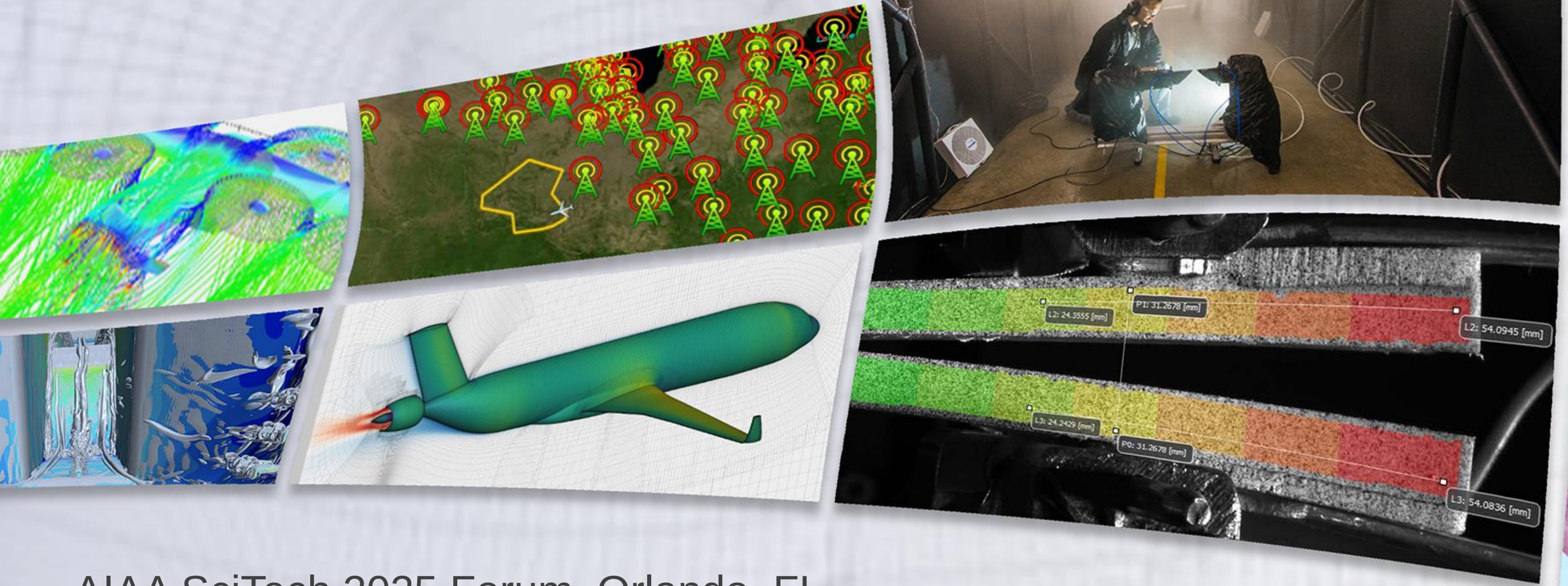
National Aeronautics and Space Administration

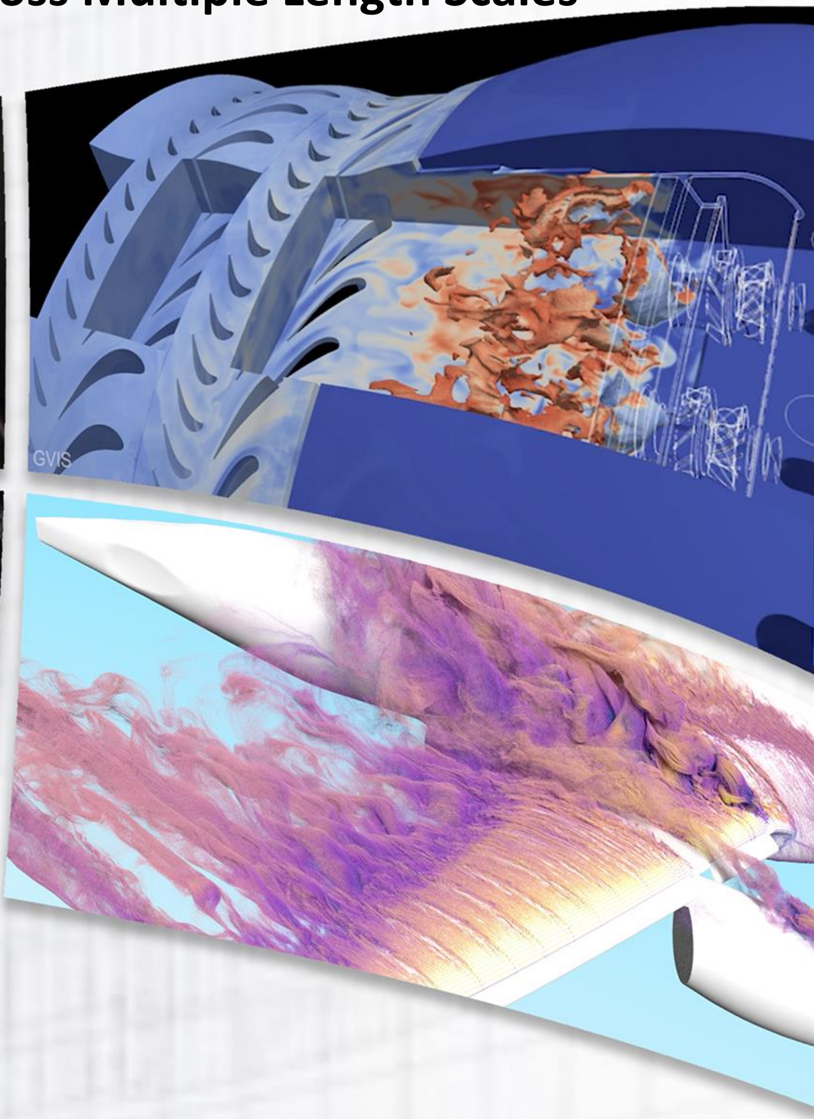
Transformational Tools and Technologies (T^3) Project

A Workflow to Rapidly Interrogate Multiscale Model Simulation Results Across Multiple Length Scales

Trenton M. Ricks, Brett A. Bednarcyk, Steven M. Arnold, Evan J. Pineda

NASA Glenn Research Center (GRC), Cleveland, OH





AIAA SciTech 2025 Forum, Orlando, FL

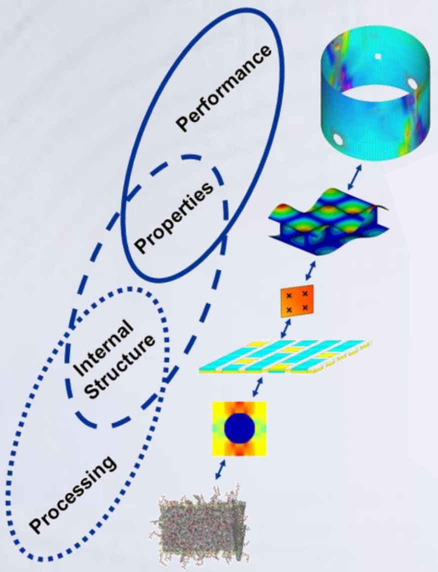
January 9, 2025

Innovative solutions through foundational research and cross-cutting tools

Vision 2040

A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems

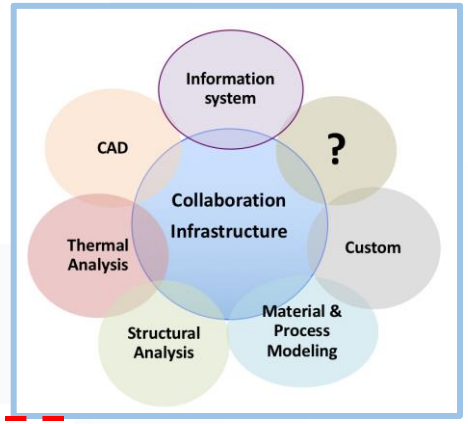
Provides a public/private investment strategy for the design of fit-for-purpose materials and structures



