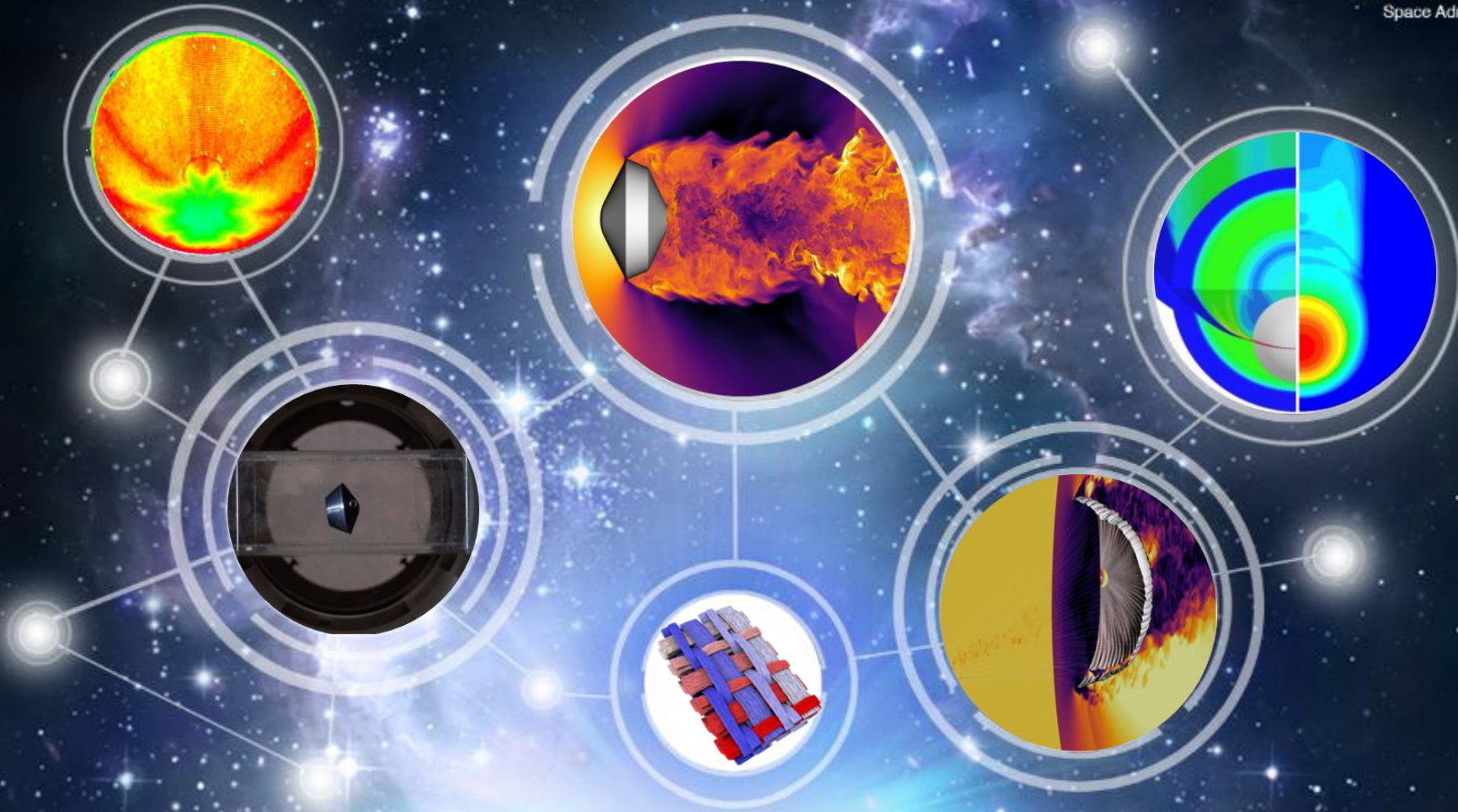




Multiscale and Multifidelity Modeling of a 3D Woven Composite Thermal Protection System

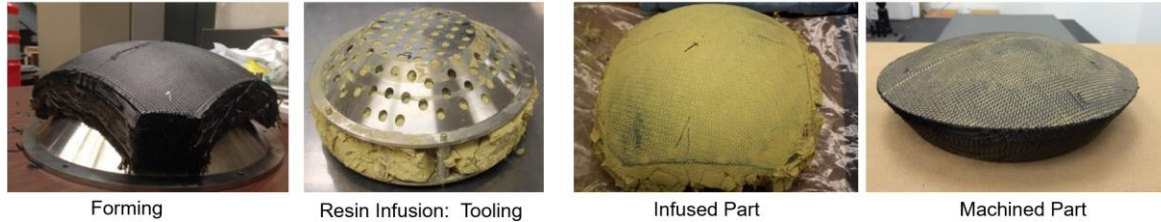
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- Increasing use of 3D woven composites in recent years
- Enhanced damage tolerance and customizability
- Multiple systems explored by NASA for space missions:
 - Adaptive Deployable Entry Placement Technology (ADEPT)
 - 3D Multifunctional Ablative Thermal Protection System (3D-MAT)
 - **Heatshield for Extreme Entry Environment Technology (HEEET)**
 - 3D Medium Density Carbon Phenolic (3MDCP)
 - Several systems for Composite Technologies for Exploration (CTE)
- Predominant modeling approach in the literature:
 - Single-scale analysis
 - Highly-refined finite element analysis
 - Idealized architectures



Heatshield for Extreme Entry Environment Technology (HEEET)



Images from: Gasch, M. (2019) "Heatshield for Extreme Entry Environment Technology (HEET) Thermal Protection System (TPS)" MS&T19, Portland OR.

