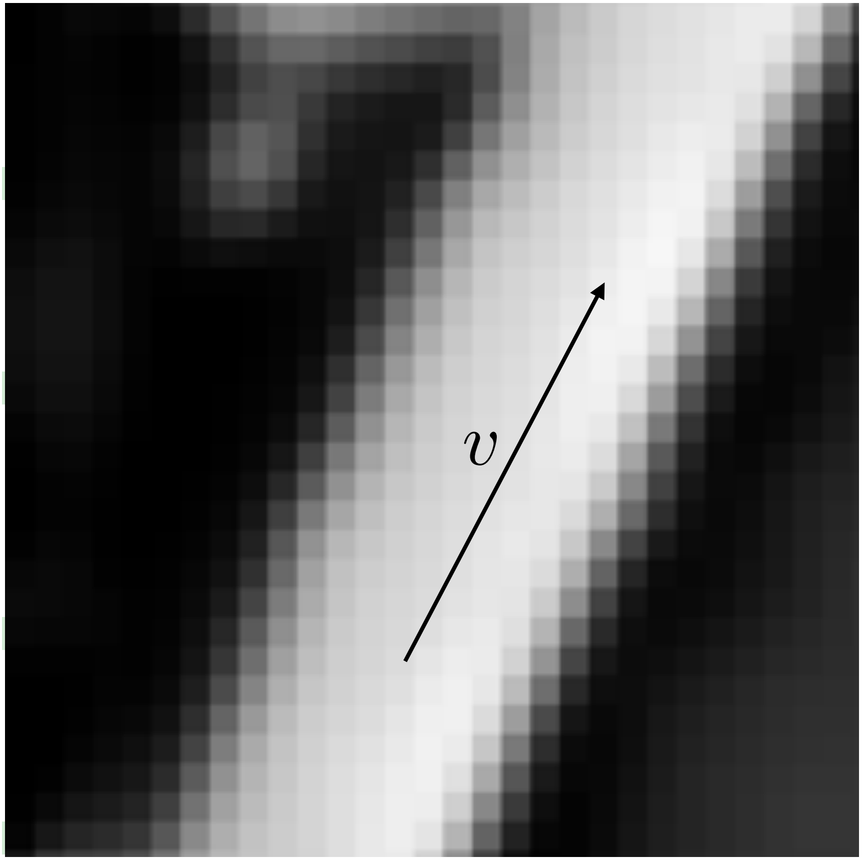
Artificial Flux





$$T_{i+1/2} = \frac{k_{i+1}}{k_i + k_{i+1}} T_{i+1} + \frac{k_i}{k_i + k_{i+1}} T_i$$

Structure Tensor

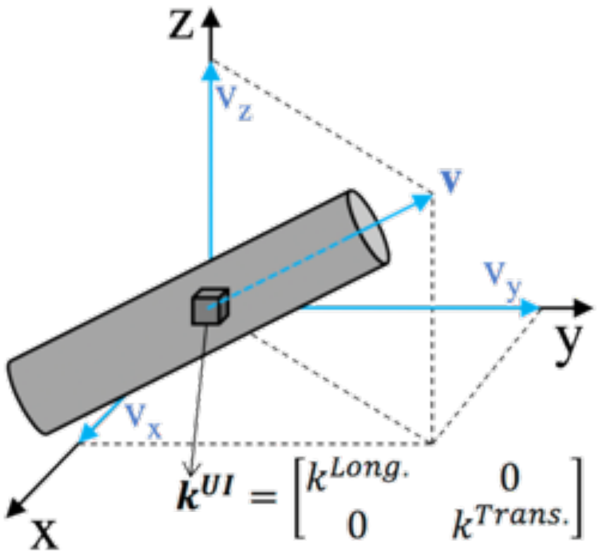


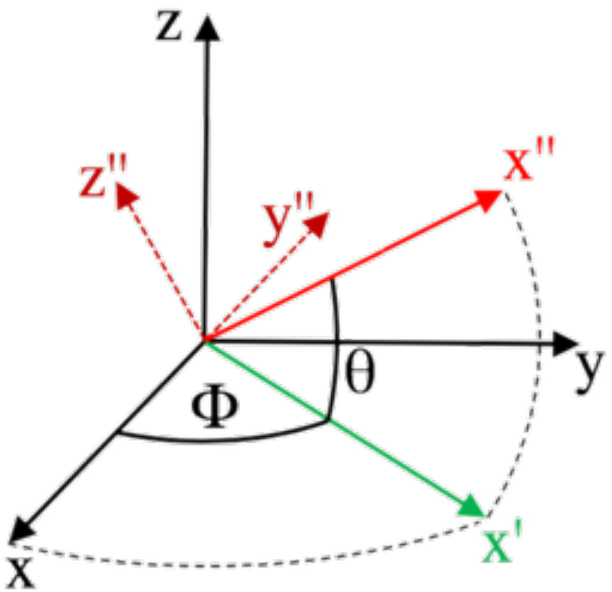
- $(I(x+v) - I(x))^2 \approx 0$

4 Steps:

1. $\nabla I_\sigma(x) = \nabla(\sigma * I(x))$
2. $\nabla I_\sigma \nabla I_\sigma^T = \begin{pmatrix} I_x^2 & I_x I_y & I_x I_z \\ I_x I_y & I_y^2 & I_y I_z \\ I_x I_z & I_y I_z & I_z^2 \end{pmatrix}$
3. $J_\rho(x) = \rho * (\nabla I_\sigma \nabla I_\sigma^T)$
4. Local orientation vector v is the eigenvector related to the smallest eigenvalue of $J_\rho(x)$