NASA CR 2018-219771

https://ntrs.nasa.gov

cyber-physical-social ecosystem



Nine Identified Key Element Discipline Areas

1. Models and Methodologies
2. Multiscale Measurement & Characterization Tools and Methods
3. Optimization & Optimization Methodologies
4. Decision Making and UQ
5. Verification & Validation
6. Data, Informatics, & Visualization
7. Workflows & Collaboration Frameworks
8. Education & Training
9. Computational Infrastructure

2040 Vision State:

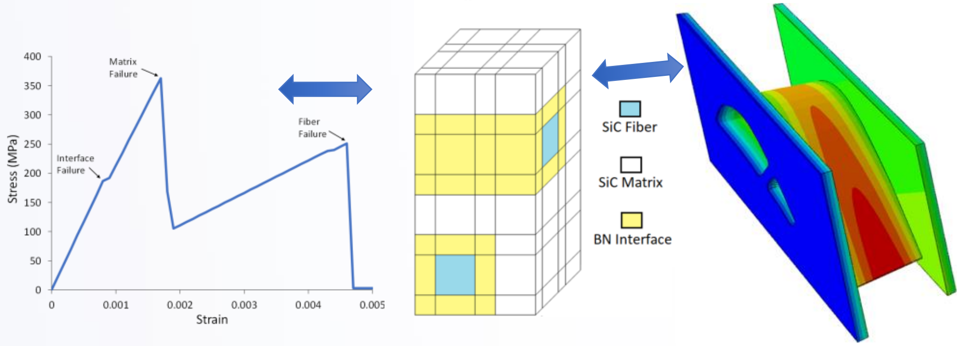
*A cyber-physical-social ecosystem that impacts the supply chain to **accelerate** model-based concurrent design, development, and deployment of materials and systems throughout the product lifecycle for **affordable**, **producible** aerospace applications*

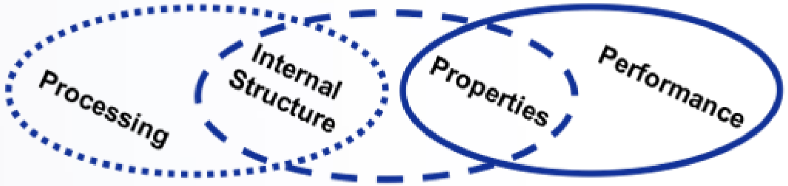
Why Should You Care About Multiscale Visualization?

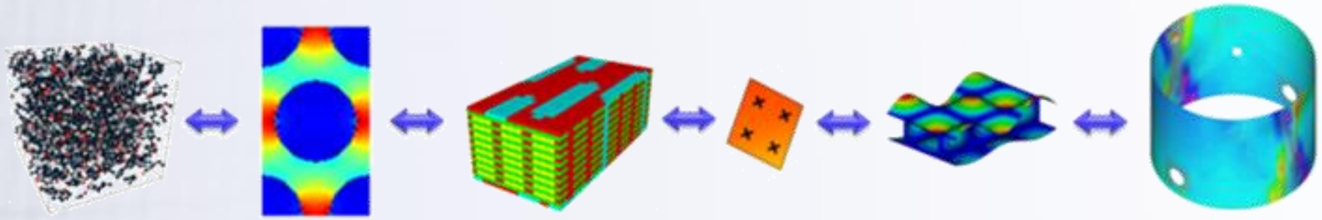
- Many materials have mechanisms and features at multiple length scales
  - Allows a detailed interrogation of driving forces at appropriate subscales for a given mechanism
  - Example problems in this presentation demonstrate this
- Verification and validation of constitutive, damage, and failure models requires detailed visualization capabilities
  - Becomes even more essential for multiscale problems
- Most visualization tools show results at only one scale
  - Q: how can you trust results and know they are accurate?
- Allows users to leverage large amounts of data generated during an analysis to make better informed decisions
- Multiscale visualization allows users to rapidly perform trade studies on individual methods

NASA Multiscale Analysis Tool (NASMAT)

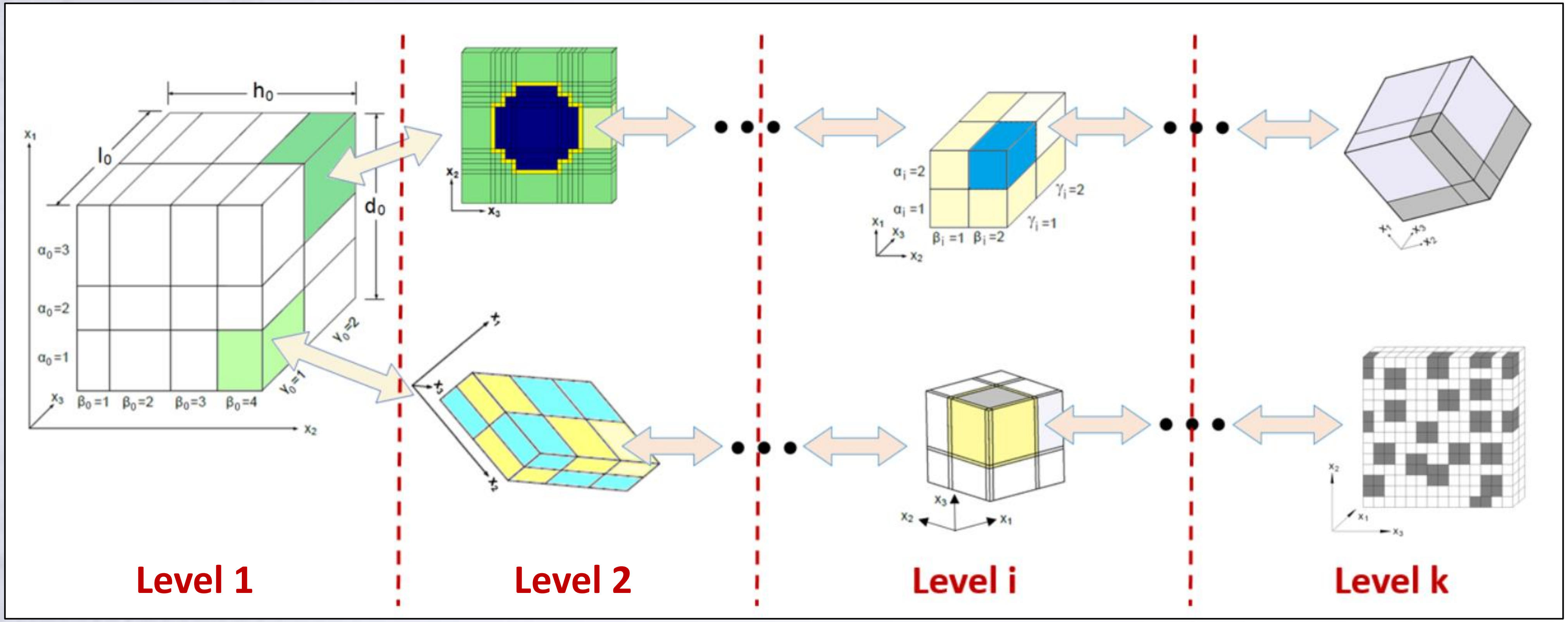
- Successor to MAC/GMC and FEAMAC toolsets
- A framework designed to support massively multiscale modeling
    - Solves real, large-scale, non-linear, thermo-mechanical problems
- Modular design to support "plug-and-play" capabilities
    - Operational components categorized into NASMAT procedures
- 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







Multiscale Recursive Micromechanics (MsRM)



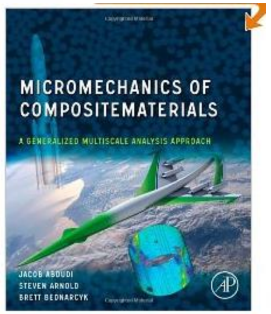
A Brief History of Micromechanics and Multiscale Analysis at NASA GRC*

