Heat Shield Methods Applied to Extraterrestrial Regolith Composites

Andrew P. Santos[1]

Heat shield modeling: AS, Lauren J. Abbott[1], Justin Haskins[1]

Natural fiber-bioresin modeling: AS, Lauren J. Abbott[1]

Regolith project: Tane Boghonzian[2], AS, Sergio Fraile Izquierdo[2], Jaehyun Cho[2], Dan Rasky[3]

[1]*Thermal Protection Materials Branch;* [2]*AMA Inc, Thermal Protection Materials Branch;* [3]*Strategic Partnerships*

NASA Ames Research Center, Moffett Field, CA, USA

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University of Illinois - Chicago

Overview

The core focus of the NASA Ames **Thermal Protection Materials Branch** is to:
Apply and develop **experimental and computational methods to size, characterize, understand and develop materials for entry**

These methods apply to other materials, including:

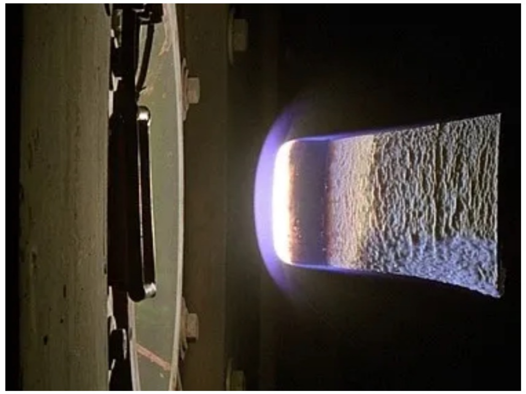
- Asteroids
- **Aviation components**
- **In-situ resource utilization (ISRU) for heat shields, landing pads, other operations**

Talk outline

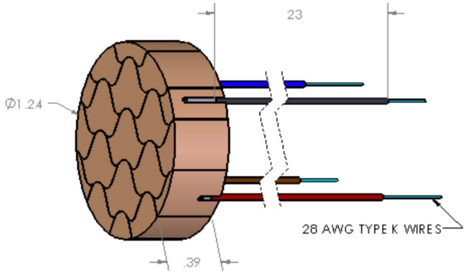
1. heat shield composites
2. Aviation composites
3. ISRU composites

Thermal Protection Materials Branch at Ames

Thermal Protection System (TPS) Materials Development

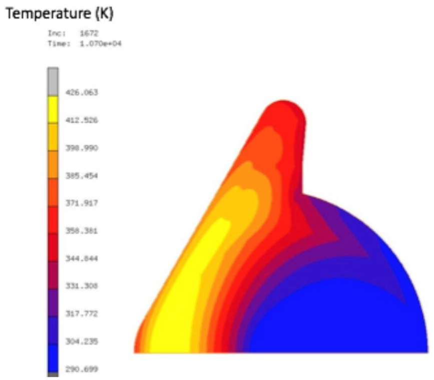


Testing and Fabrication



Sensors for Flight and TPS Development

Computational Materials



Design and Analysis

SPACE SHUTTLE

Galileo

LOFTID

ORION

DRAGONFLY

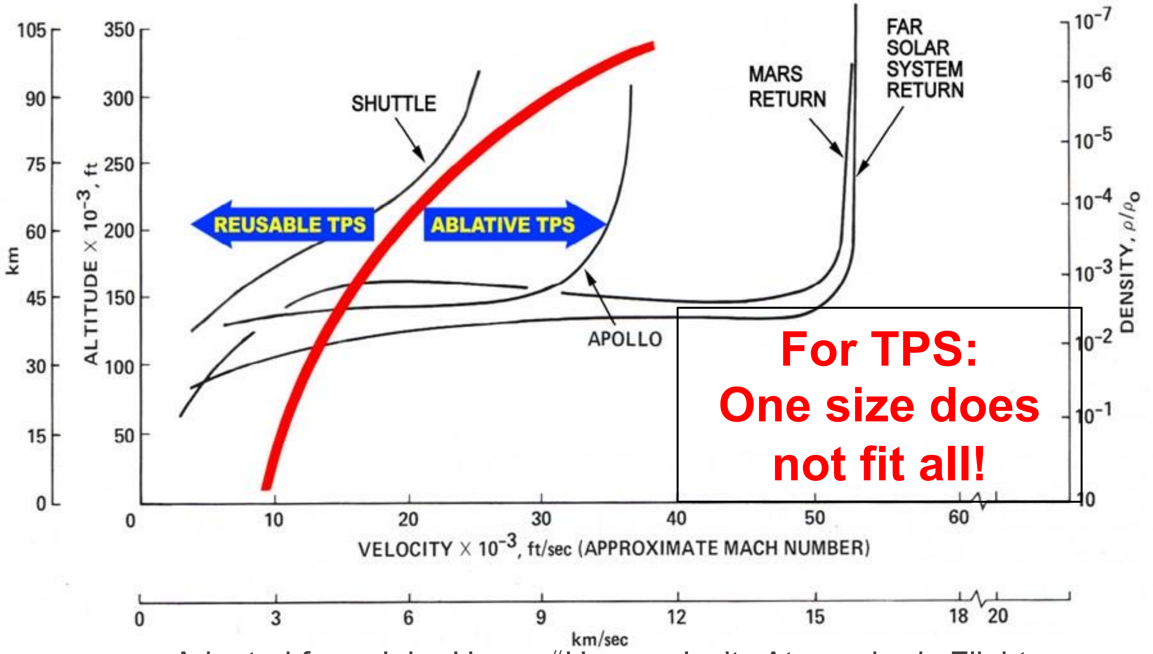
NASA | ESA MARS SAMPLE RETURN

TSM supports almost every mission that enters an atmosphere

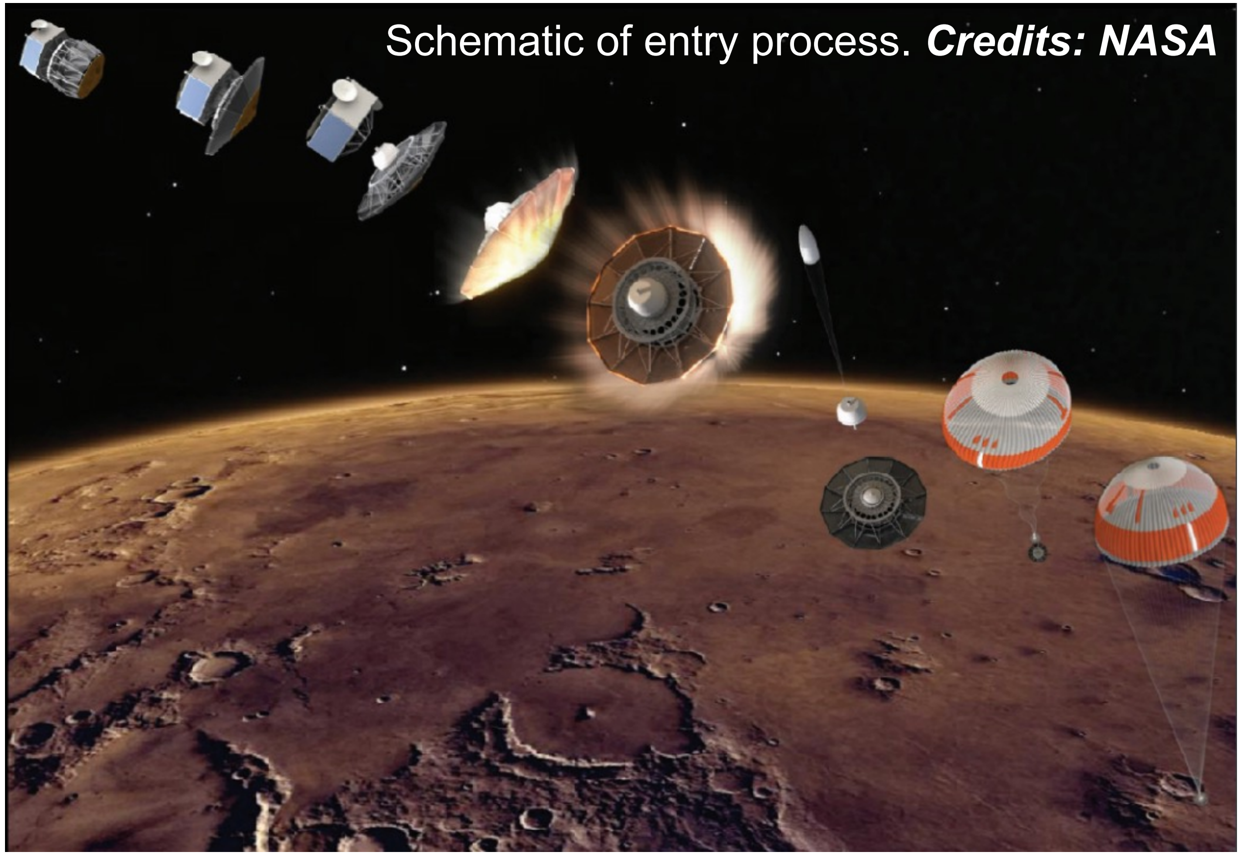
A Heat Shield for Every Mission

Heat shields, thermal protection systems (TPS) provide:
- thermal protection
- help slow down vehicles during entry
- mechanical strength