Conductivity Tensor Rotation





$$\boldsymbol{v} = v_x\boldsymbol{i} + v_y\boldsymbol{j} + v_z\boldsymbol{k}$$

$$\boldsymbol{k}'' = \begin{bmatrix} k^{Long.} & 0 & 0 \\ 0 & k^{Trans.} & 0 \\ 0 & 0 & k^{Trans.} \end{bmatrix}$$

$$\theta = \arcsin v_z \quad \phi = \arctan\frac{v_y}{v_x}$$

$$\boldsymbol{q} = \underbrace{\left[\boldsymbol{R}^{-1}\boldsymbol{k}''\boldsymbol{R}\right]}_{\boldsymbol{k}} \nabla T$$

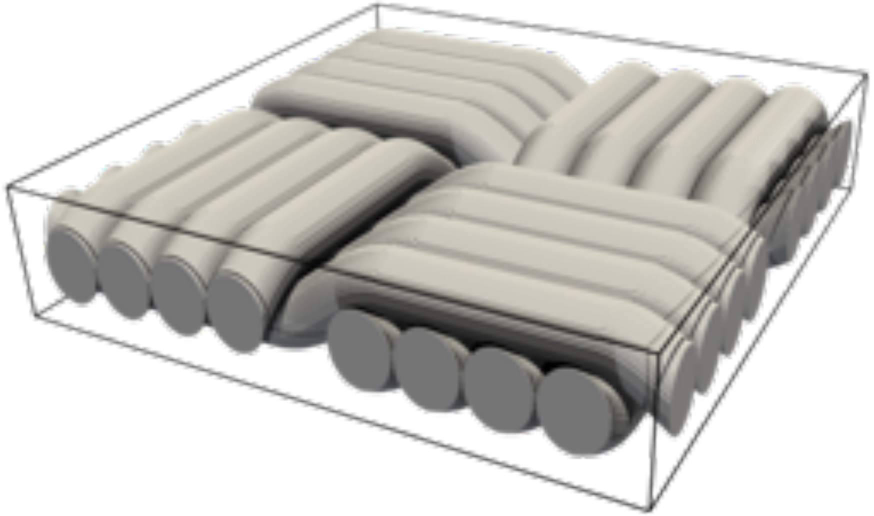
$$\boldsymbol{R} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

APPLICATION TO MATERIALS

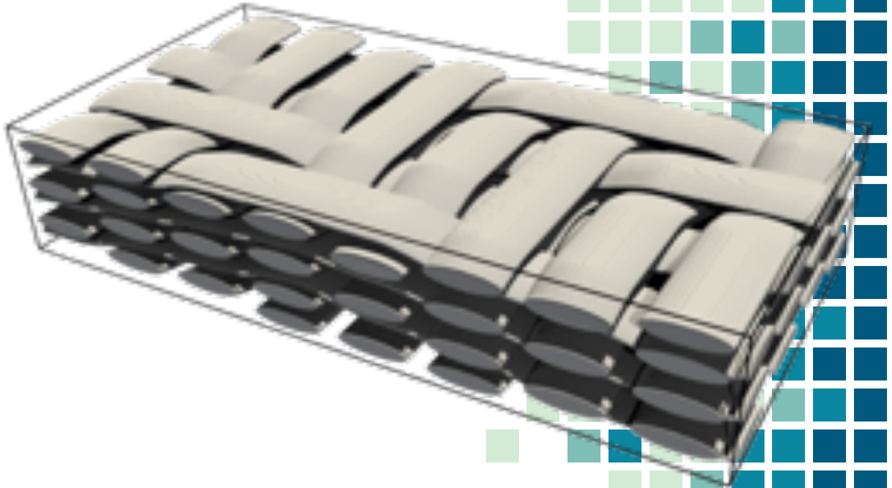
Parametric Study

Artificial Straight Fibers

2D Weave



3D Weave



Methods' Inputs

Ray Casting (RC)

Ray angle separation $d\psi$

Artificial Flux (AF)

Solver Tolerance

Structure tensor (ST)

Kernel window sizes:

1. σ
2. ρ

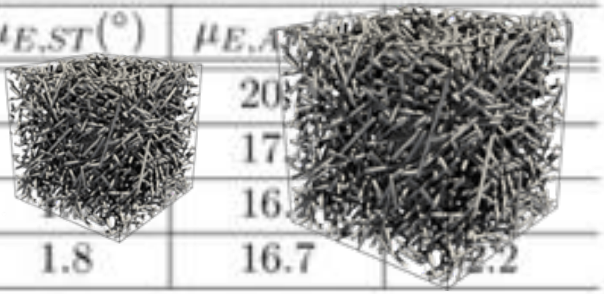
Methods' Performance

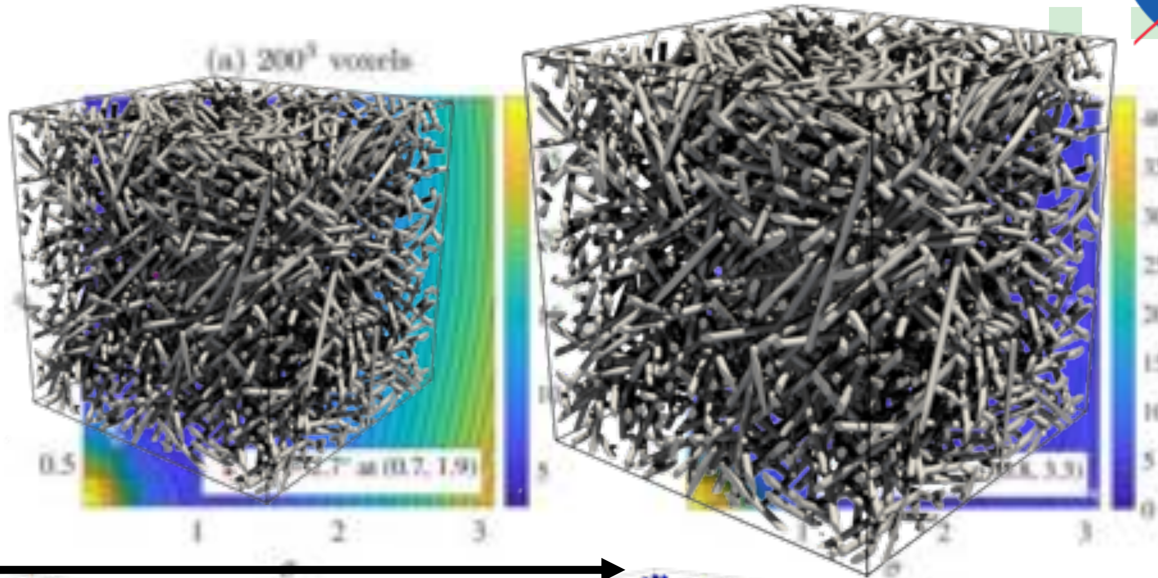
Mean Angular Error

$$\mu_E = \sum_{n=1}^{N_{solid}} \frac{\alpha_n(x)}{N_{solid}}$$

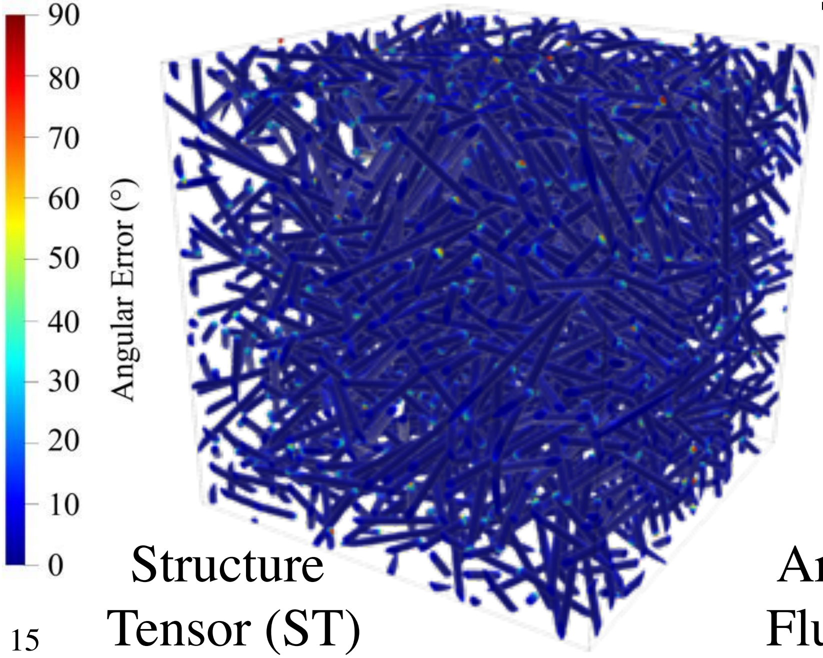
Results on Artificial Fibrous Samples

Resolution (vox)	$\mu_{E,ST}$(°)	$\mu_{E,A...}$	
200^3	[illegible]	20...	[illegible]
400^3	[illegible]	17...	[illegible]
600^3	[illegible]	16...	[illegible]
800^3	1.8	16.7	...2.2