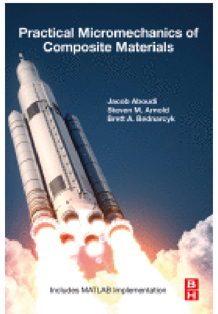
1992 – 2002: Development of basic tools/theories/methods

- Inelastic deformation/constitutive model development
- Fiber-matrix debonding/interfaces
- Fatigue, creep fatigue
- Laminate dominated

Focus shift:

- Woven/braided composites
- Multiscale
- Visualization tools
- Damage/failure

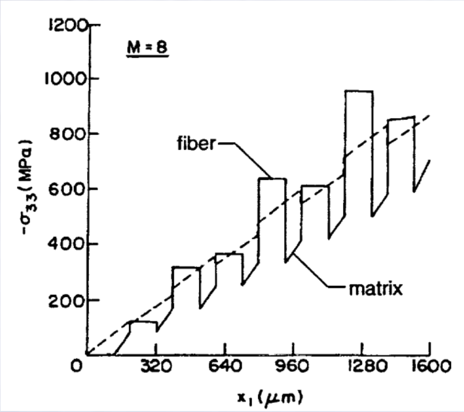


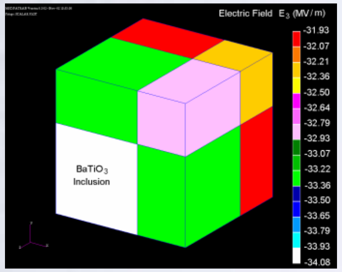


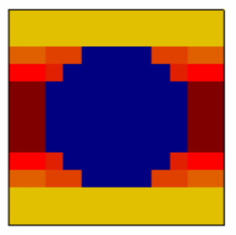
1987	MOC
1991	Aboudi Book
1992	GMC
1993	NASA Funded
1994	MAC 1.0
1995	GMC - 3D
1996	MAC/GMC 2.0
1997	FEAMAC 1.0
1999	MAC/GMC 3.0, MACPOST
2001	HFGMC
2002	MAC/GMC 4.0
2003	FEAMAC 2.0
2005	HyperMAC
2009	MSGMC
2010	MACE Est., FEAMAC-Pre/Post
2011	GrantaMAC
2013	Book Pub.
2016	NASMAT Dev. Starts
2018	NASMAT 1.0
2020	NASMAT 2.0
2021	Book Pub.
2022	NASMAT 3.0
2024	NASMAT 4.0

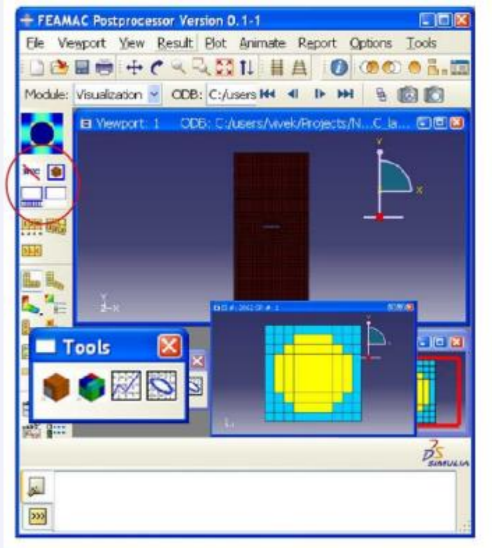
*Limited to our research group, not including seminal work of others (C. Chamis)

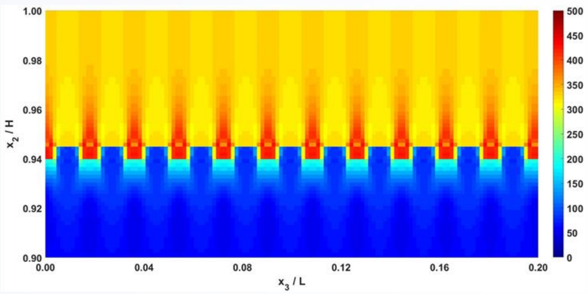
A Brief History of Micromechanics and Multiscale Analysis at NASA GRC











Detailed Visualization Limited to Two Scales!

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Pace of Methods Development and Application Has Far Exceeded Visualization Capabilities!

NASMAT PrePost

A Solution for Efficiently Visualizing Multiscale Modeling Results

Requirements

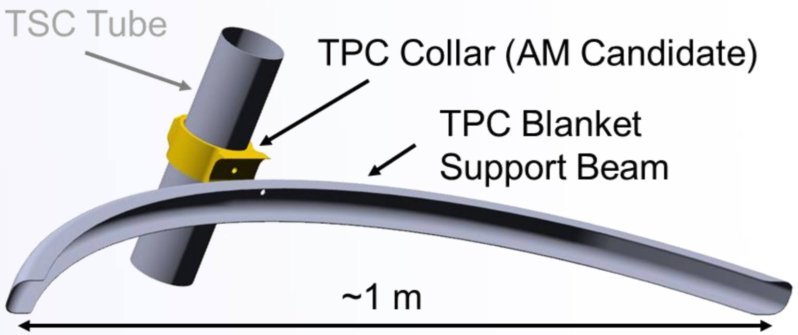
- Utilizes state-of-the-art visualization tools not dependent on paid software licenses
- Able to generate NASMAT models and incorporate legacy tools
- Can ingest large datasets and **quickly** visualize results at multiple scales
- Separate user-interface and utility functions for flexibility

Two example problems shown that capture relevant features across multiple length scales

Features/Capabilities

- Python development primarily utilizing PyQt5, VTK, H5py packages
- Standardized functions for developing NASMAT inputs and **processing NASMAT outputs**
- Able to seamlessly transition between results at multiple length scales
- User-interface separated from "guts" of code to allow standalone result viewing
- Converter to input VTU/VTI geometries from tools such as TexGen or PuMA
- Support utility to add NASMAT Abaqus results to NASMAT H5 file for viewing

Thermoplastic Terrestrial Point Design Collar

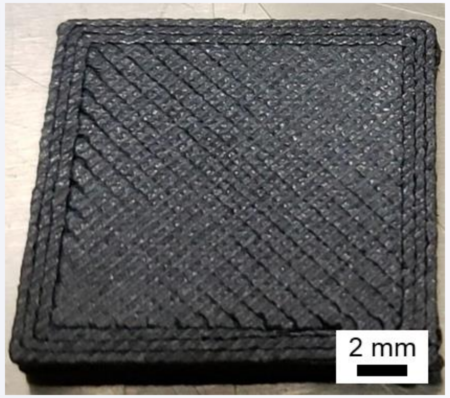


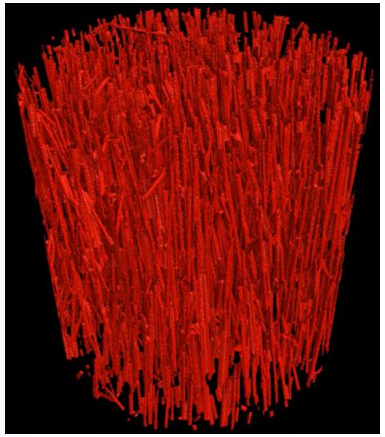
- Support collar and beam concept, adapted from hardware for Roman Space Telescope Deployable Aperture Cover

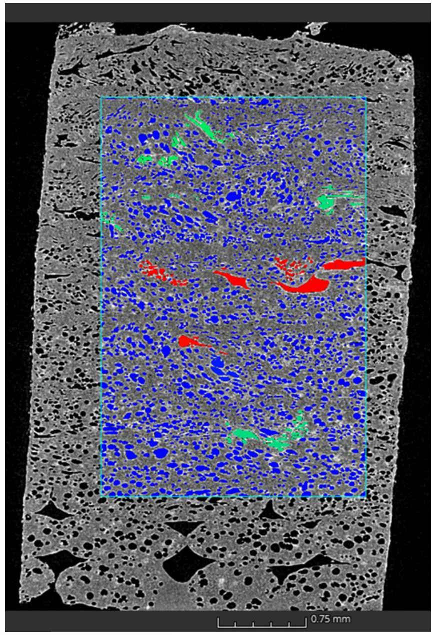
- Fused deposition printing fills in layers with a specified raster pattern

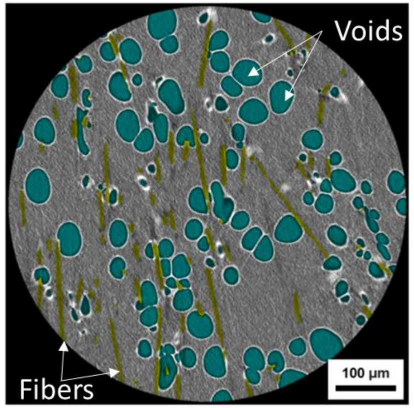
- Composite additive manufacture (AM) of collar sub-element

- PEEK matrix + ~10 vol% discontinuous carbon fiber









Bednarcyk, B.A., Mulhearn, W.D., Kaleel, I., Pineda, E.J., Steele, P.E. “Multiscale Modeling of Short fiber Additively Manufactured Composites,” presented at the ASME ASME Aerospace Structures, Structural Dynamics, and Materials Conference, April 29 – May 1, 2024, Renton, WA.