Mission's trajectory and entry environments set the thermal and mechanical requirements



Adapted from John Howe, "Hypervelocity Atmospheric Flight: Real Gas Flow Fields," NASA TM 101055, 1989



TPS composite materials have a wide range of microstructures and properties.

Thermal Protection Systems (TPS) Types

Reusables | Deployables | Ablators

Great for entry from low-earth orbit and backshells

Light, porous, low thermal conductivity, non-ablative, fibrous, ceramic.

X-37b with TUFROC wing leading edge. NASA

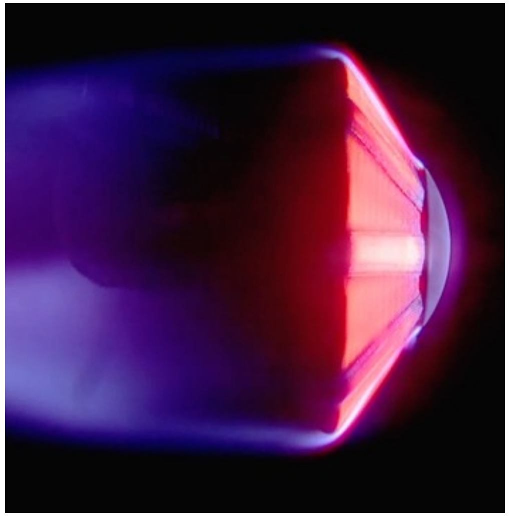
Shuttle era HRSI LI-900 tile. NASA

Thermal Protection Systems (TPS) Types

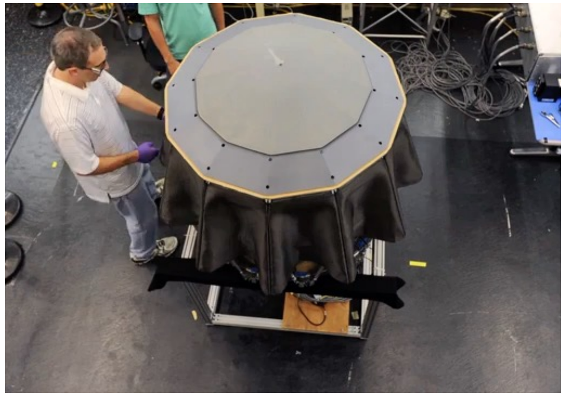
Reusables **Deployables** Ablators

Great for slowing down

3D TPS woven with carbon fibers in an umbrella-type design

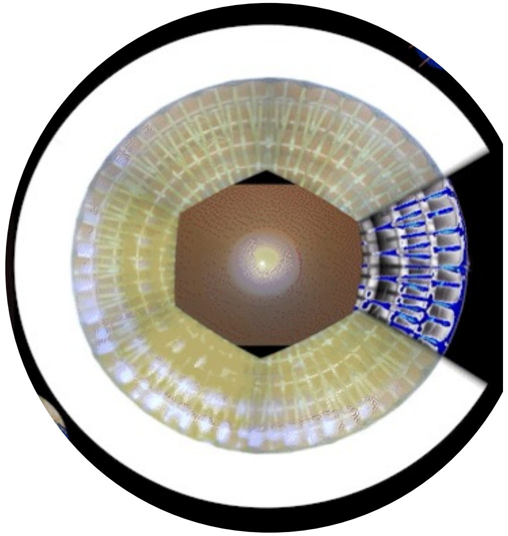


Adept in the Arc Jet. NASA



Adept deploying. NASA

Hypersonic Inflatable Aerodynamic Decelerator uses donut/torus shaped balloons



LOFTID entry. NASA

LOFTID deployment before entry. NASA

Thermal Protection Systems (TPS) Types

Reusables

Deployables

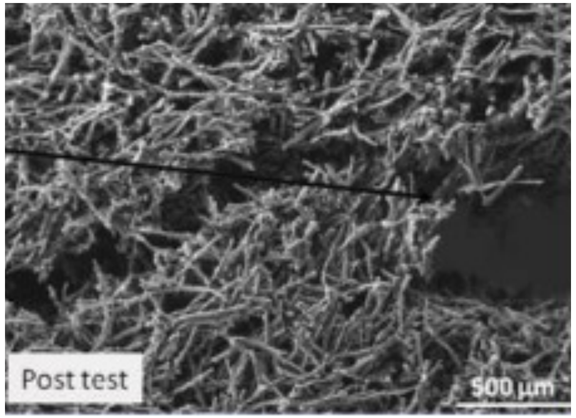
Ablators

Infused Fiber Networks

- Avcoat, PICA, SIRCA
- Lower density

Weaves

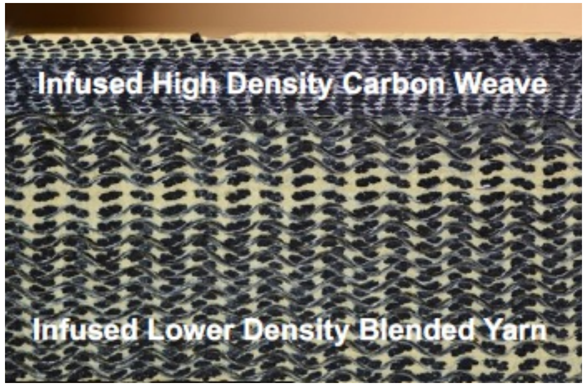
- HEEET, 3MDCP, 3D-MAT, Carbon-carbon
- Higher density for more extreme entry



SEM of fractured PICA

Artemis I Avcoat heat shield. NASA

Full infused weave demonstration unit



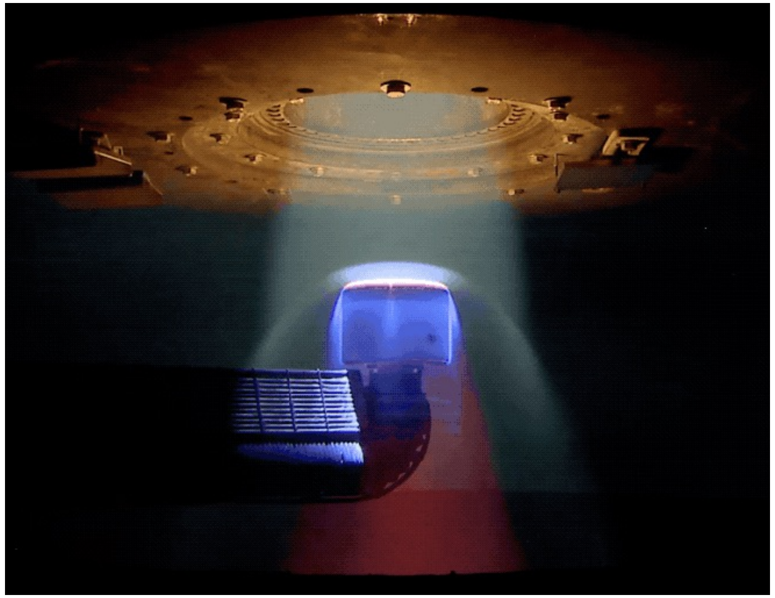
Infused 3D weave microstructure

D Ellerby et al, MS&T, 2019 • A Vanaerschot et al, Composite Structures, 2017, 173, 44-52
Agrawal, Chavez-Garcia, *J. Spacecraft Rockets*, (4) 50, 2013