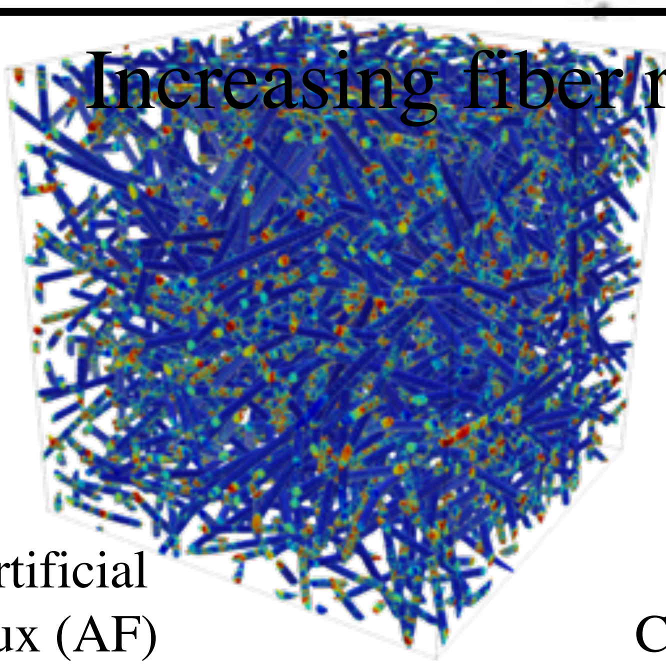




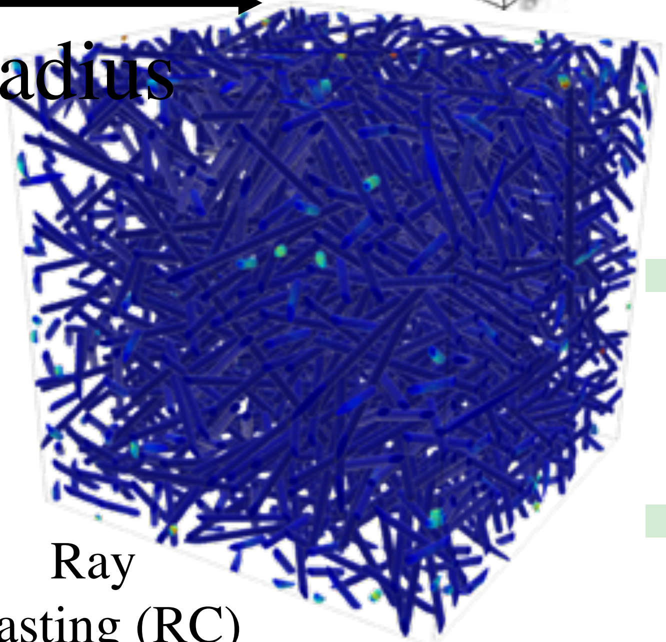
Increasing fiber radius



Structure Tensor (ST)

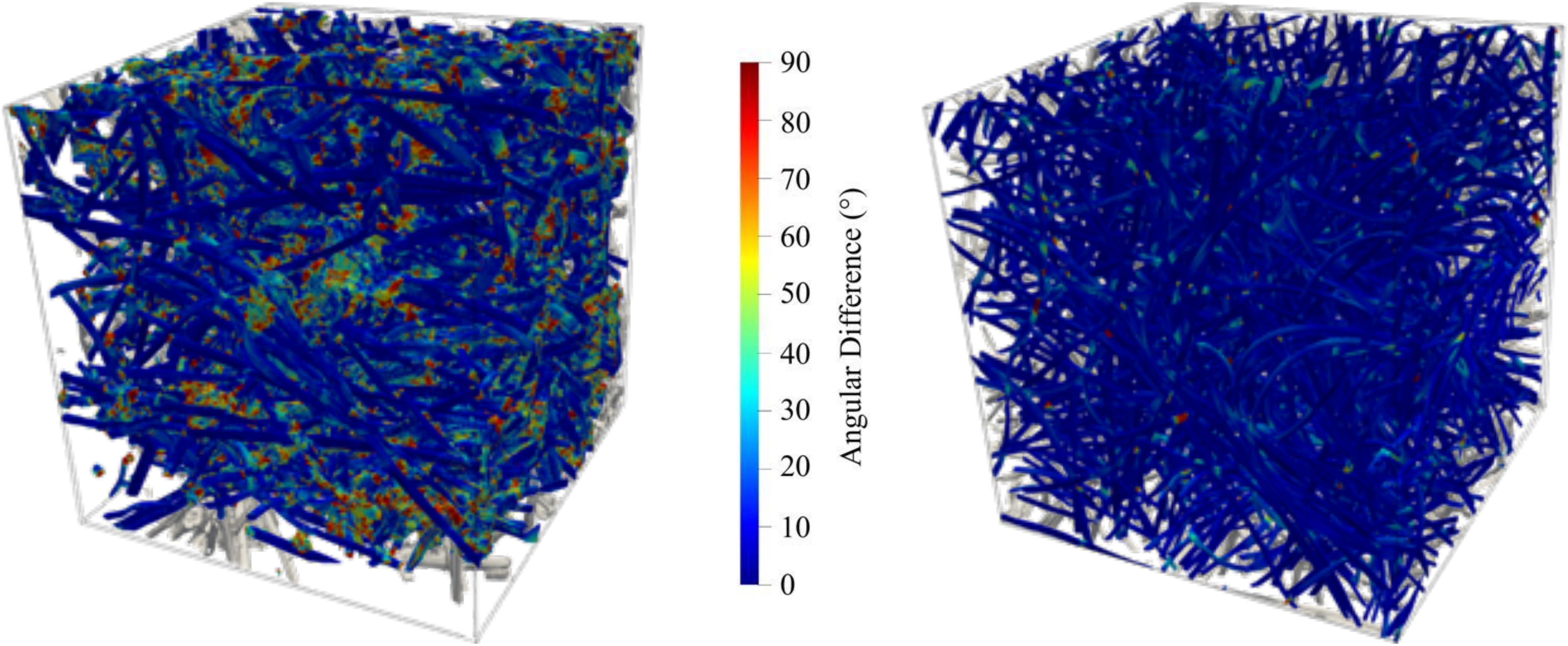


Artificial Flux (AF)



Ray Casting (RC)