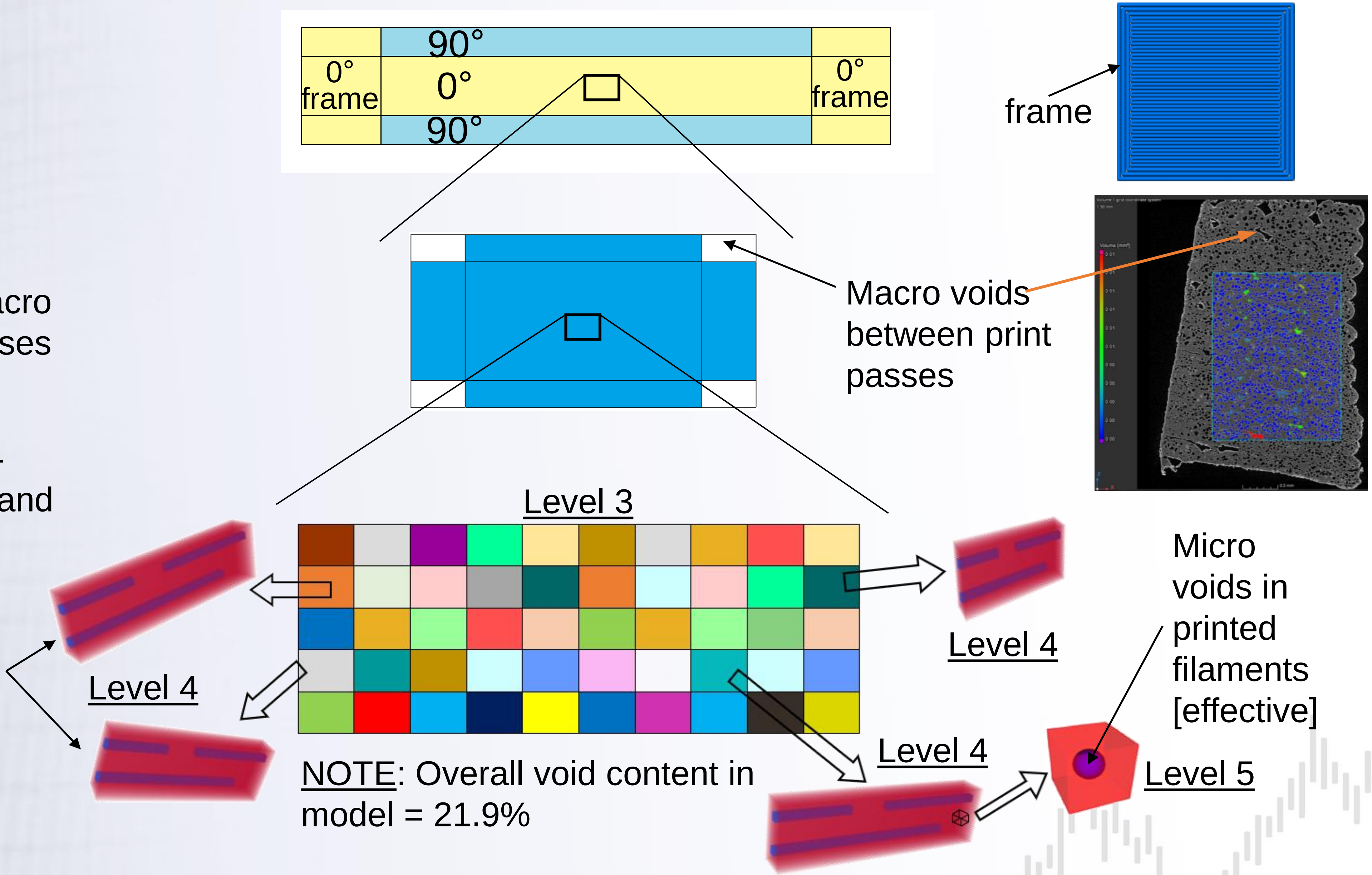
Multiscale AM Problem Setup

Level 1
Layered AM composite with framing

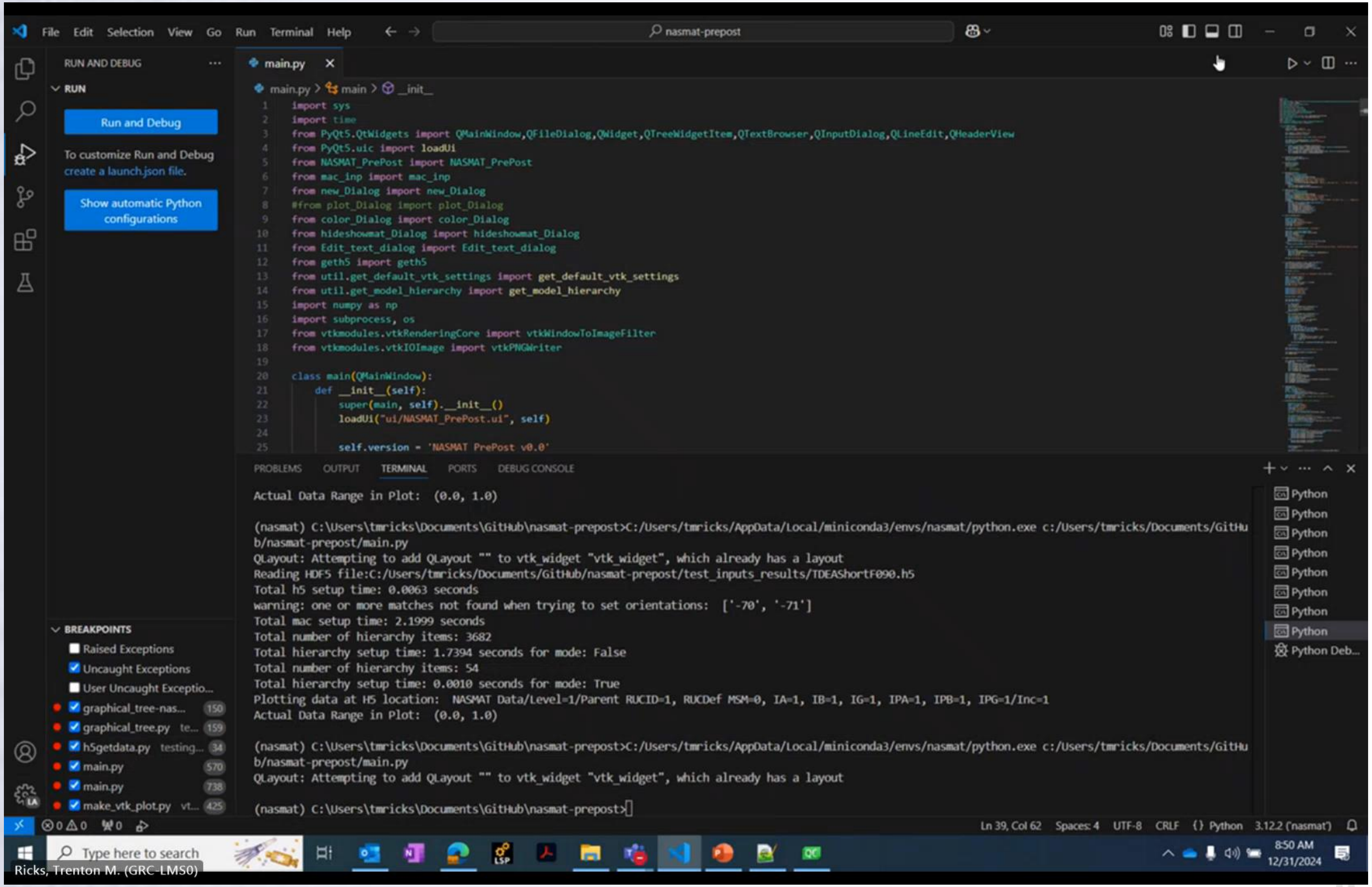
Level 2
Printed filament with macro voids between print passes