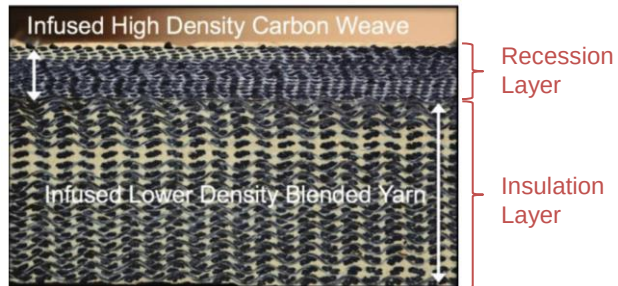
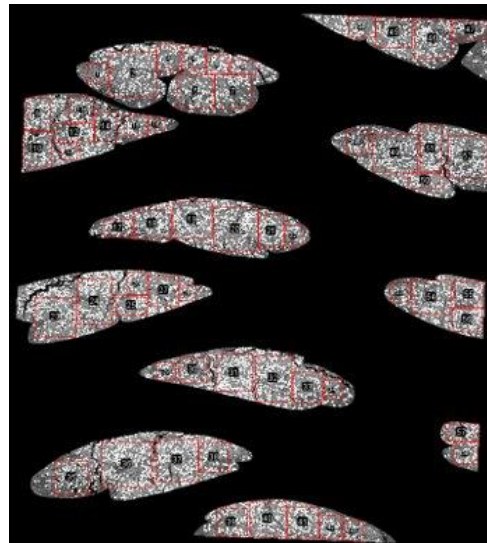
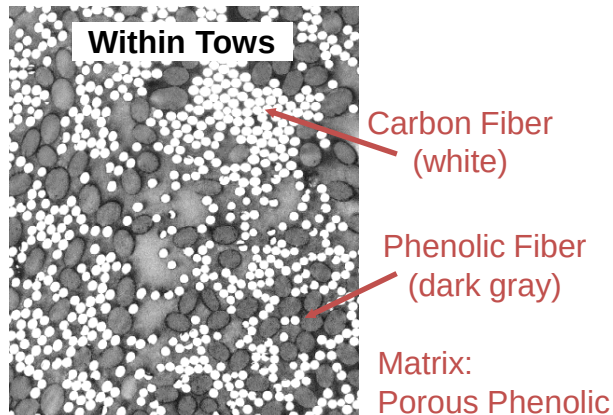


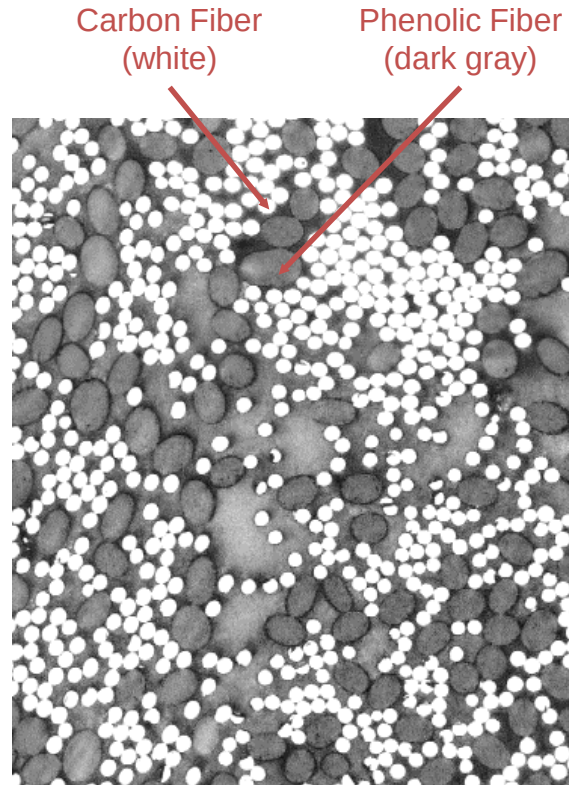
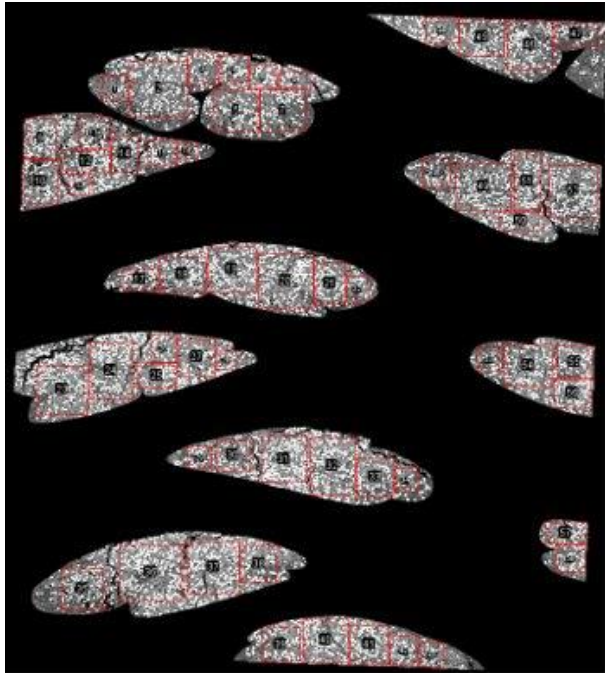
Image from: Fahy, W.P., Chang, A., Wu, H., and Koo, J.H. "Recent Developments of Ablative Thermal Protection Systems for Atmospheric Entry", AIAA SciTech 2021, 19–21 January, 2021.



- HEET designed to be part of the thermal protection system for re-entry spacecraft
- HEET comprised of two 3D woven layers:
 - Recession and Insulation
- Blended carbon and phenolic fiber tows
- Four tows twisted to form a yarn
- Yarns are woven to create preform
- Preform infused with a highly porous phenolic resin
 - Inter-yarn porosity (local): 0.846*
 - Intra-yarn porosity (local): 0.552*
- Optical microscopy and x-ray computed tomography (CT) data obtained and analyzed