Results on Real Fibrous Samples



FiberForm™ 800^3 voxels

$$\mu_\alpha = 21.6^\circ$$

Structure Tensor
v.s.
Ray Casting

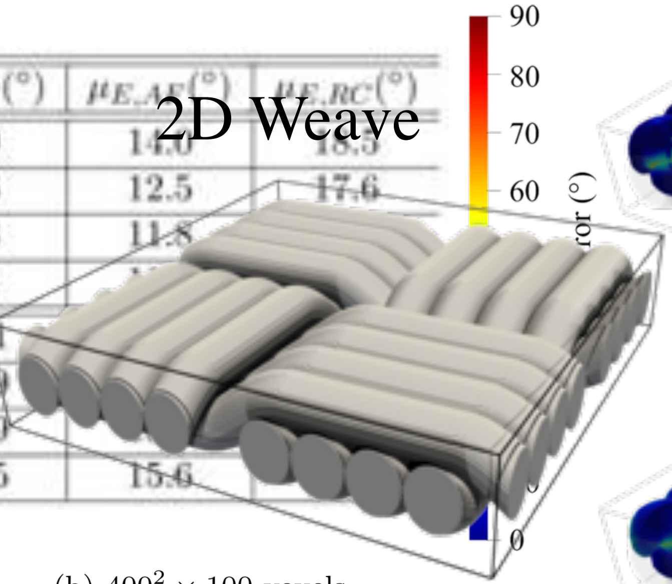
Morgan Felt 800^3 voxels

$$\mu_\alpha = 8.5^\circ$$

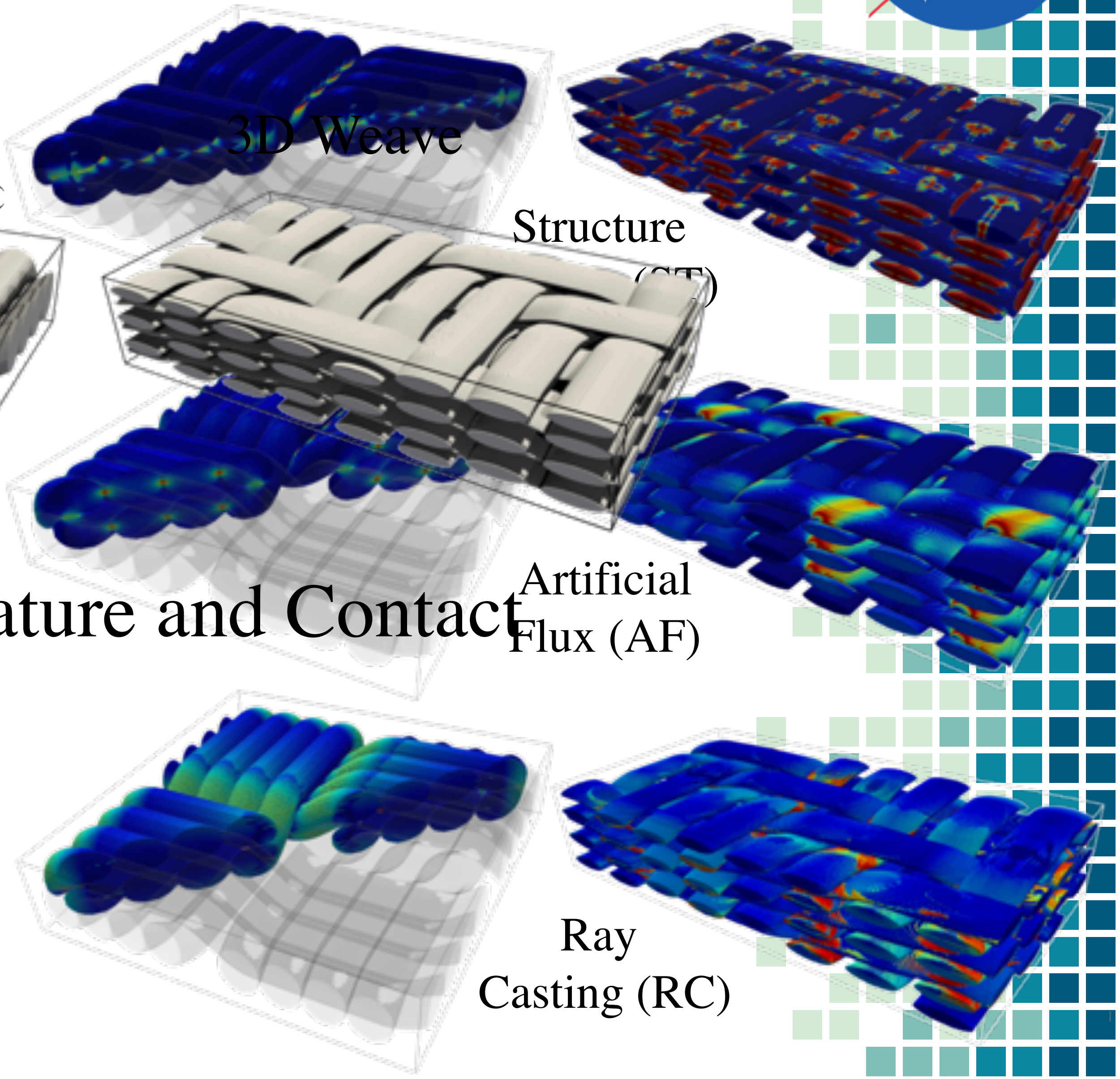
Results on Artificial Woven Samples

Design	Resolution (vox)	$\mu_{E,ST}$(°)	$\mu_{E,AF}$(°)	$\mu_{E,RC}$(°)
Circular Tows	$200^2 \times 50$	4.9	14.0	18.5
	$400^2 \times 100$	4.6	12.5	17.6
	$600^2 \times 150$	4.8	11.8	[illegible]
	$800^2 \times 200$	5.1	[illegible]	[illegible]
Elliptical Tows	$200 \times 400 \times 80$	30.1	[illegible]	[illegible]
	$400 \times 800 \times 160$	25.9	[illegible]	[illegible]
	$600 \times 1200 \times 240$	25.9	[illegible]	[illegible]
	$800 \times 1600 \times 320$	26.5	15.6	[illegible]