Ablative TPS Mass Loss

Designed

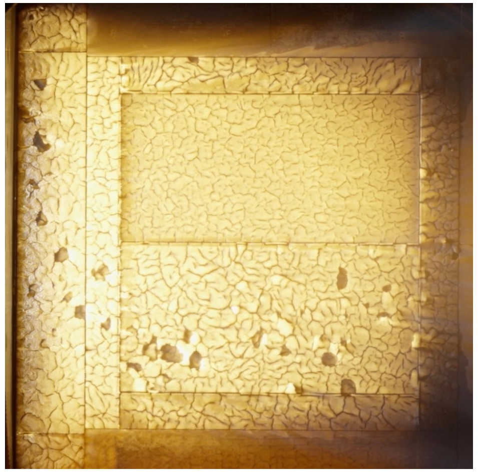
- Ablation
- Spallation



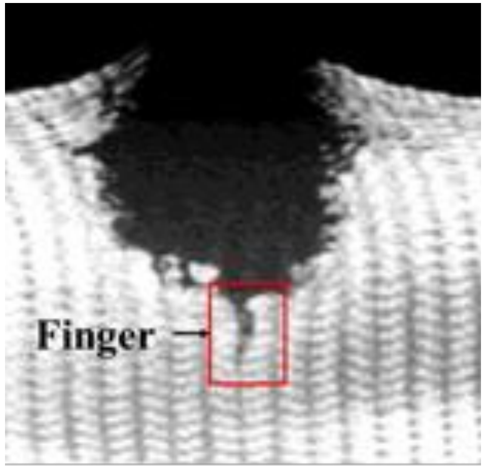
PICA ablating in the ArcJet. NASA

Anomalous

- Manufacturing impurity and damage
- Impacts from Micrometeoroid and Orbital Debris
- Entry-induced
  - Ablation, large deformation and heating



Avcoat fracture in ArcJet. NASA



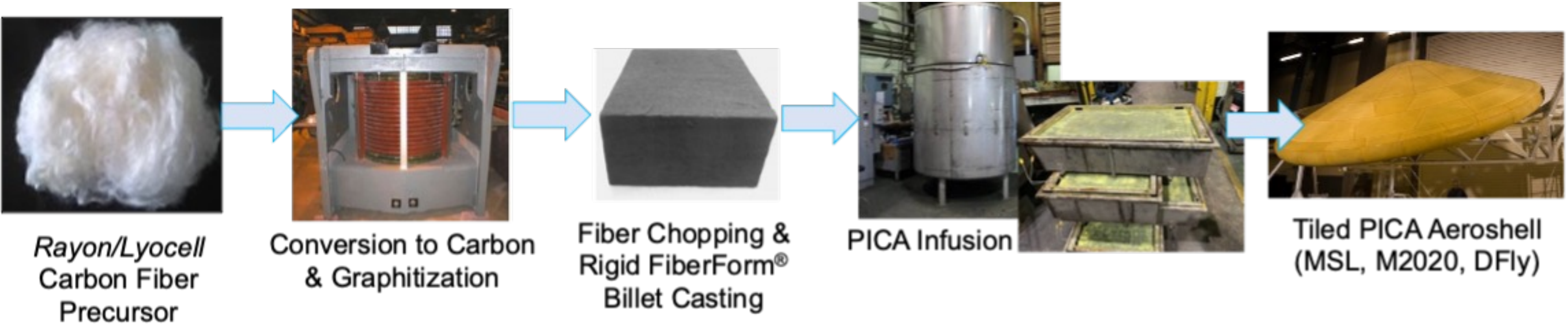
Impact of a woven TPS

Libben, et al (2019)

Phenolic Impregnated Carbon Ablator (PICA)

- Developed in the 1980s at NASA Ames TSM
- Low density, high porosity, robust
- Efficient ablator
- Can be manufactured into a
  - single piece
  - multi-tiled heat shield

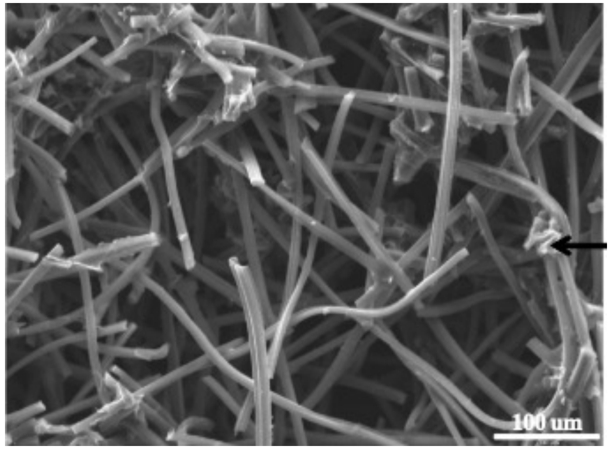
Missions
- Stardust (1999)
- Mars Science Laboratory (rovers) (2011)
- OSIRIS-Rex (2023)
- Mars 2020
- OSIRIS-Rex (2023)
- SpaceX's Dragon (2010-current)
- Dragonfly (2028)



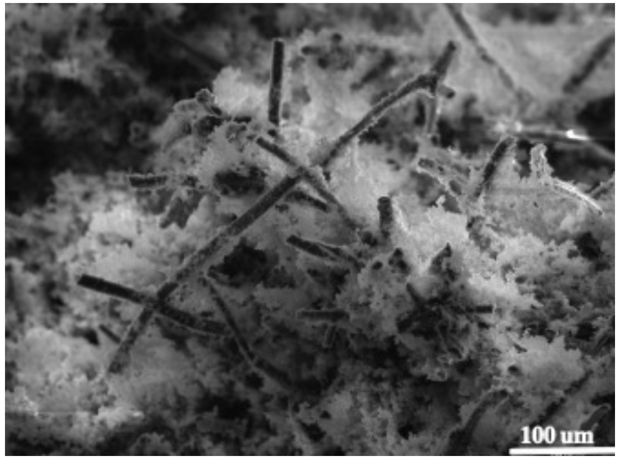
The PICA manufacturing process. NASA

Phenolic Impregnated Carbon Ablator (PICA)

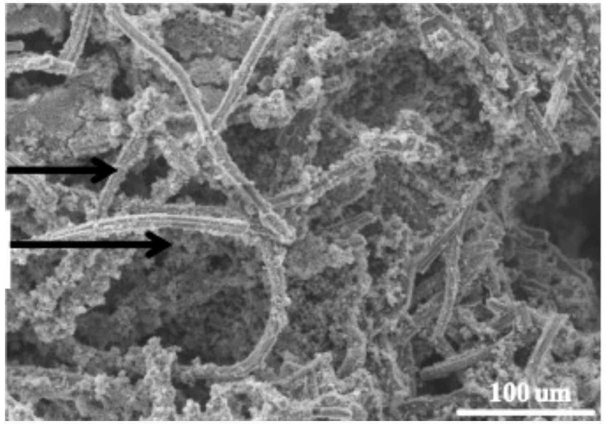
<u>Microstructure</u>:
- Fiborous
- Anisotropic
- Very porous



FiberForm



virgin PICA



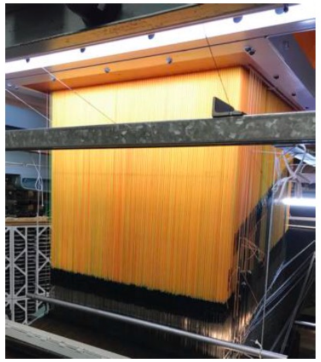
charred PICA

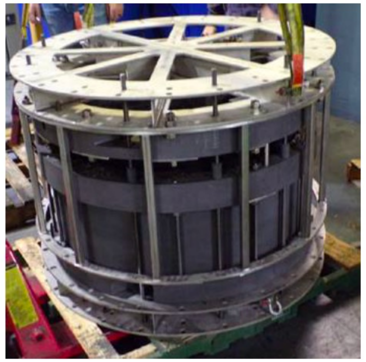
<u>Modelling challenges</u>:
- Manufacturing, heat-shield scale design and microstructure affect fracture
- Entry is a thermo-chemical-mechanical coupled response