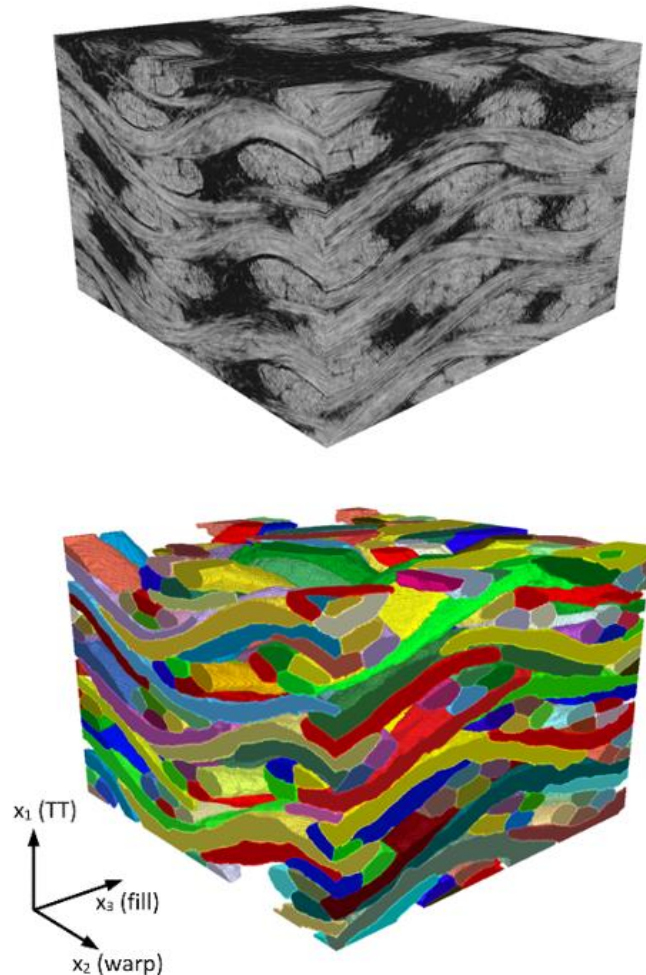
*Bednarczyk, B.A., Ricks, T.M., Pineda, E.J., Murthy, P.L.N., Mital, S.K., Hu, Z., Gustafson, P.A.: Multiscale Recursive Micromechanics of Three-Dimensional Woven Composite Thermal Protection Materials Thermal Conductivities. AIAA Journal, 60(12), 6506–19, (2022). <https://doi.org/10.2514/1.J061920>.

HEEET-IL Composite Characterization



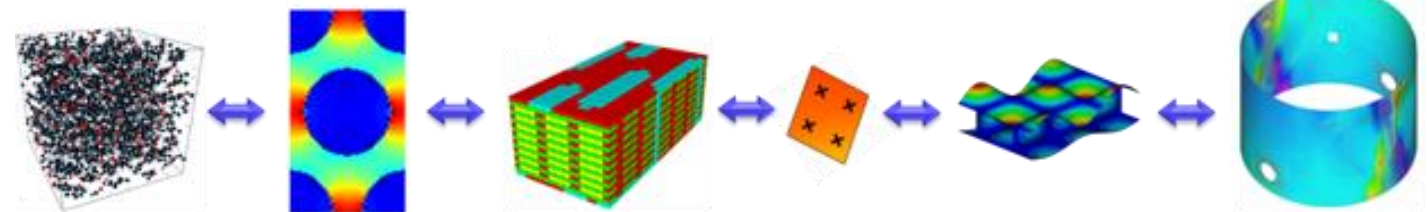
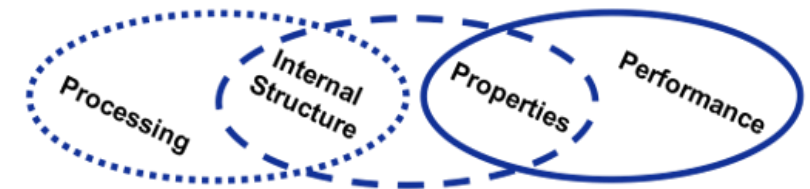
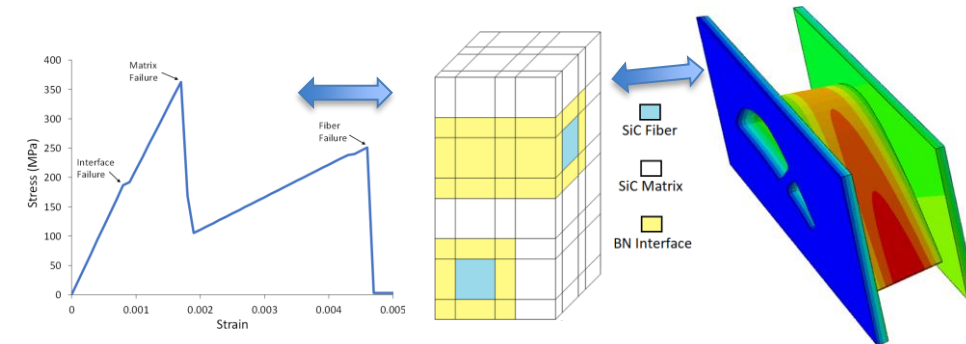
- Optical microscopy performed to characterize constituent volume fractions within a tow
- Section of HEEET insulation layer imaged with a 0.2 micron resolution
- Semantic and instance segmentation utilized to isolate individual fibers from a series of 75 selections (red boxes)
- Overall volume fractions and fiber dimensions determined:
 - Carbon fiber – 6.8 micron diameter
 - Phenolic fiber – 19 micron x 14 micron diameter

Constituent	Volume Fraction
Carbon Fiber	0.329
Phenolic Fiber	0.286
Intra-yarn Porous Matrix	0.321
Cracks	0.064