2D Weave



3D Weave



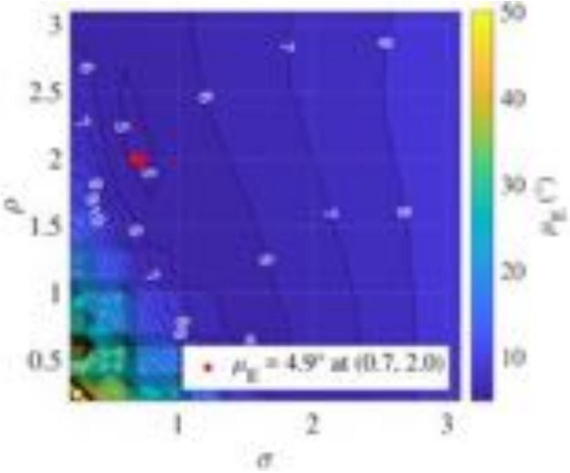
Structure Tensor (ST)

Artificial Flux (AF)

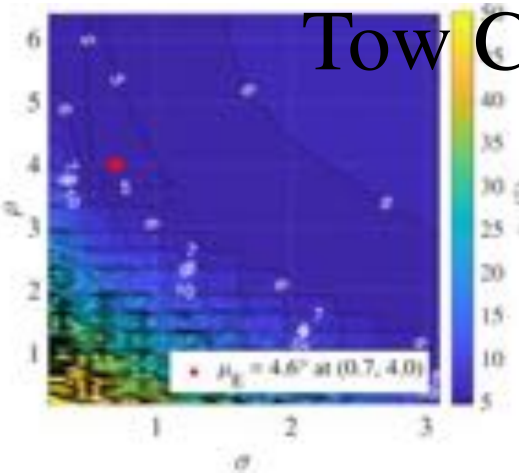
Ray Casting (RC)