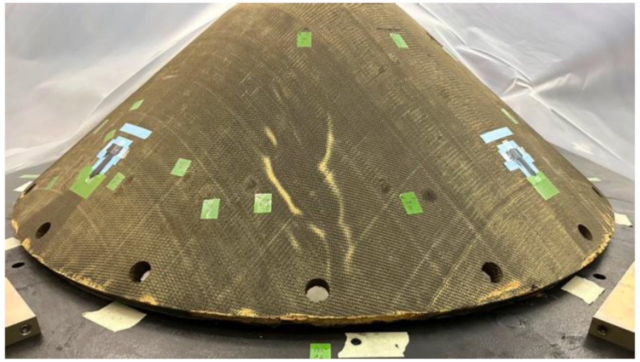
Agrawal, Chavez-Garcia, *J. Spacecraft Rockets*, (4) 50, 2013

The PICA manufacturing process. NASA

Sources of Variability in Woven TPS



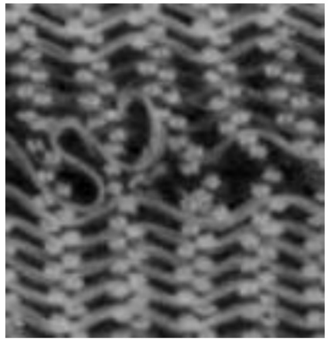




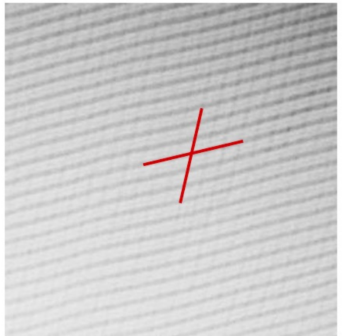
- Twisted and stretch-broken yarn
- 3D woven preform
- Formed and trimmed sphere-cone preform
- Infused heatshield
- Machined heatshield
- Integrated on substructure

Constituent variability

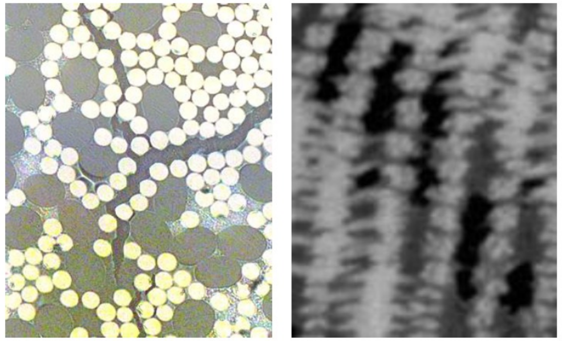
Variability in yarn stacking during weaving process