Level 3
Printed filament with as-measured fiber lengths and angles

Level 4
RUC with 2 short fibers



Thermoplastic AM Composite Visualization with NASMAT PrePost



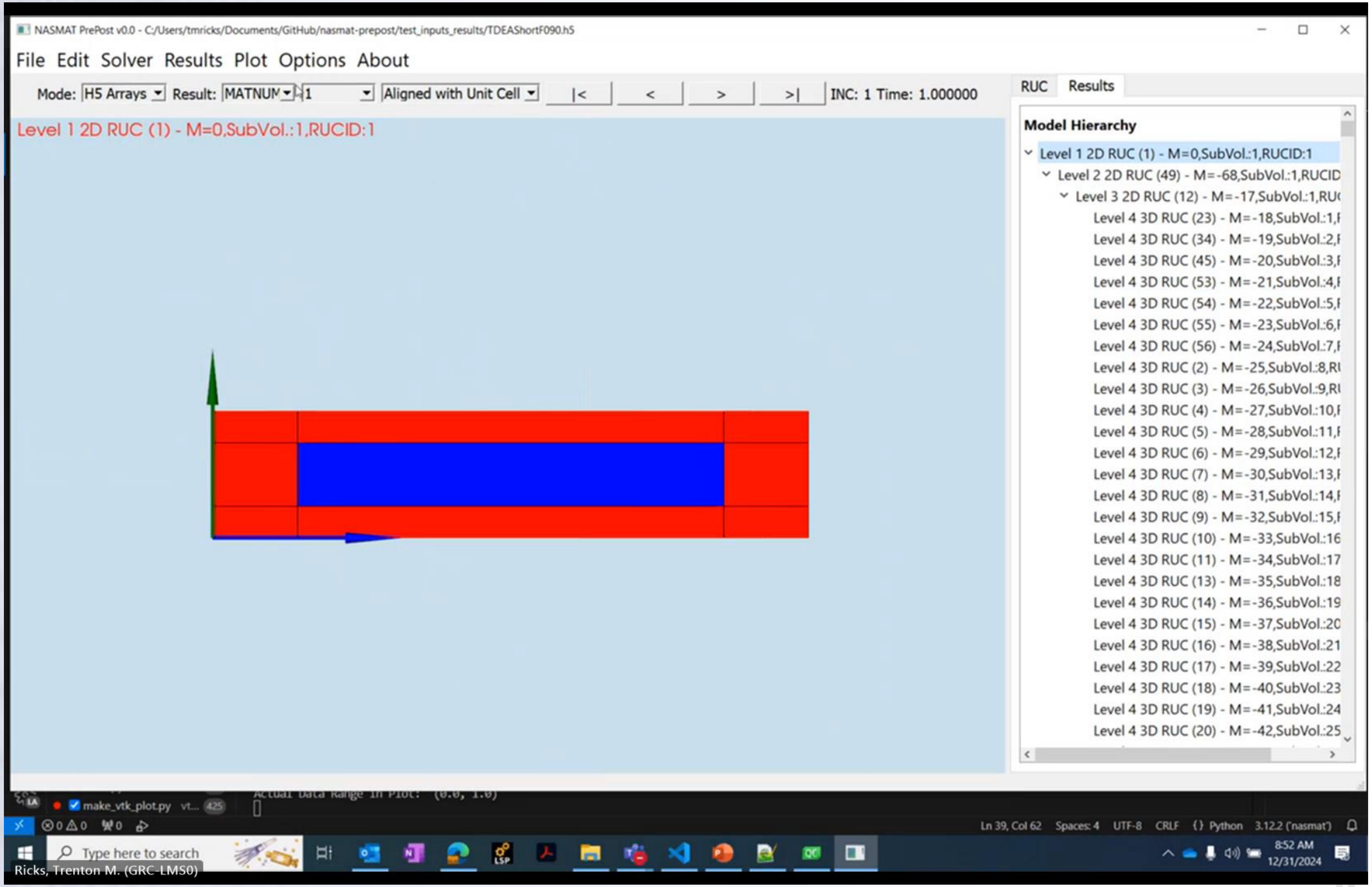
Green Arrow

RUC 2-direction

Blue Arrow

RUC 3-direction

Thermoplastic AM Composite Visualization with NASMAT PrePost



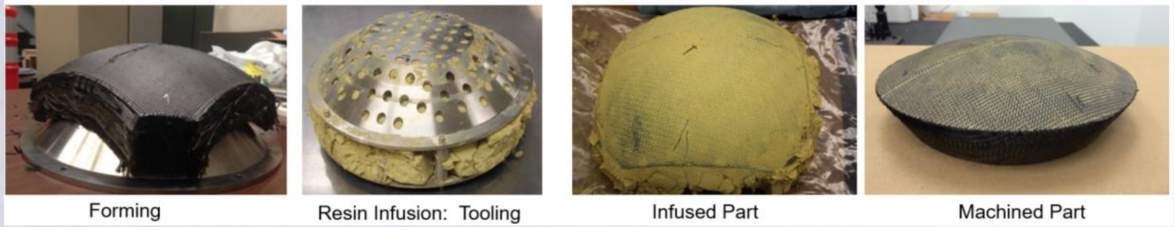
<u>Green Arrow</u>

RUC 2-direction

<u>Blue Arrow</u>

RUC 3-direction

Heatshield for Extreme Entry Environment Technology (HEEET)



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

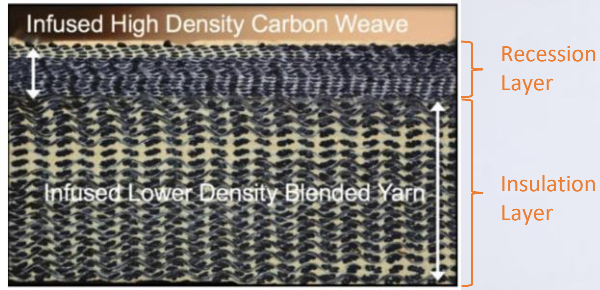
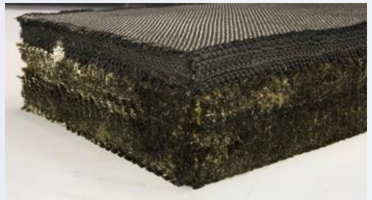
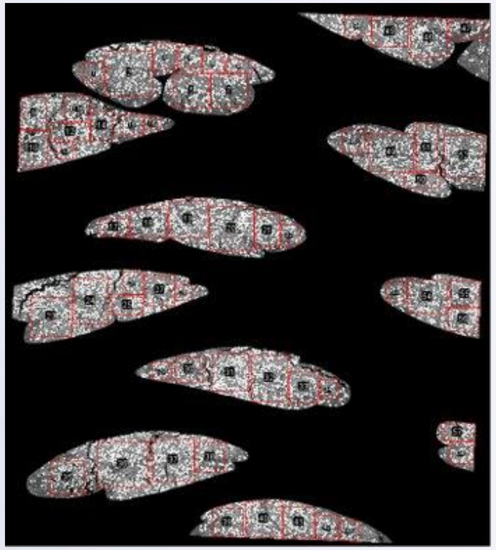
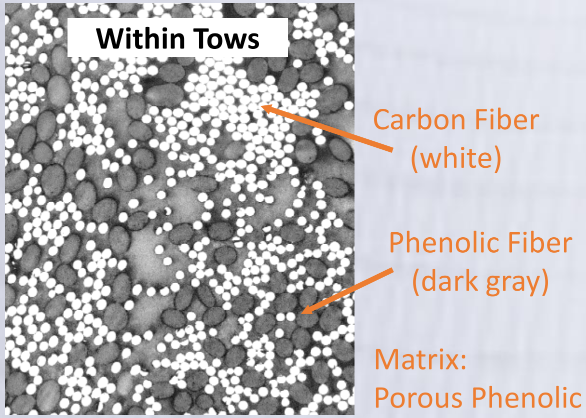


Image from: Fahy, W.P., Chang, A., Wu, H., and Koo, J.H. “Recent Developments of Ablative Thermal Protection Systems for Atmospheric Entry”, AIAA SciTech 2021, 19–21 January, 2021.