Tow Curvature and Contact

(a) $200^2 \times 50$ voxels

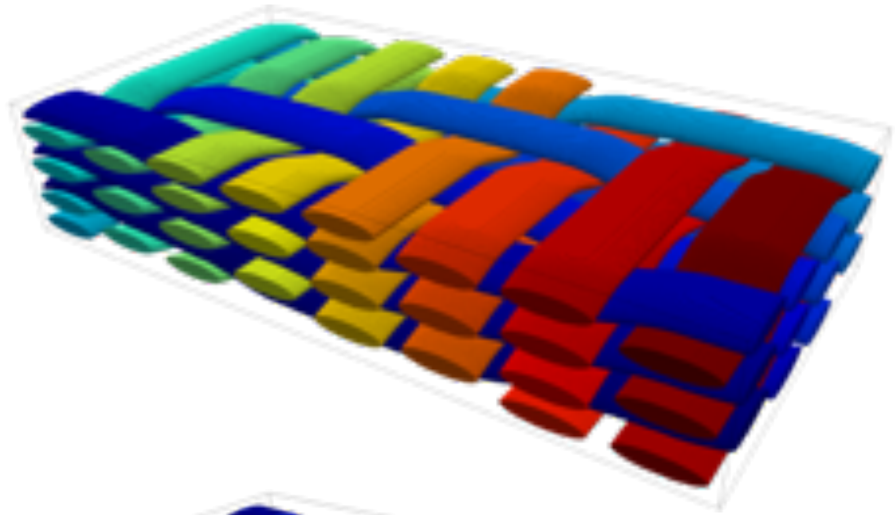


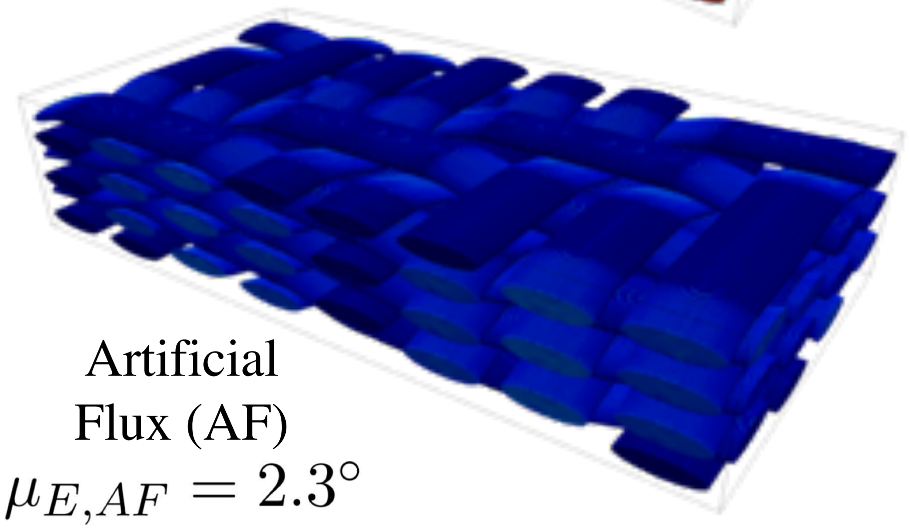
(b) $400^2 \times 100$ voxels



Improved Workflow for Weave Orientation

Individual tow segmentation

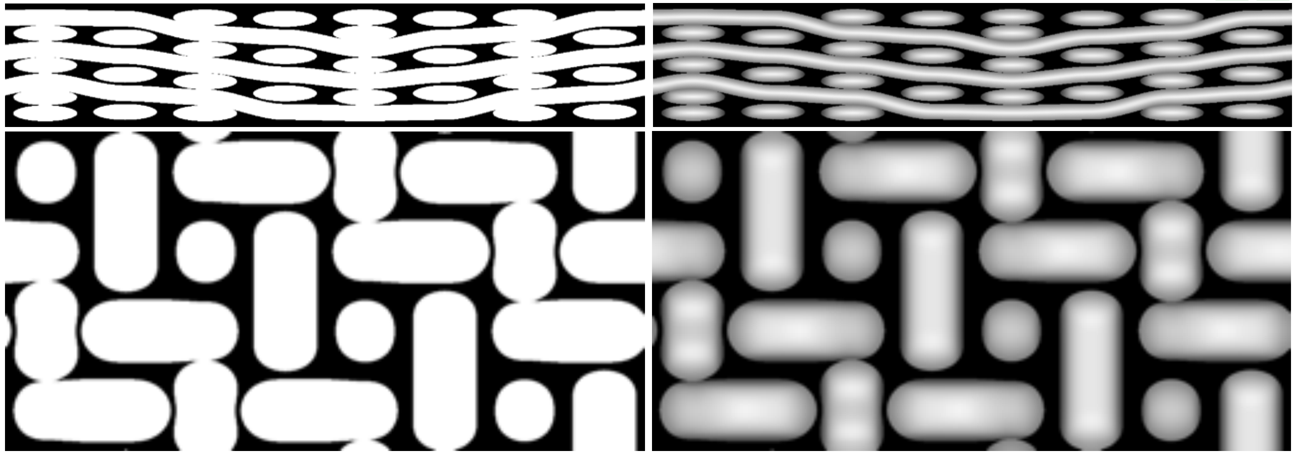


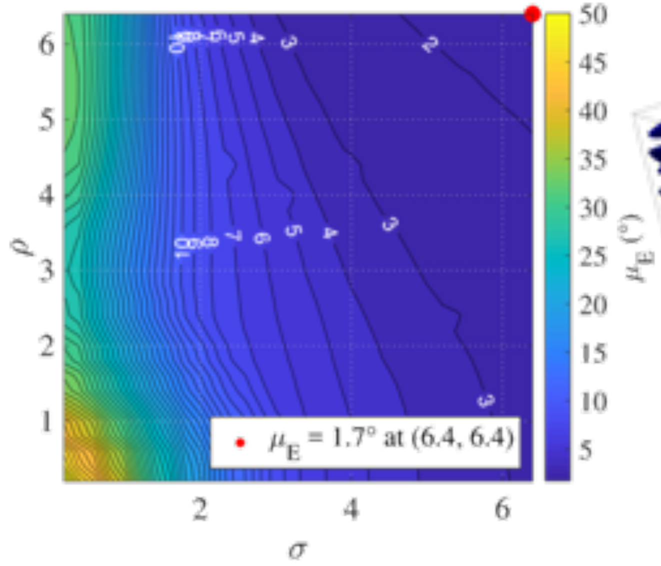


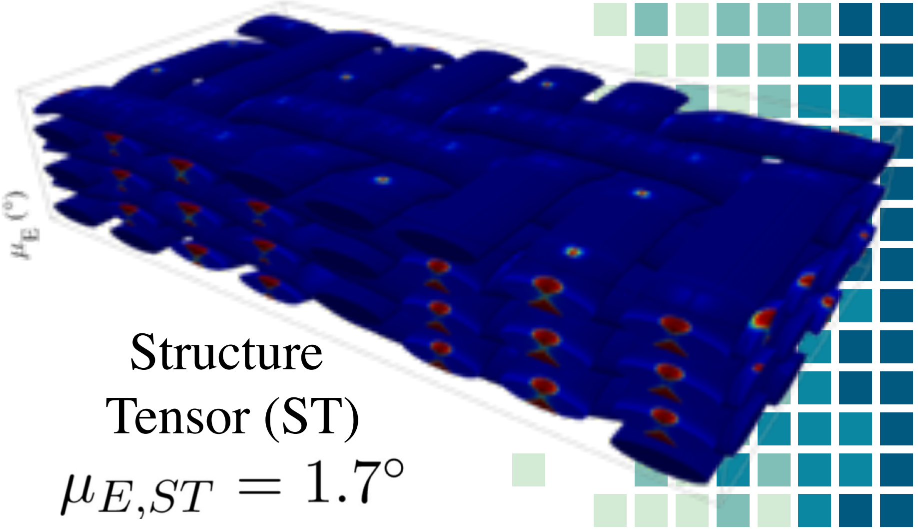
Artificial Flux (AF)