Weaving defects



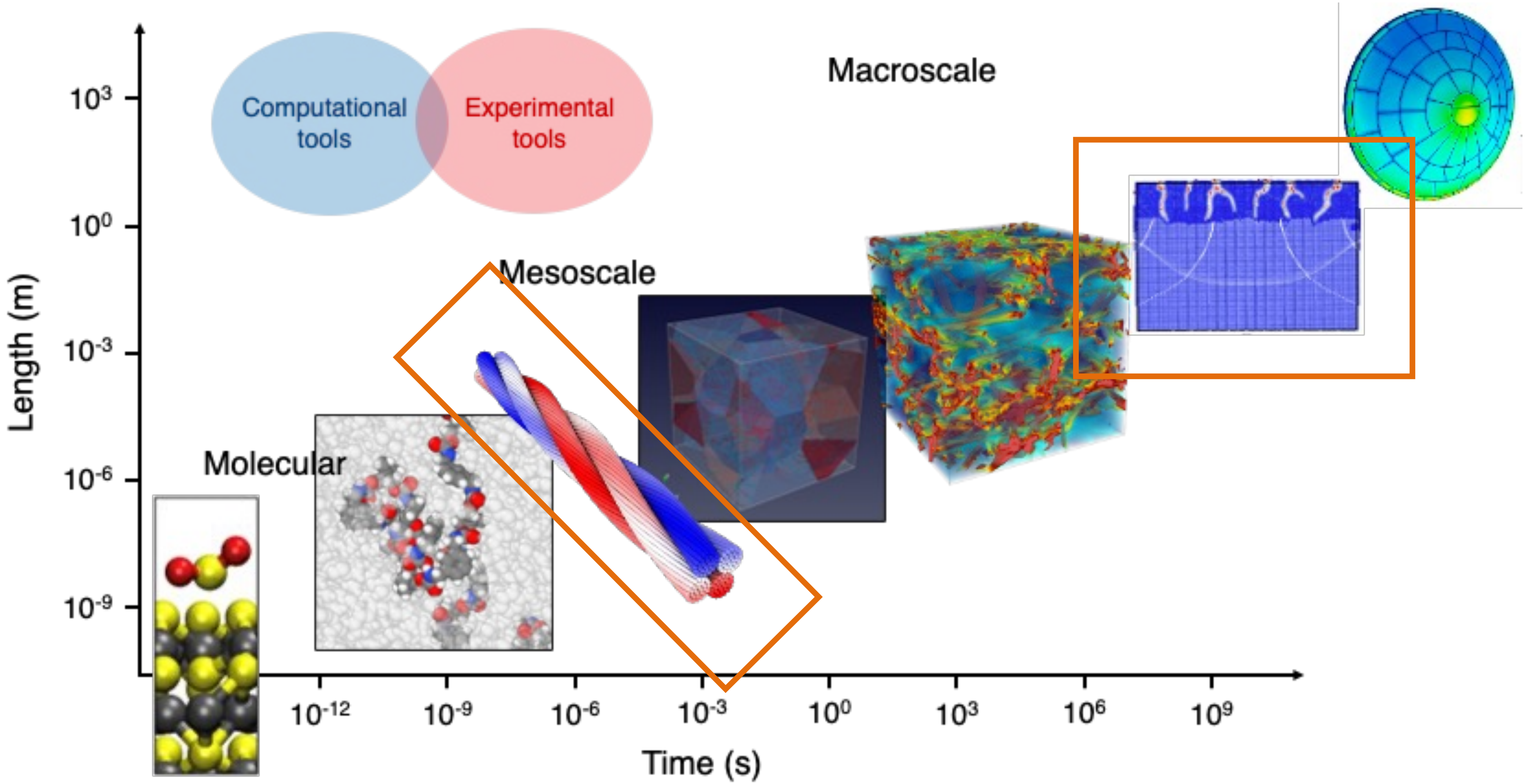
Weave scissoring during forming



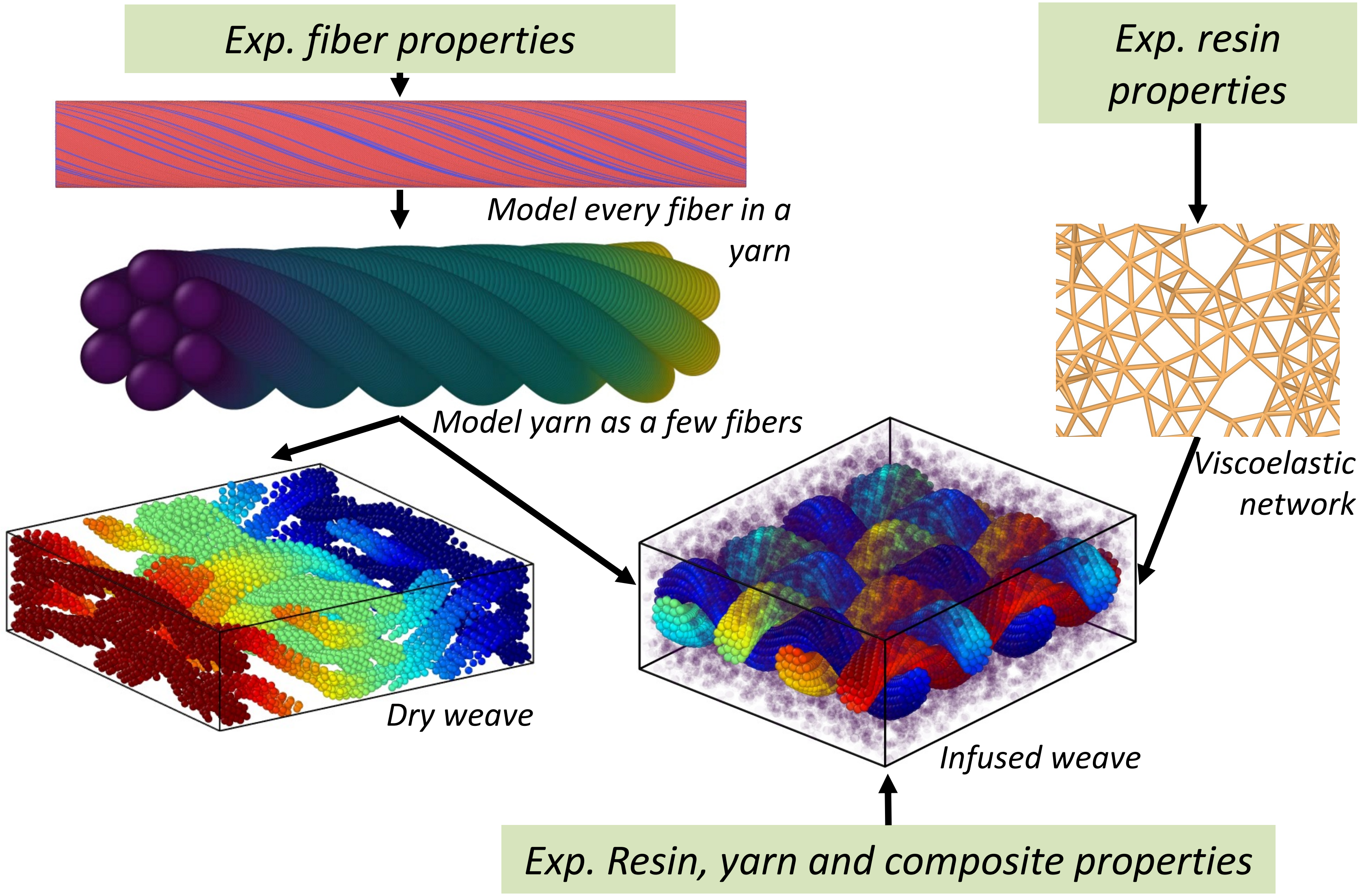
Infusion cracks and voids

Abbott, 2025; ESM-CBA; TEAM, Bally Ribbons, Schappes

Computational tools



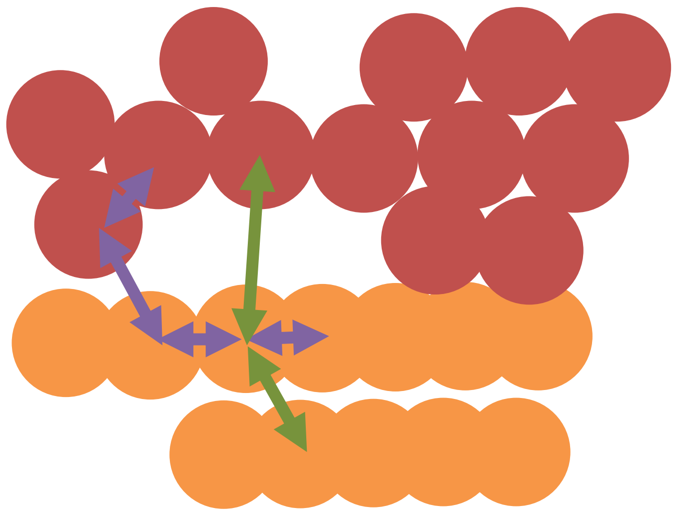
Bonded Particle Models



Bonded Particle Model Parameterization

Micromechanics-informed model:

- Intra-fiber, fiber-resin, resin-resin[1,2], bonded forces
  - Elastic stretch, bend, shear, twist
  - Viscous damping
  - Rupture
- Inter[3]-fiber and fiber-(void)-resin, contact forces
  - Friction
  - Viscoelastic repulsion
  - Cohesion



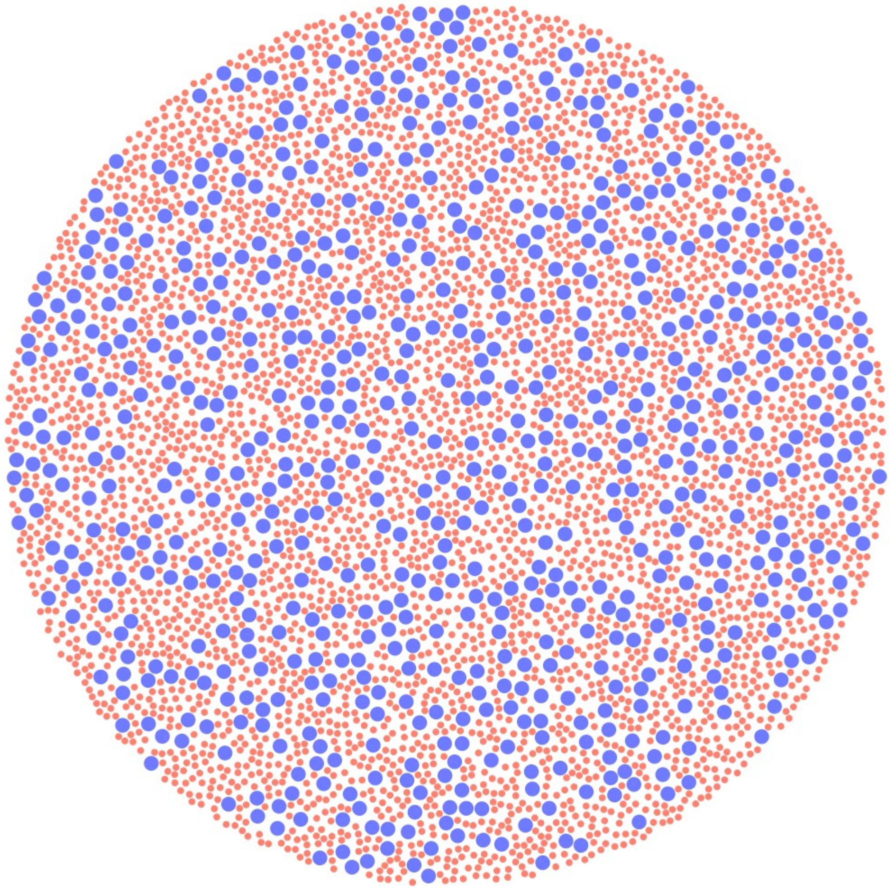
Resin scale matched to fiber: 10^4-10^{10} monomers/particle

Fiber-to-particle ratio:
- refined fiber=0.1
- fiber=1
- Yarn=1000

Component	Input Property for Model Parameterization
Resin	porosity, tanδ
Fibers	density, diameter, friction twist modulus & strength
Resin, fibers, resin-fiber bonds	tensile, shear, flexural moduli & strength
Weaves and braids	pattern, PPI, areal weight, layer thickness

Yarn generation

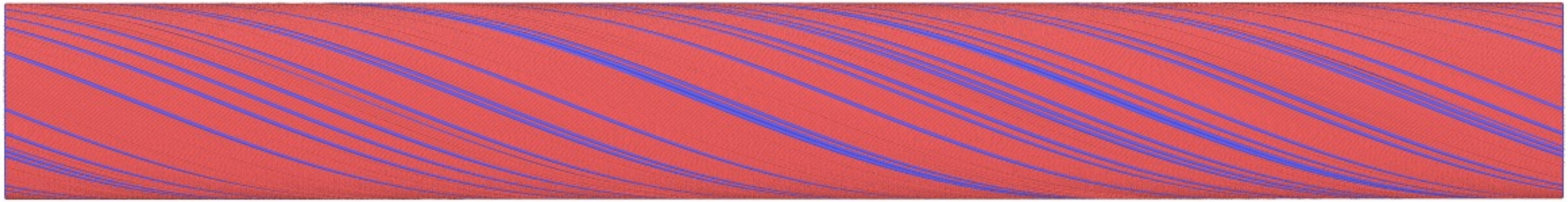
- Ellipsoidal cross sections
- Ordered and random packing
- Blends with different radii
- **Packing density**
- Weave density
- Matrix fill