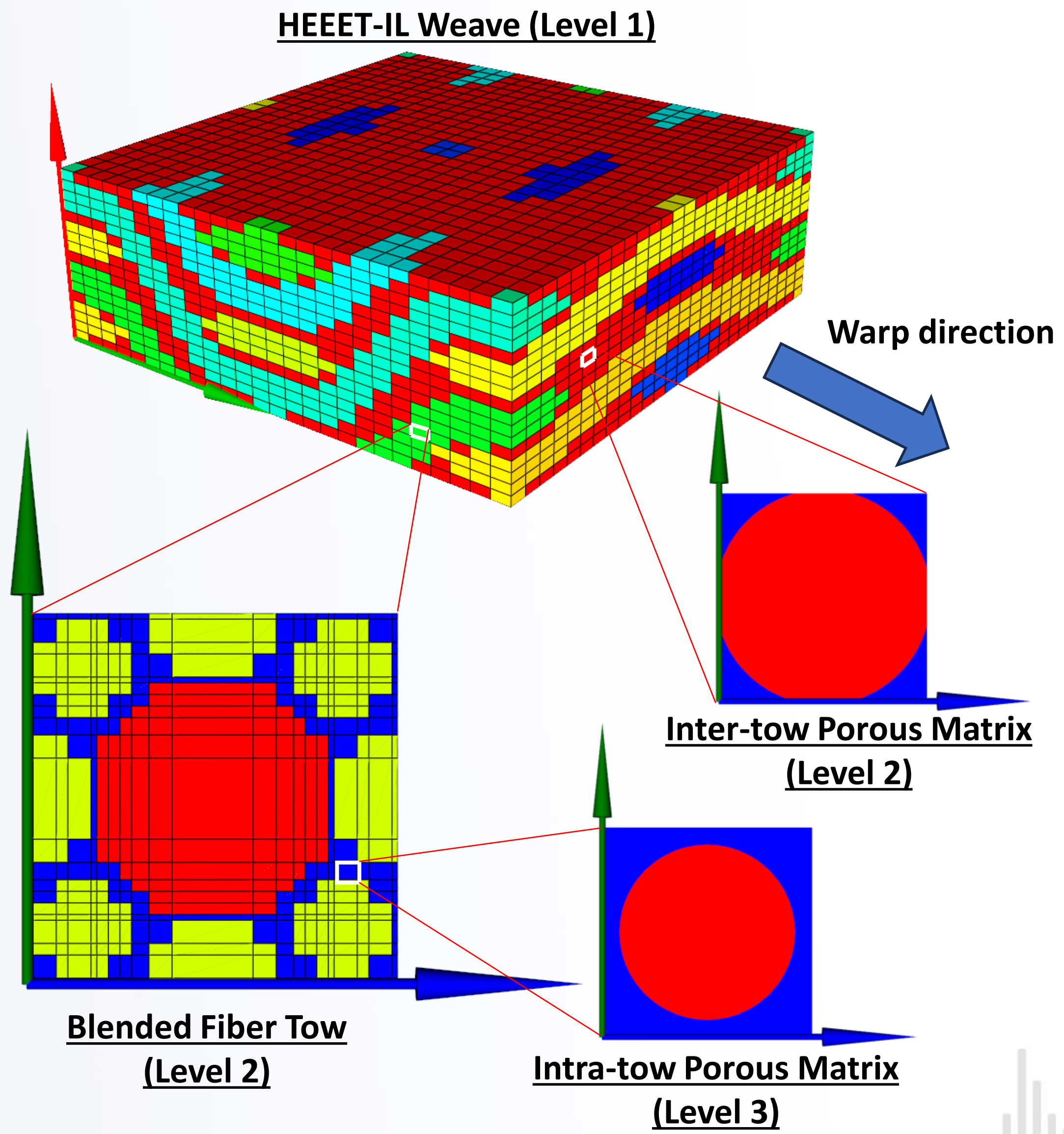


- **HEEET designed to be part of the thermal protection system for re-entry spacecraft**
- **HEEET comprised of two 3D woven layers:**
  - Recession and **<u>Insulation (IL)</u>**
- **Blended carbon and phenolic fiber tows**
- **Four tows twisted to form a yarn**
- **Yarns are woven to create preform**
- **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**

Ricks, T.M., Bednarcyk, B.A., Fraile Izquierdo, S., Abbott, L.J., & Aboudi, J. “Multiscale and Multifidelity Modeling of a 3D Woven Composite Thermal Protection System,” in the proceedings of the American Society for Composites Thirty-Ninth Technical Conference, October 21-23, 2024, San Diego, CA.