$\mu_{E,AF} = 2.3°$

Mean Filtering



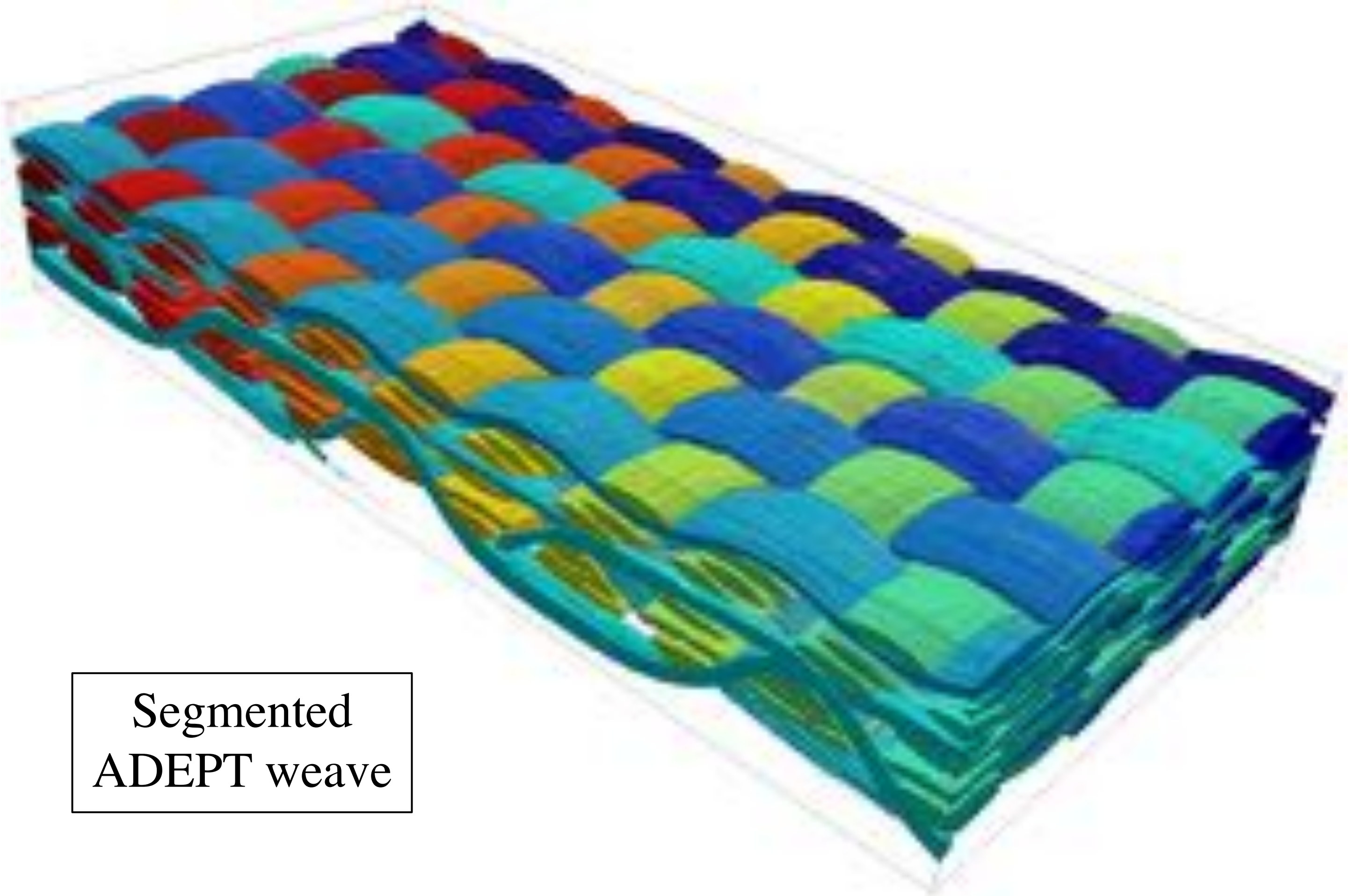




Structure Tensor (ST)

$\mu_{E,ST} = 1.7°$

Real Woven Sample*[1]


Segmented ADEPT weave

*[1] J. M. L. MacNeil, D. M. Ushizima, F. Panerai, N. N. Mansour, H. S. Barnard, D. Y. Parkinson, Interactive volumetric segmentation for textile micro-tomography data using wavelets and nonlocal means, *Statistical Analysis and Data Mining: The ASA Data Science Journal 12* (4) (2019) 338–353

Summary

1. **Ray Casting:**

   - Performs well on artificial straight fibers ($\mu \sim 3-5°$) and similar to other methods on binarized woven structures ($\mu \sim 10-15°$). Slight improvement in new workflow ($\mu \sim 9°$)
   - Limitation: affected by large fiber curvatures and computational expensive

2. **Artificial Flux:**

   - Easy to use because independent on inputs. Performs similar to other methods on binarized weaves ($\mu \sim 15°$). Very accurate when using new workflow for woven materials ($\mu \sim 1-3°$)
   - Limitation: Performs poorly on artificial straight fibers due to regions not being in the path of heat flux through the material ($\mu \sim 15-20°$)

3. **Structure Tensor:**

   - Performs effectively on artificial straight fibers ($\mu \sim 1-5°$) and similar to other methods on binarized weaves ($\mu \sim 20°$). Very accurate when using new workflow for woven materials ($\mu \sim 1-2°$)
   - Limitation: hard to define optimal window a priori. For high resolutions, window must be sufficiently large, which can be very expensive