Random 2d initial position of a bidisperse blended yarn

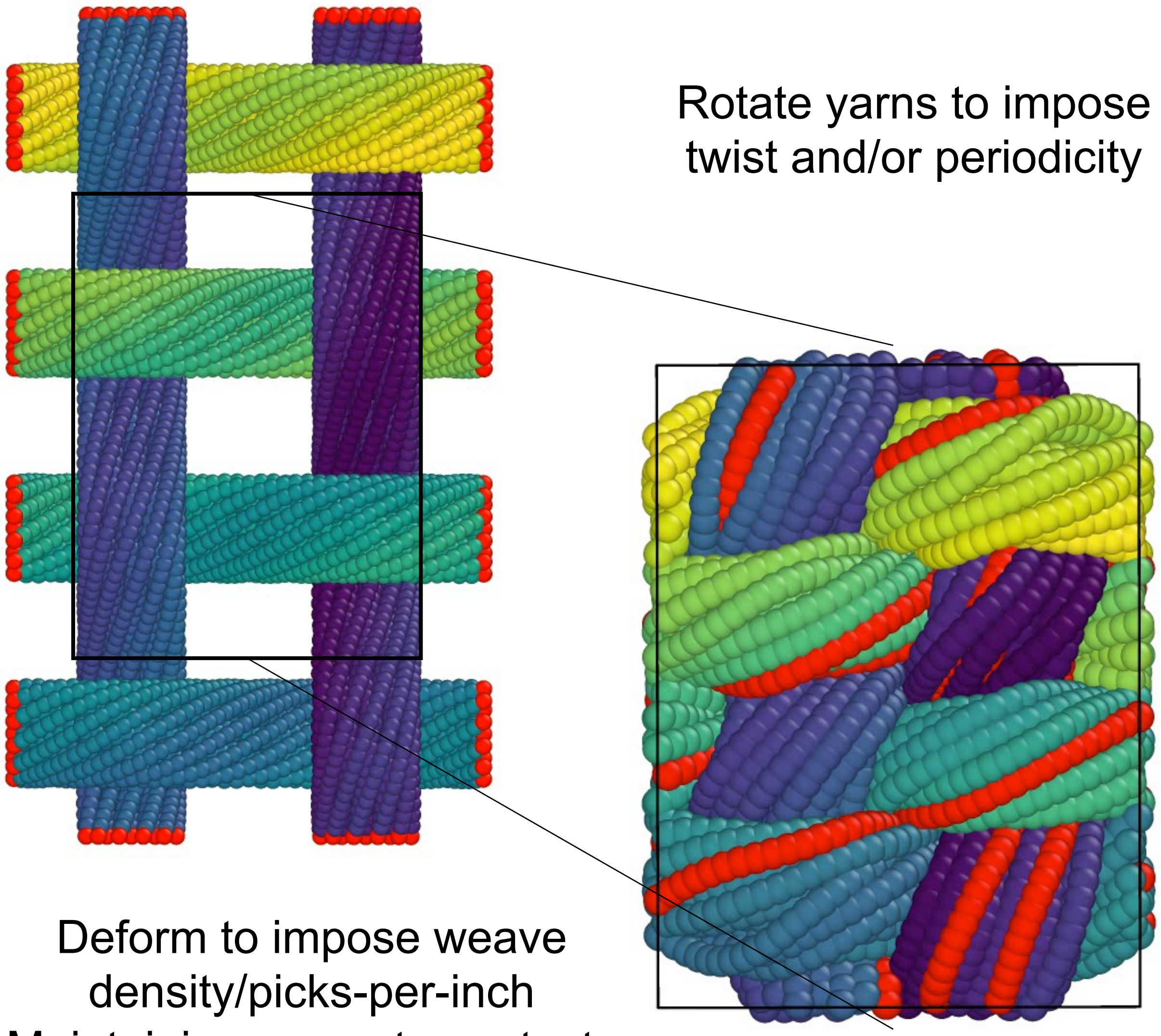
Pack the yarn to a set density, satisfying contact mechanics

Project 2d packing along the yarn path with or without twist



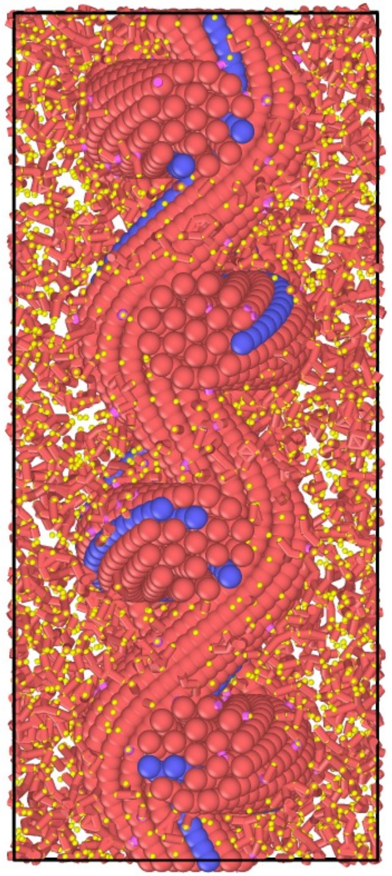
Weave Manipulation

- Ellipsoidal cross sections
- Ordered and random packing
- Blends with different radii
- Packing density
- **Weave density**
- Matrix fill



Weave Infusion

- Ellipsoidal cross sections
- Ordered and random packing
- Blends with different radii
- Packing density
- Weave density
- **Matrix fill**



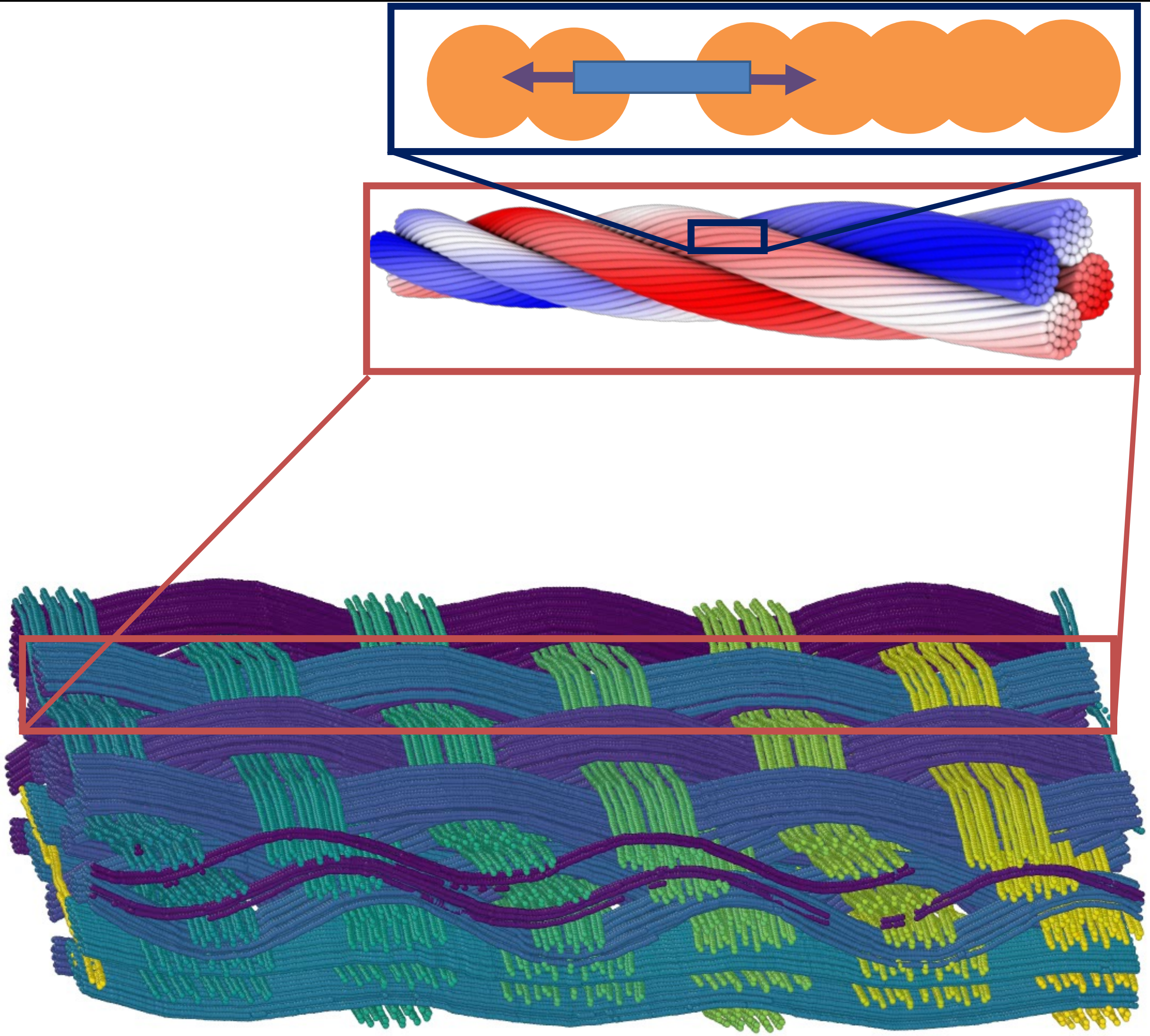
Insert particles at a certain filling density