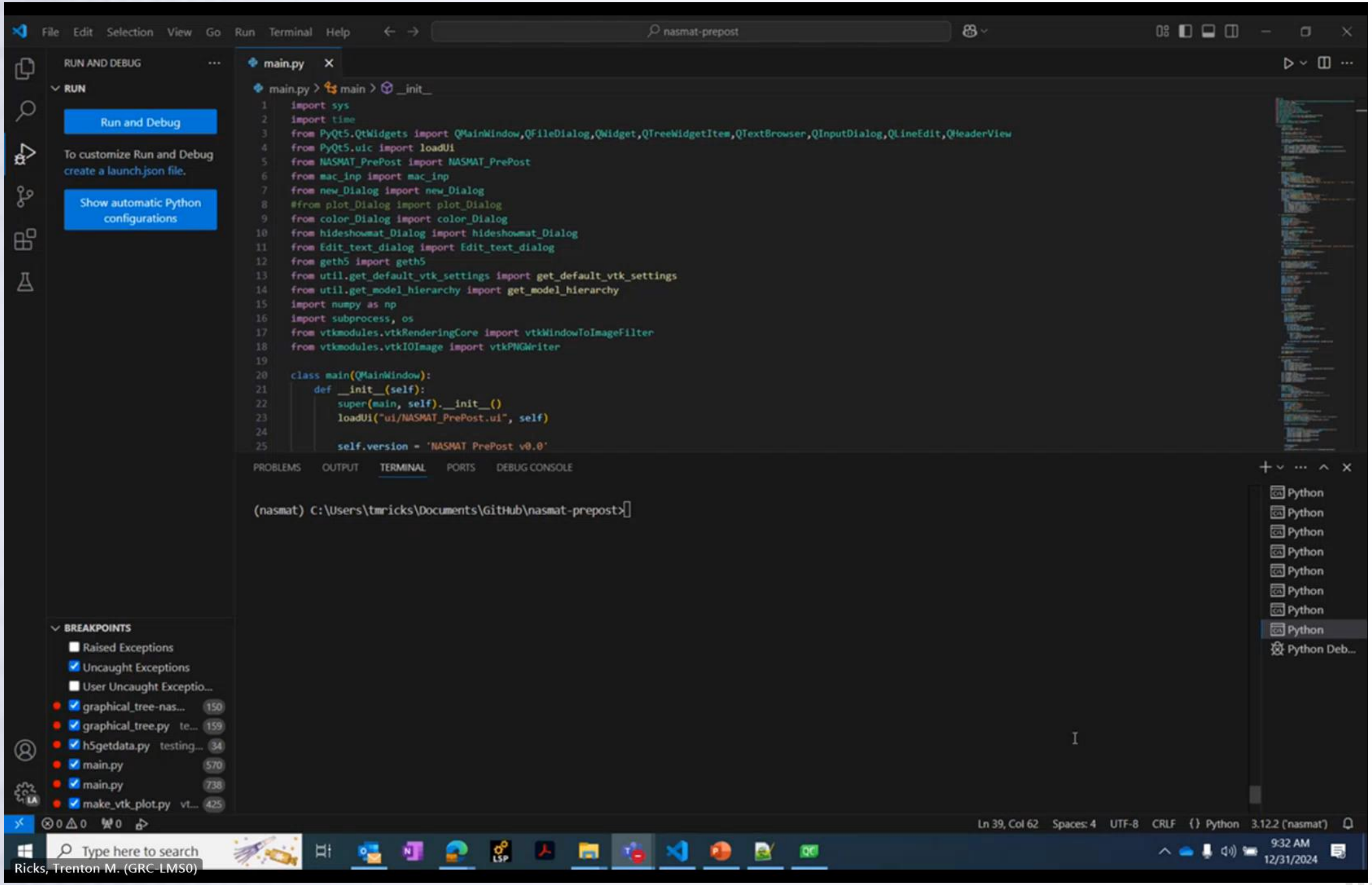
HEEET-IL Problem Setup

- Weave geometry and properties utilized from previous work*
- 17x26x26 subvolume grid generated in TexGen and solved with HFGMC3D
- Blended carbon and phenolic fiber tows modeled with a 21x21 subvolume grid and solved with HFGMC2D
- Inter-tow and intra-tow porosity modeled using spherical Mori-Tanaka
- Applied mechanical strain in warp-direction
- Subvolume elimination method used for failure
  - Max strain failure criterion (carbon fiber)
  - Hashin stress-based failure criterion (phenolic fiber and matrix)



*Bednarcyk, Brett A., et al. "Effect of Damage Progression on the Thermal Conductivity of 3D Woven Composite Thermal Protection System Materials." *AIAA SCITECH 2023 Forum*.
*Izquierdo, Sergio Fraile, Andrew P. Santos, and Lauren J. Abbott. "Certification by Analysis of Woven TPS: Fiber- and Weave-Scale Modeling." *NASA Ames EDL Summer Series*. 2023.