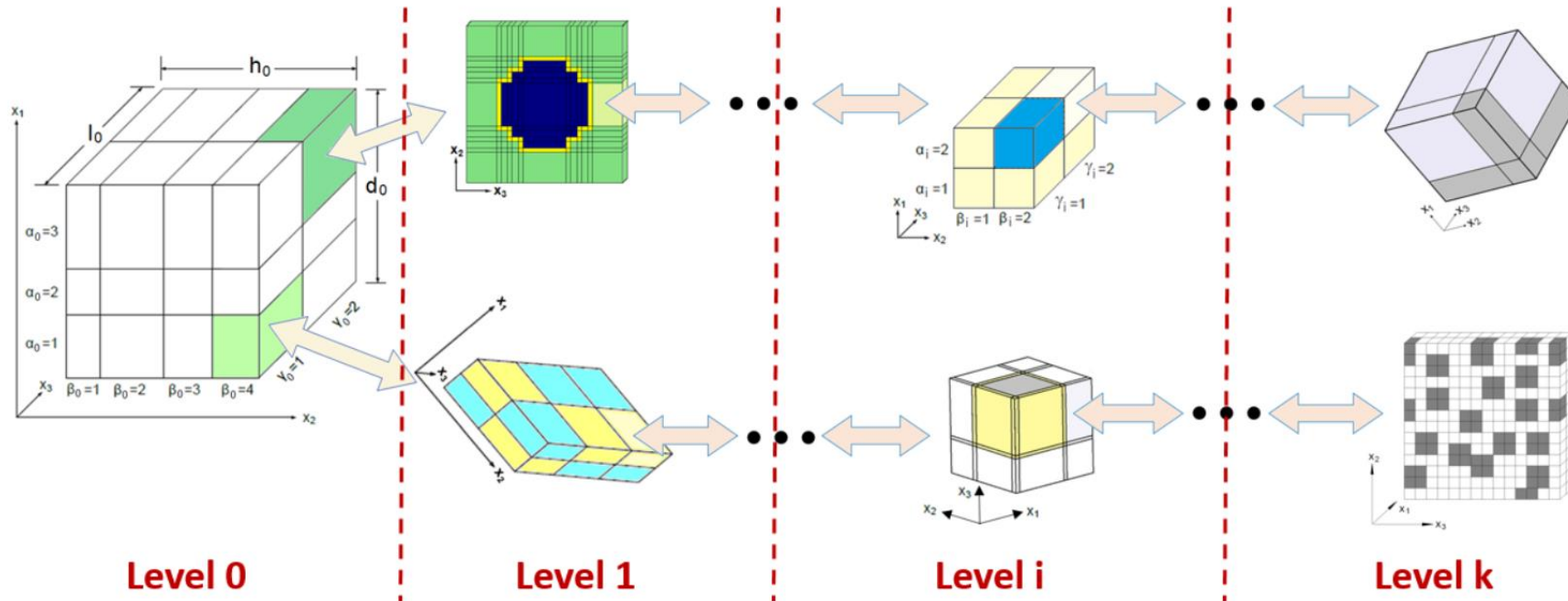


- X-ray CT data obtained using a Zeiss Xradia 520 Versa
- 12.7 mm x 12.7 mm x 25.4 mm section of HEEET insulation layer imaged with an 11 micron resolution
- 496 x 471 x 329 voxels in the warp, fill, and through-thickness (~77 million voxels).
- 3D Slicer utilized to segment each of the four tows within every yarn, inter-yarn porous matrix, and cracks
- Relevant volume fractions calculated:
 - Yarns: 0.576
 - Inter-yarn porous matrix: 0.403
 - Cracks: 0.021

- Successor to MAC/GMC and FEAMAC toolsets
- A framework designed to support massively multiscale modeling
 - Solves real, large-scale, non-linear, thermo-mechanical problems
- Modular design to support “plug-and-play” capabilities
- Operational components categorized into NASMAT procedures
- Developed for enhanced interoperability
 - Integrates with 3rd party structural analysis codes (e.g., FEA)
- Library of constitutive laws/damage models
- Ideal for “design with” or “design of” the material
- Enables Integrated Computational Materials Engineering (ICME)
- Developed to support Vision 2040*



*Liu, Xuan, et al. *Vision 2040: a roadmap for integrated, multiscale modeling and simulation of materials and systems*. NASA/CR-2018-219771.



Temperature gradient

$$\left[\frac{\partial T}{\partial x_j} \right]_i^{(\alpha_i)} = -\mathbf{X}_i^{(\alpha_i)}$$

Heat flux

$$\mathbf{q}_i^{(\alpha_i)} = \boldsymbol{\kappa}_i^{(\alpha_i)} \mathbf{X}_i^{(\alpha_i)}$$

Concentration equation
(HFGMC*)

$$\mathbf{X}_i^{(\alpha_i)} = \mathbf{A}_i^{(\alpha_i)} \bar{\mathbf{X}}_i$$

HFGMC – High-Fidelity Generalized Method of Cells

Homogenization

Localization

$$\boldsymbol{\kappa}_0^* = \sum_{\alpha_0} v_{\alpha_0} \left\{ \left(\mathbf{T}_2^1 \right)^{-1} \sum_{\alpha_1} v_{\alpha_1} \left[\left(\mathbf{T}_2^2 \right)^{-1} \sum_{\alpha_2} v_{\alpha_2} \boldsymbol{\kappa}_2^{(\alpha_2)} \mathbf{A}_2^{(\alpha_2)} \right]^{(\alpha_1)} \mathbf{A}_1^{(\alpha_1)} \right\}^{(\alpha_0)} \mathbf{A}_0^{(\alpha_0)}$$