Add bonds between matrix and fiber particles

Weave relaxation

Model
- micromechanics-informed intra[1,2]- and inter[3]-fiber forces
- bonds break
- weave: 1 yarn = 1+ string of particles bonded together
- phenolic matrix = random network of bonded particles

Method
- off-lattice
- dynamic
- apply heat and deformation
- microstructure can change during simulation
- implemented in an open-source parallelized code[4]



[1]Chen, X. et al. Comparative Assessment and Unification of Bond Models in DEM Simulations. *Granular Matter* **2021**, *24* (1), 29.
[2]Wang, Y. and Sun, X. Digital-Element Simulation of Textile Processes. *Composites Sci. Tech.* **2001**, *61* (2), 311–319.
[3]Silbert, L. E. et al., Granular Flow down an Inclined Plane: Bagnold Scaling and Rheology. *Phys. Rev. E* **2001**, *64* (5), 051302.
[4]Plimpton, S. J. et al., LAMMPS … . *Comp. Phys. Comm.* **2022**, *271*, 108171

Andrew Santos (ARC-TSM) [AMA] Andrew.P.Santos@nasa.gov

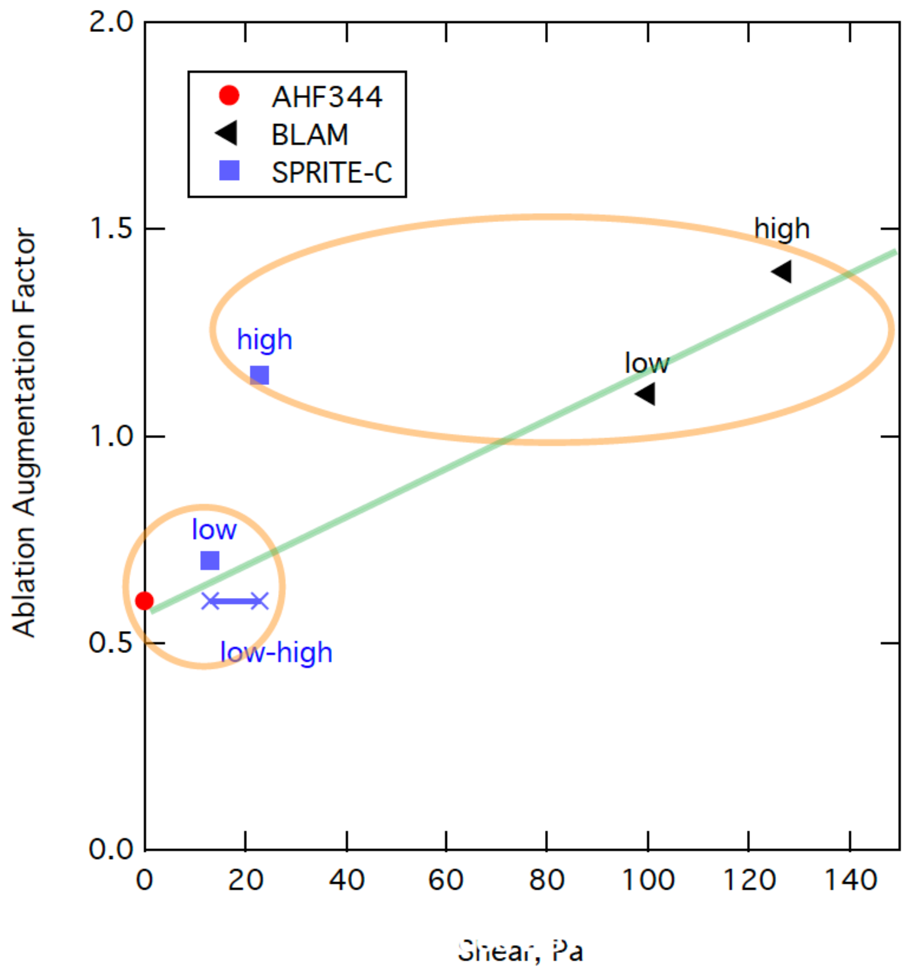
State of Weave Ablation Modeling

- Available ablation model (FIAT) shows that the standard approach to ablation (chemical only) underpredicts experimental recession values

- Ablation augmentation factor (AF) was proposed to scale chemical ablation rate to fit experiments:

$$\frac{\partial m}{\partial t} = (1 + AF)\frac{\partial m_c}{\partial t}$$

- The AF is not well posed but does appear to correlate to available surface shear stresses in some cases

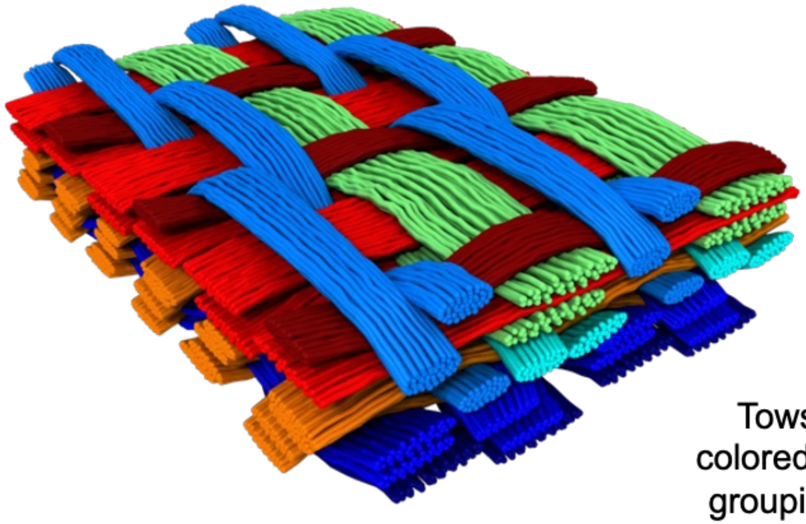


Courtesy F. Milos

Ablative Disconnection of Yarns

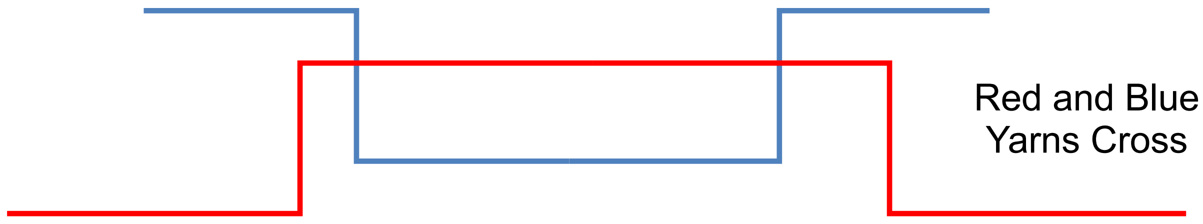
- Erosion of the weave such that regions of tows become disconnected and “fall off” from having no structural connection to the remaining weave