HEEET-IL Visualization with NASMAT PrePost



Red Arrow

RUC 1-direction

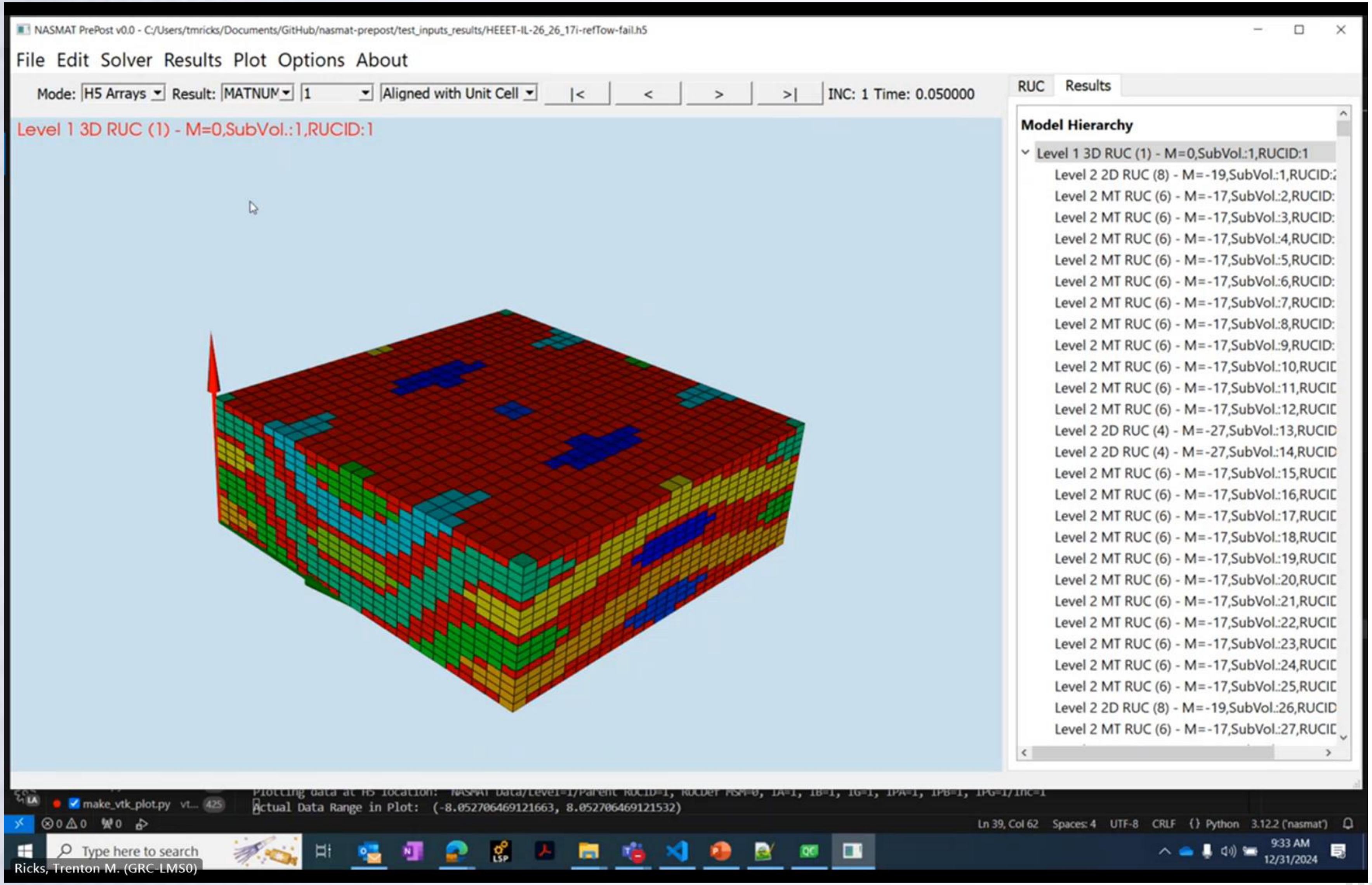
Green Arrow

RUC 2-direction

Blue Arrow

RUC 3-direction

HEEET-IL Visualization with NASMAT PrePost



Red Arrow

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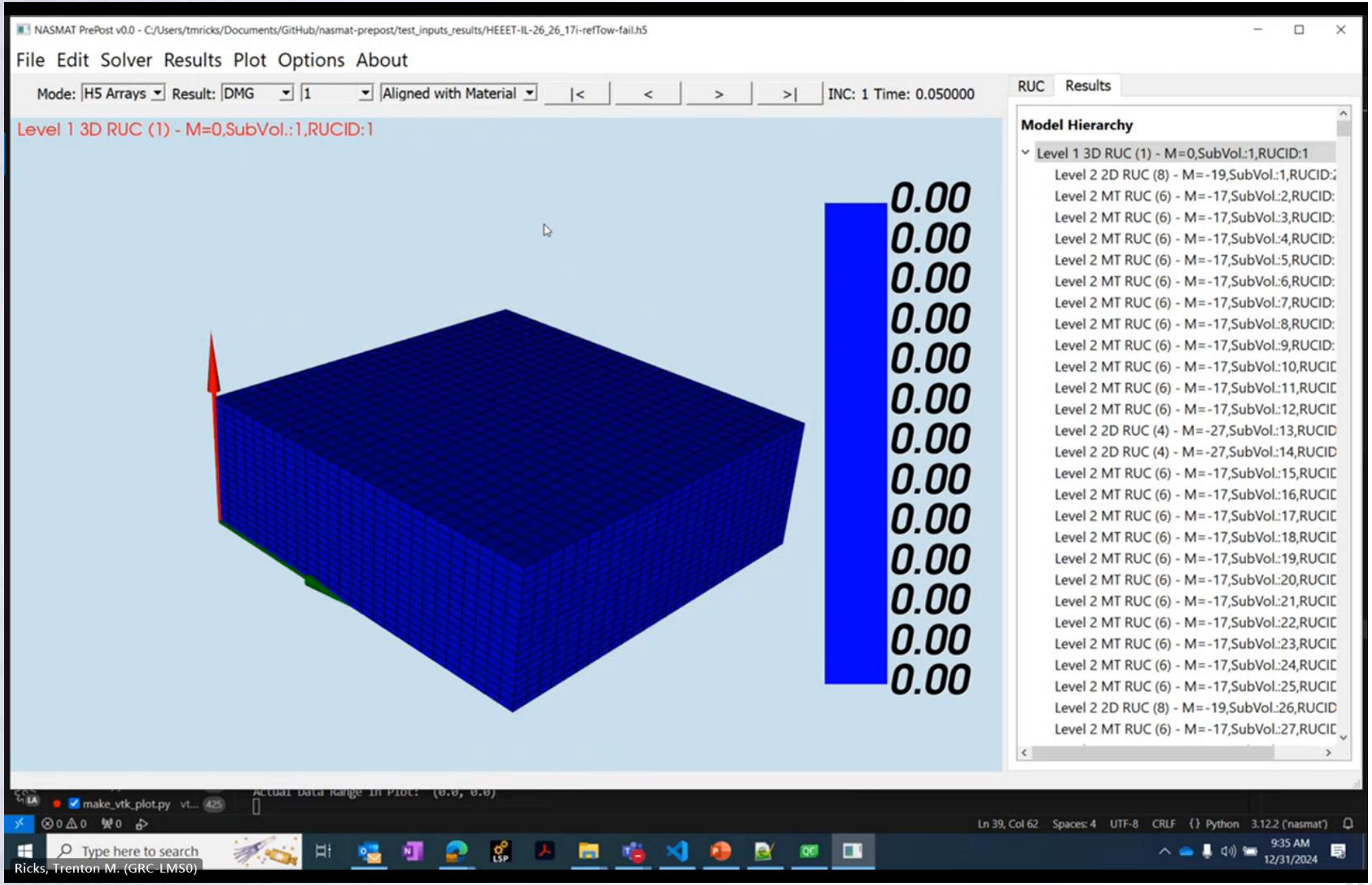
RUC 3-direction

HEEET-IL Visualization with NASMAT PrePost

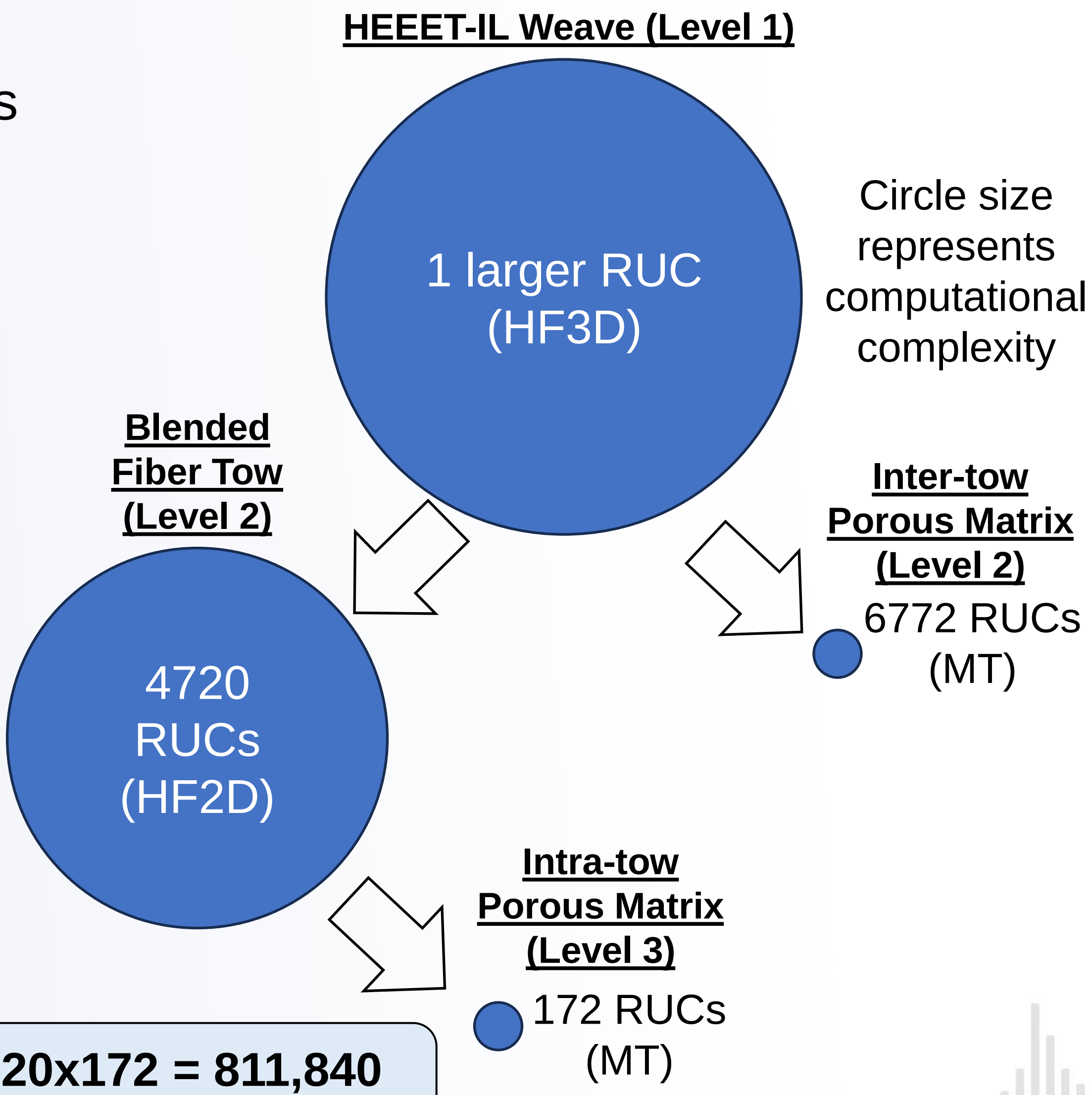


<u>Red Arrow</u>
RUC 1-direction
<u>Green Arrow</u>
RUC 2-direction
<u>Blue Arrow</u>
RUC 3-direction

What happened to the Intra-tow Matrix Results?

- HEEET-IL multiscale model included calculations for intra-tow porous matrix (including failure)
- Entire problem took 3.7 hrs to run on a single CPU
- Level 3 results not able to be efficiently output
- Methods to judiciously output results required

Real-time results viewing is less of a problem than outputting results to view



4720x172 = 811,840 unique Level 3 RUCs!

Summary and Conclusions

- Developed a new open-source Python tool for visualizing multiscale model simulation results generated with NASMAT
- Demonstrated workflow for two large multiscale analysis problems
- Modern software visualization packages can efficiently handle large multiscale datasets
- Data output limitation is a key challenge for visualizing multiscale results
    - Methods under development to judiciously output relevant data
- Version 1.0 specific to NASMAT, intent to generalize to allow multiscale visualization from other tools
- NASMAT PrePost expected to be posted to NASA Github (open-source) in Spring 2025

Acknowledgments

- Software development supported by the NASA Aeronautics Research Mission Directorate's Transformational Tools and Technologies Project

- Example applications supported by the NASA Space Technology Mission Directorate's Thermoplastics Development for Exploration Applications and Entry Systems Modeling projects

Request NASMAT via the NASA Software Catalog

- new version released Sept. 2024

NASA