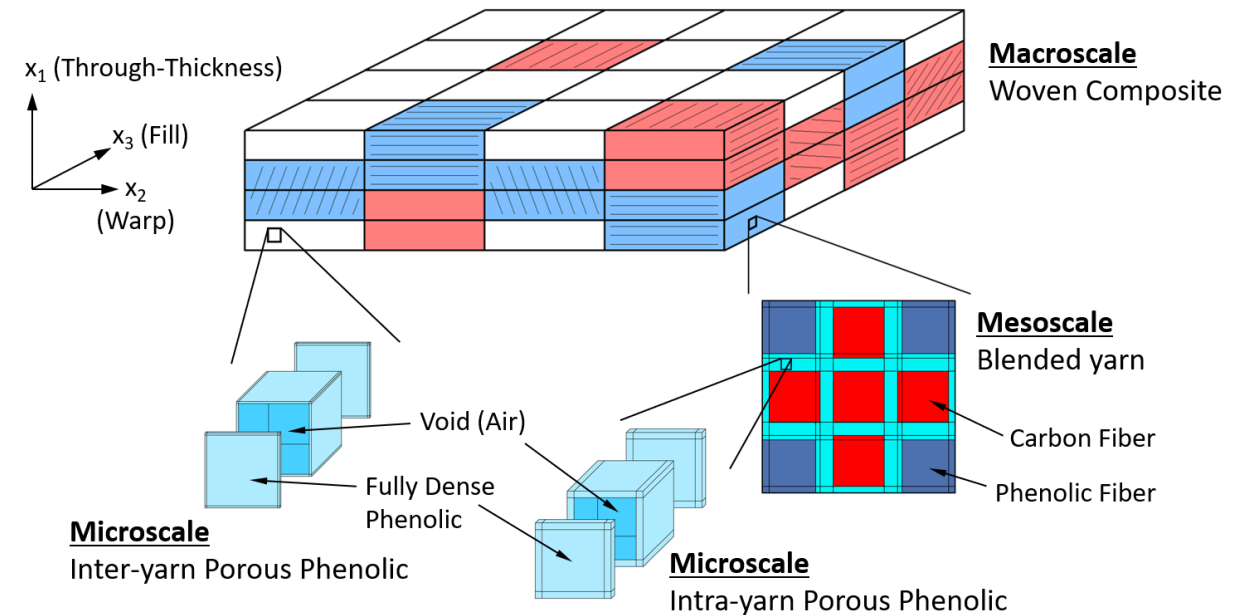
$$\mathbf{C}_0^* = \sum_{\alpha_0} v_{\alpha_0} \left\{ \left(\mathbf{T}_4^1 \right)^{-1} \sum_{\alpha_1} v_{\alpha_1} \left[\left(\mathbf{T}_4^2 \right)^{-1} \sum_{\alpha_2} v_{\alpha_2} \mathbf{C}_2^{(\alpha_2)} \mathbf{A}_2^{(\alpha_2)} \right]^{(\alpha_1)} \mathbf{A}_1^{(\alpha_1)} \right\}^{(\alpha_0)} \mathbf{A}_0^{(\alpha_0)}$$

$$\left\{ \left[\mathbf{X}_2^{(\alpha_2)} \right]^{(\alpha_1)} \right\}^{(\alpha_0)} = \left\{ \left[\mathbf{A}_2^{(\alpha_2)} \right]^{(\alpha_1)} \right\}^{(\alpha_0)} \left\{ \left[\mathbf{T}_2^2 \right]^{(\alpha_1)} \right\}^{(\alpha_0)} \left\{ \mathbf{A}_1^{(\alpha_1)} \right\}^{(\alpha_0)} \left\{ \mathbf{T}_1^1 \right\}^{(\alpha_0)} \mathbf{A}_0^{(\alpha_0)} \bar{\mathbf{X}}_0$$

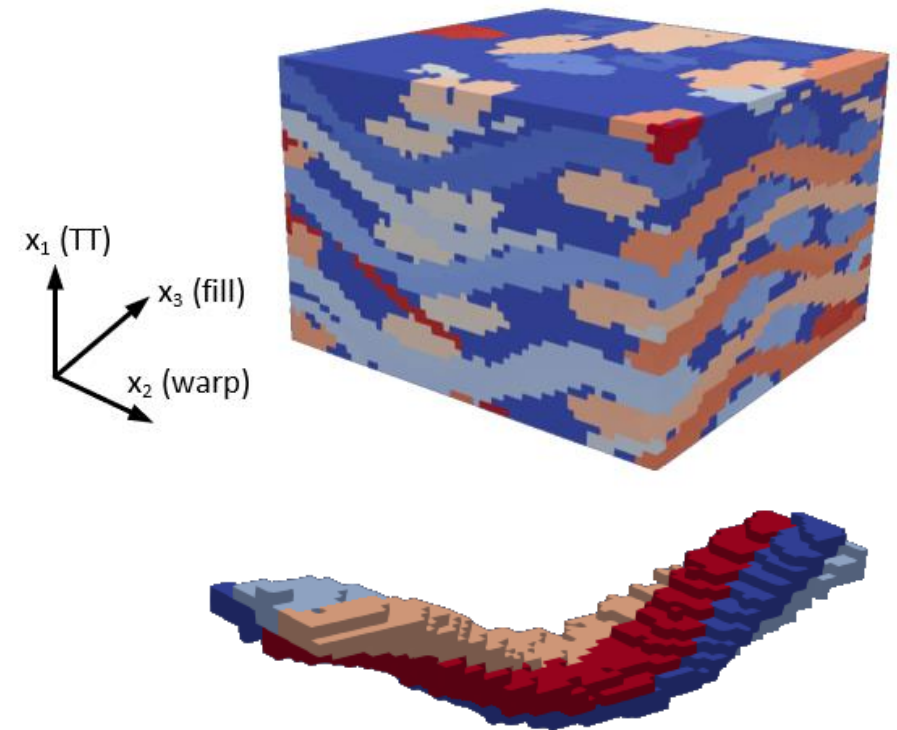
$$\left\{ \left[\boldsymbol{\varepsilon}_2^{(\alpha_2)} \right]^{(\alpha_1)} \right\}^{(\alpha_0)} = \left\{ \left[\mathbf{A}_2^{(\alpha_2)} \right]^{(\alpha_1)} \right\}^{(\alpha_0)} \left\{ \left[\mathbf{T}_2^2 \right]^{(\alpha_1)} \right\}^{(\alpha_0)} \left\{ \mathbf{A}_1^{(\alpha_1)} \right\}^{(\alpha_0)} \left\{ \mathbf{T}_2^1 \right\}^{(\alpha_0)} \mathbf{A}_0^{(\alpha_0)} \bar{\boldsymbol{\varepsilon}}_0$$

- **Idealized NASMAT model**
- Coarse representation of weave, blended yarn, and porous phenolic
- Synergistic multiscale analysis – all scales coupled
- HFGMC micromechanics used for all unit cells for consistency
- Periodic boundary conditions applied at the macroscale
- Calculated effective moduli and thermal conductivities
- **Key Advantages:** Solution speed, coupled multiscale analysis
- **Key Disadvantage:** approximation fidelity

AS4 Carbon Fiber		Phenolic Fiber and Fully Dense Phenolic Matrix		Air inside voids	
E_{Axial} (GPa)	230	E (GPa)	3.5	E (GPa)	0.035
$E_{\text{Transverse}}$ (GPa)	20	ν (-)	0.35	ν (-)	0
ν_{Axial} (-)	0.17	κ (W/mK)	0.25	κ (W/mK)	0.025
$\nu_{\text{Transverse}}$ (-)	0.17				
G_{Axial} (GPa)	15				
κ_{Axial} (W/mK)	6.9				
$\kappa_{\text{Transverse}}$ (W/mK)	2.52				



- **NASMAT model more representative of as-manufactured composite**
- X-ray CT data iteratively downsampled to give a model with ~150k subvolumes
 - Able to capture key features of weave
 - Tow orientations calculated using PuMA
- Hierarchical multiscale analysis
 - Homogenized properties from coarse model used
- Non-periodic boundary conditions used with HFGMC
- Fields volume averaged
- Calculated effective moduli and thermal conductivities
- **Key Advantage**: model fidelity
- **Key Disadvantages**: solution speed (30x), single scale analysis

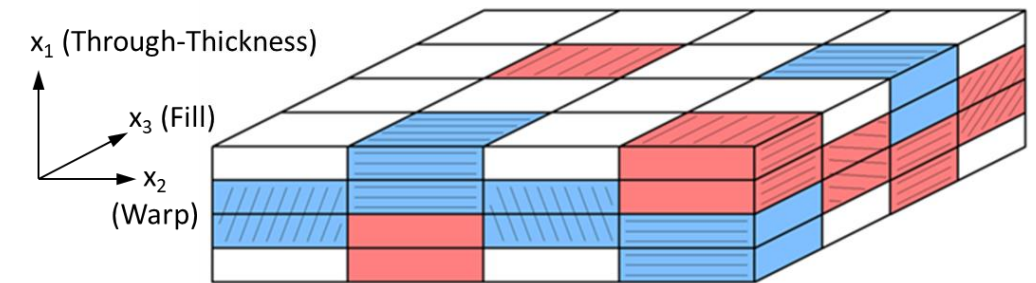
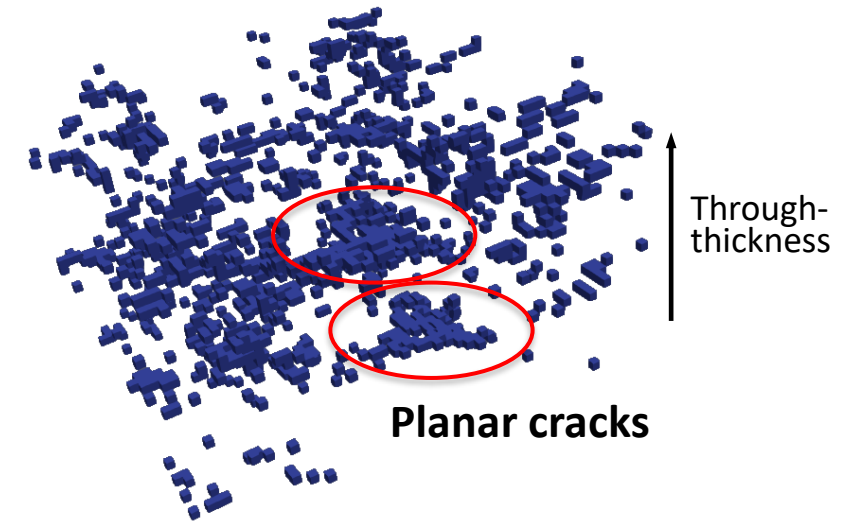


Model Comparisons

- Volume fractions slightly different between models
- Excellent agreement in in-plane mechanical results
- Good agreement in in-plane thermal results
- Approximate agreement in through-thickness results

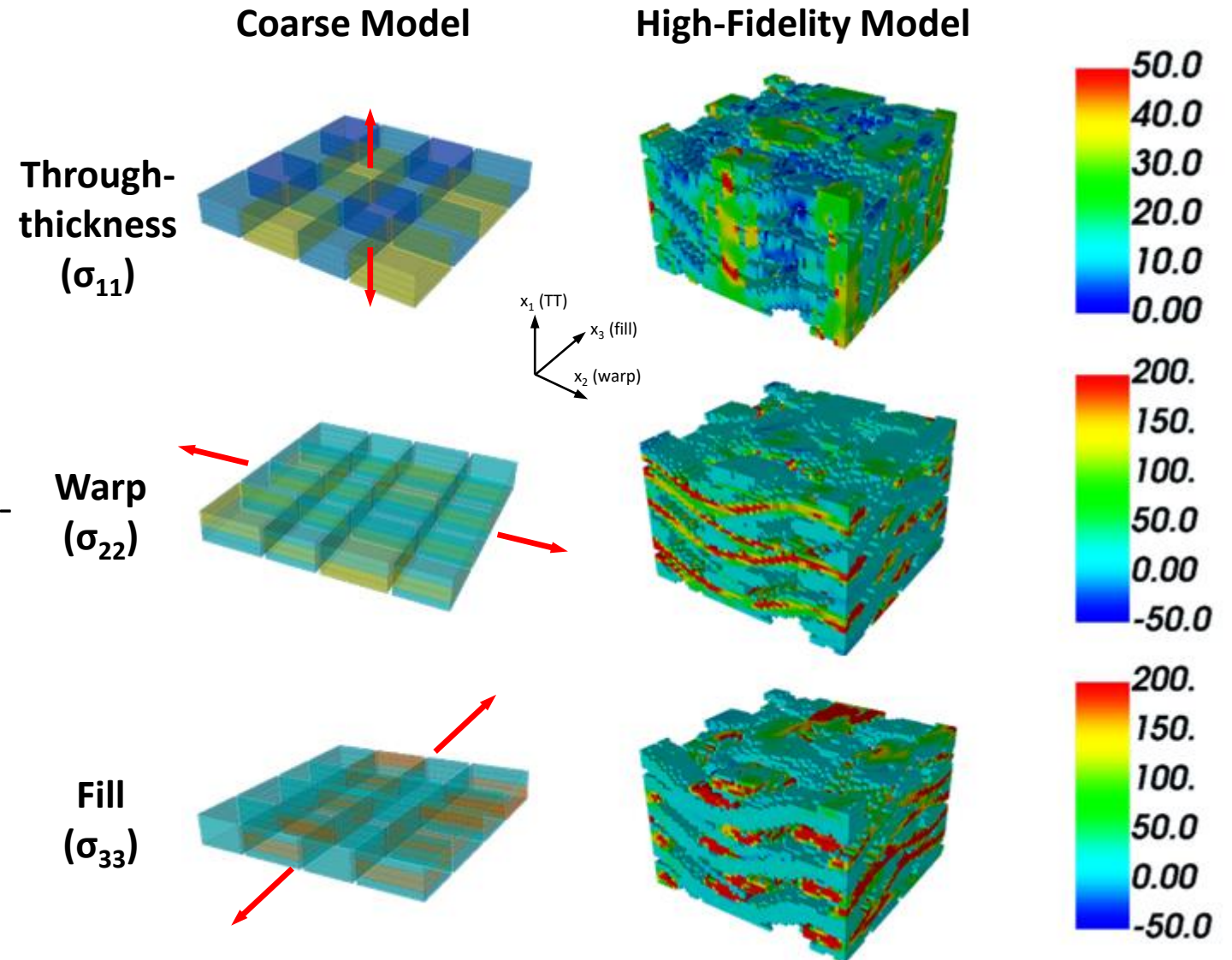
Property	Coarse Model (Periodic)	High-Fidelity Model (Non-Periodic)	Difference
%V of Yarns	51.9%	53.7%	-3.4%
%V of Inter-Yarn Matrix	48.1%	45.3%	6.2%
%V of Cracks	0%	0.9%	-
E_{warp} (MPa)	3987	4141	-3.7%
E_{fill} (MPa)	5174	5208	-0.7%
E_{TT} (MPa)	1625	1139	42.7%
κ_{warp} (W/mK)	0.512	0.548	-6.6%
κ_{fill} (W/mK)	0.581	0.542	7.2%
κ_{TT} (W/mK)	0.140	0.178	-21.3%

- **What could be causing the discrepancy between in-plane and through-thickness results?**
 - Through-thickness direction normal to stiff, highly conductive carbon fibers
 - Smaller changes result in larger percentage differences
 - Planar cracks – not present in coarse model
 - Replaced with inter-yarn porous matrix in high-fidelity model
 - Minimal effect on results (~1.5%)
 - Oversimplification of coarse model
 - Large matrix pockets
 - Statistical repeatability of high-fidelity unit cell
- Greater microstructure sensitivity in through-thickness direction



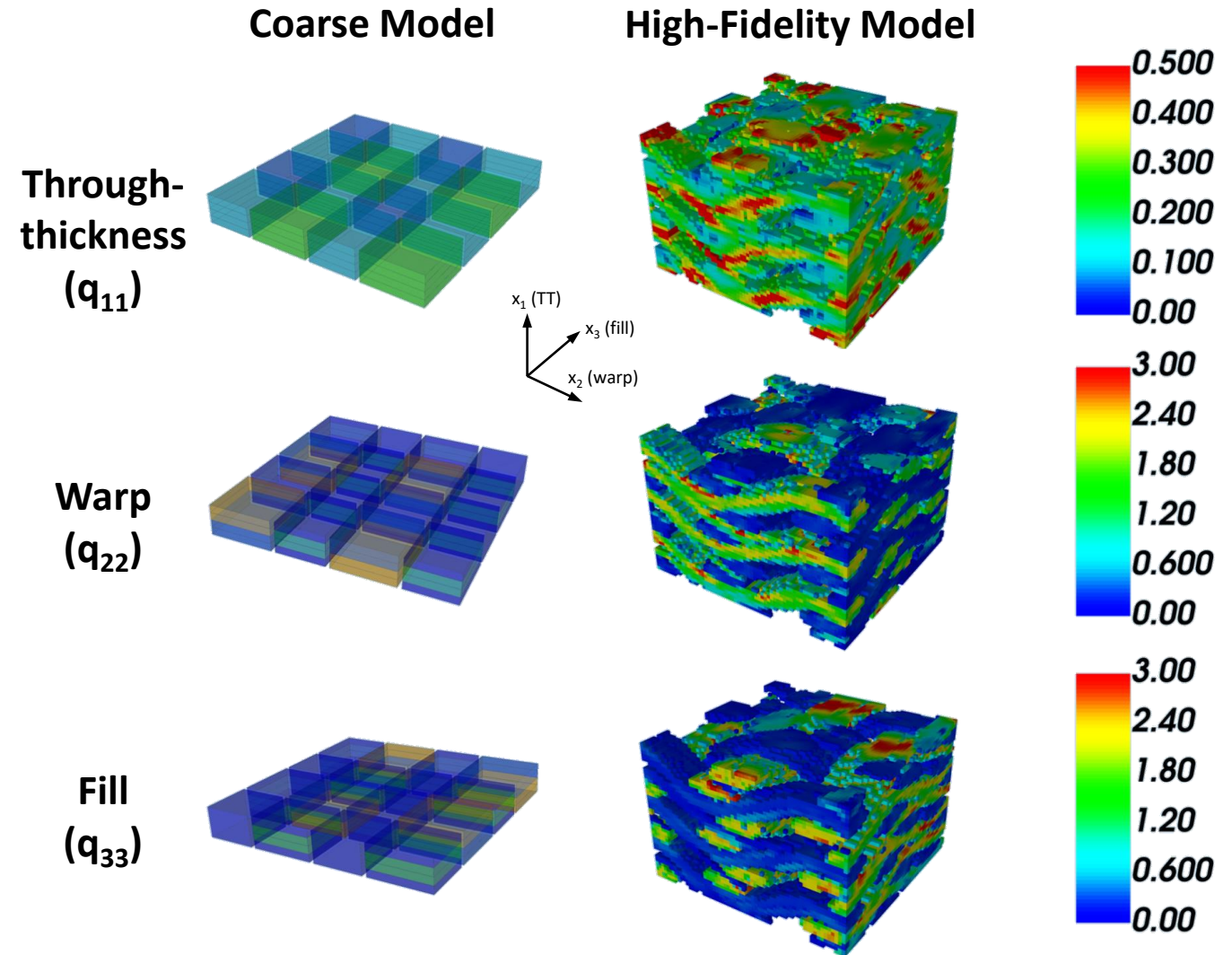
Comparison of Local Stress Fields

- Local stresses (in MPa) calculated after applying 1% global strain in each normal direction
- Coarse model results smear out local effects
- Through-thickness magnitudes less than in-plane
- Locally higher stresses for high-fidelity model results in tow overlap regions
- In-plane results for models aligned with yarn directions



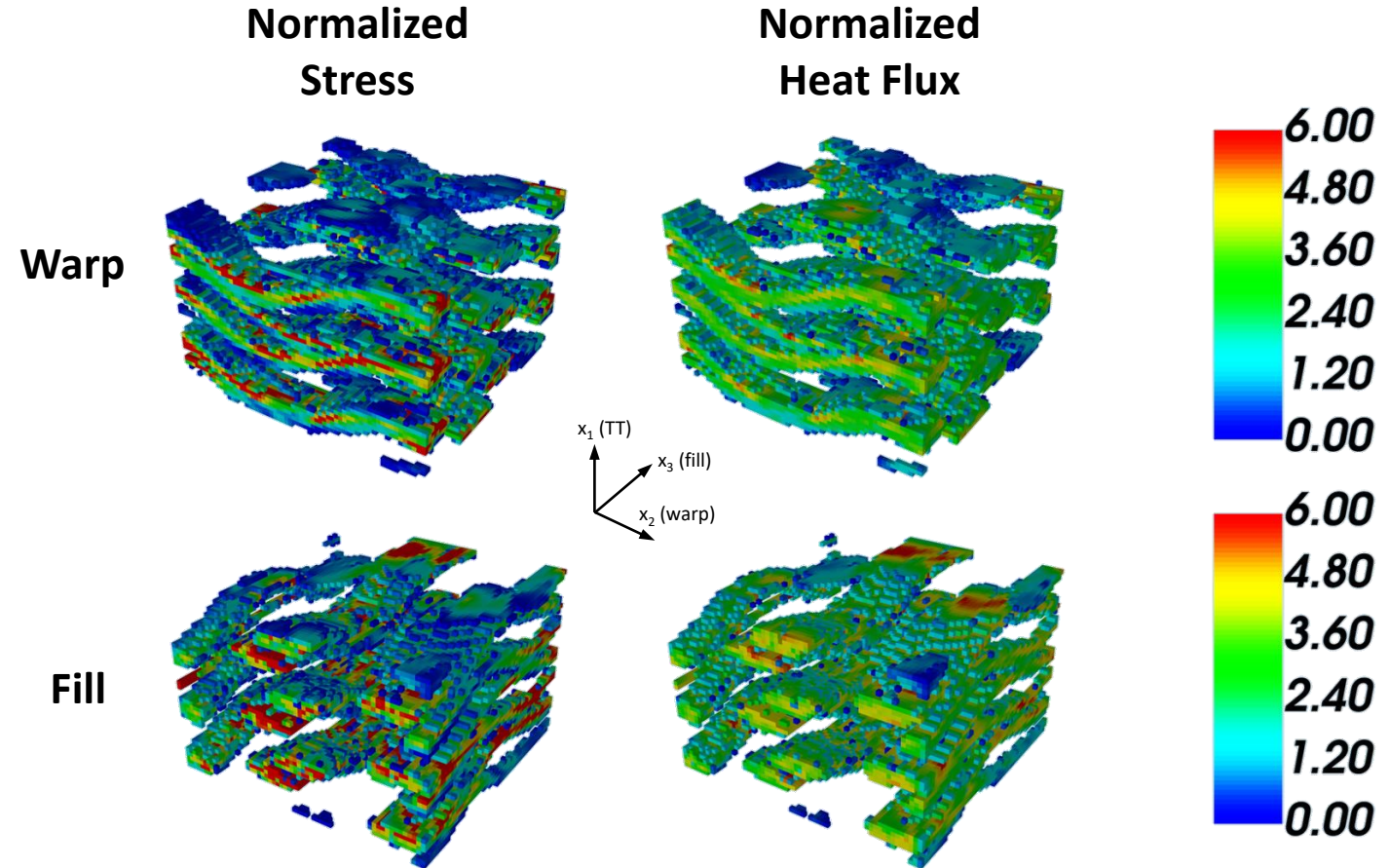
Comparison of Local Heat Flux Fields

- Local heat fluxes (in W/m²) calculated after applying a unit temperature gradient in each normal direction
- Coarse model results smear out local effects
- Through-thickness magnitudes less than in-plane
- Through-thickness results more sensitive to undulation angle rather than tow overlaps
- In-plane results for models aligned with yarn directions



Comparison of Mechanical and Thermal Results

- Only yarns in loading direction shown
- Significantly more variability in the stress fields than the heat flux fields
- Heat flux fields generally more constant along a yarn
- Normal/shear coupling present in mechanical problem, not present in thermal
 - In-plane results more sensitive to undulation angles in mechanical problem



Results normalized by volume average
of local results in particular direction

Summary and Conclusions

- Multiscale and multifidelity thermomechanical analyses of the 3D woven HEEET insulation layer performed
- Optical microscopy and x-ray CT data obtained and processed
 - Constituent inputs, high-fidelity woven architecture
- Workflow developed to convert x-ray CT data into a NASMAT model
- Two modeling approaches considered:
 - Coarse, synergistic multiscale analysis (periodic boundary conditions)
 - High-fidelity, hierarchical multiscale analysis (non-periodic boundary conditions)
- In-plane results generally in good agreement between approaches
- Some discrepancies observed in through-thickness direction
 - More sensitive to microstructure, concerns over statistical repeatability in as-manufactured system
- Reasonably good agreement in average local stress and heat flux fields
- Planning to investigate progressive damage and failure

Acknowledgements

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- new version released Sept. 2024



For questions email:
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