ADEPT Weave



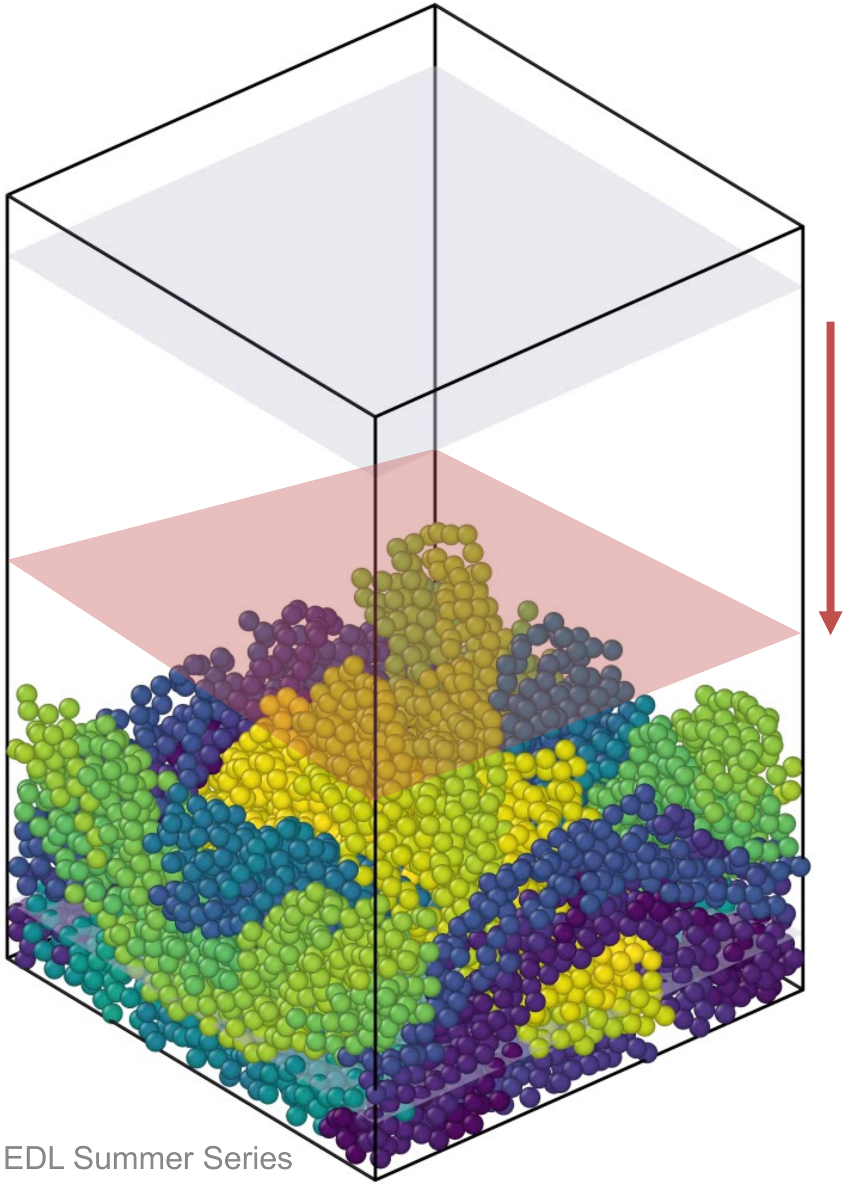
Tows colored by grouping

Weave before Ablation



Weave at some point during Ablation

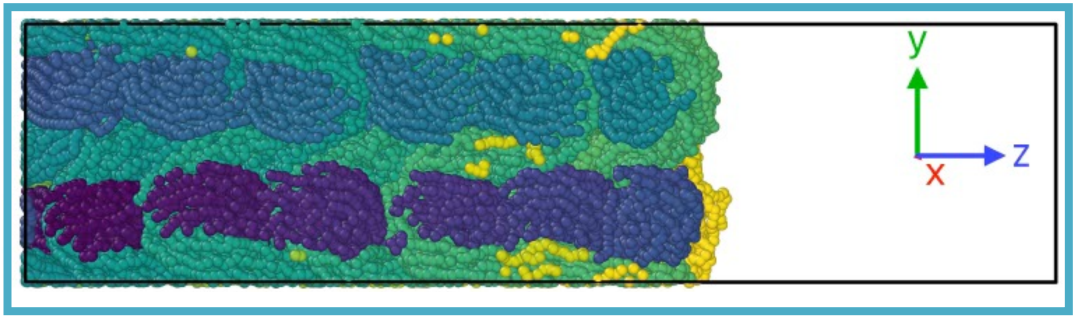
Model of Weave Ablation and Connectivity



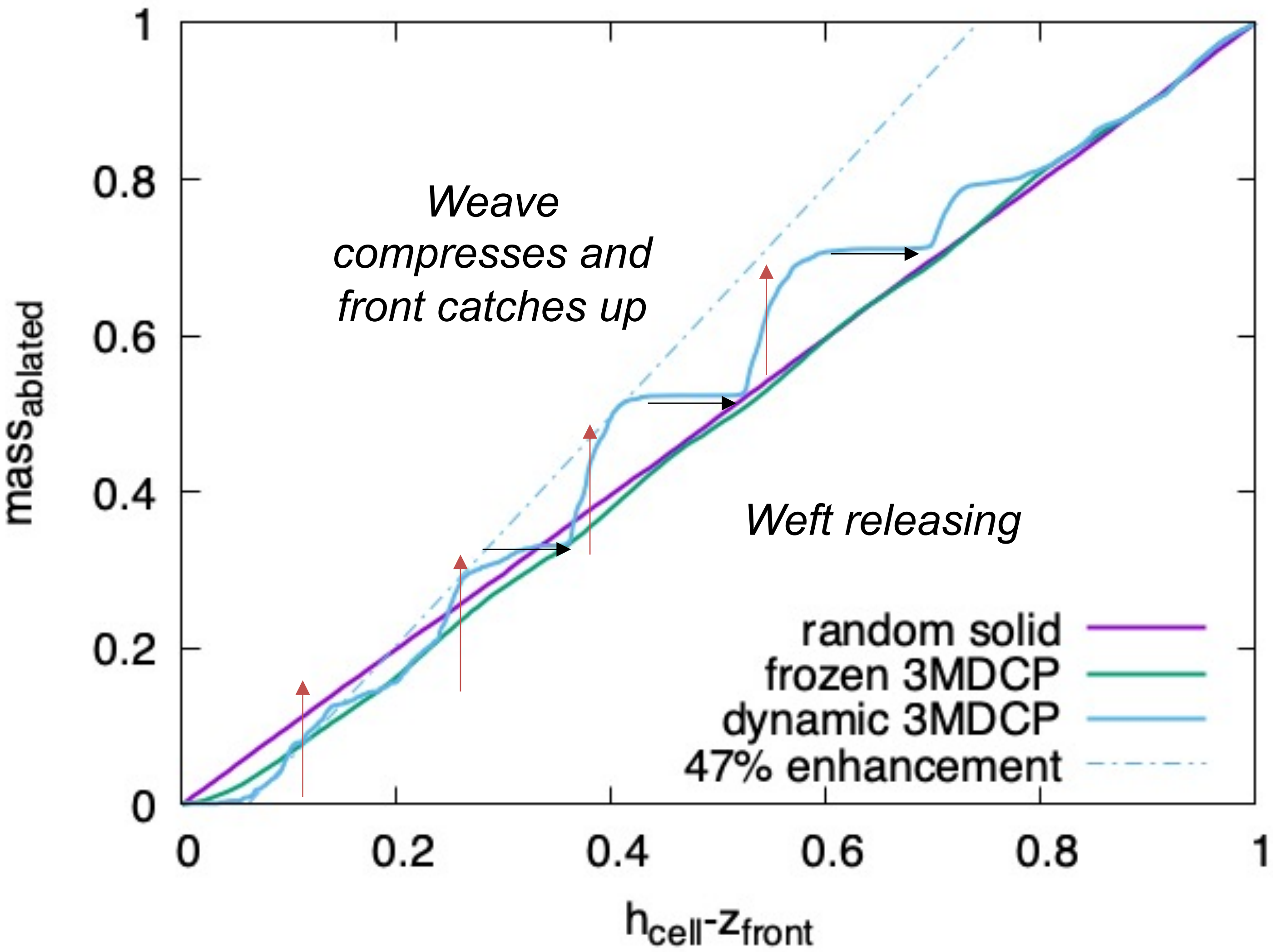
- Weave is constructed from a particle-based model
- Ablation front moves into the material and removes particles
- Forces applied such that disconnected portions of fibers are ejected from the surface into the ablation zone

Fiber tension: harmonic bonds
Fiber-fiber repulsion: viscoelasticity

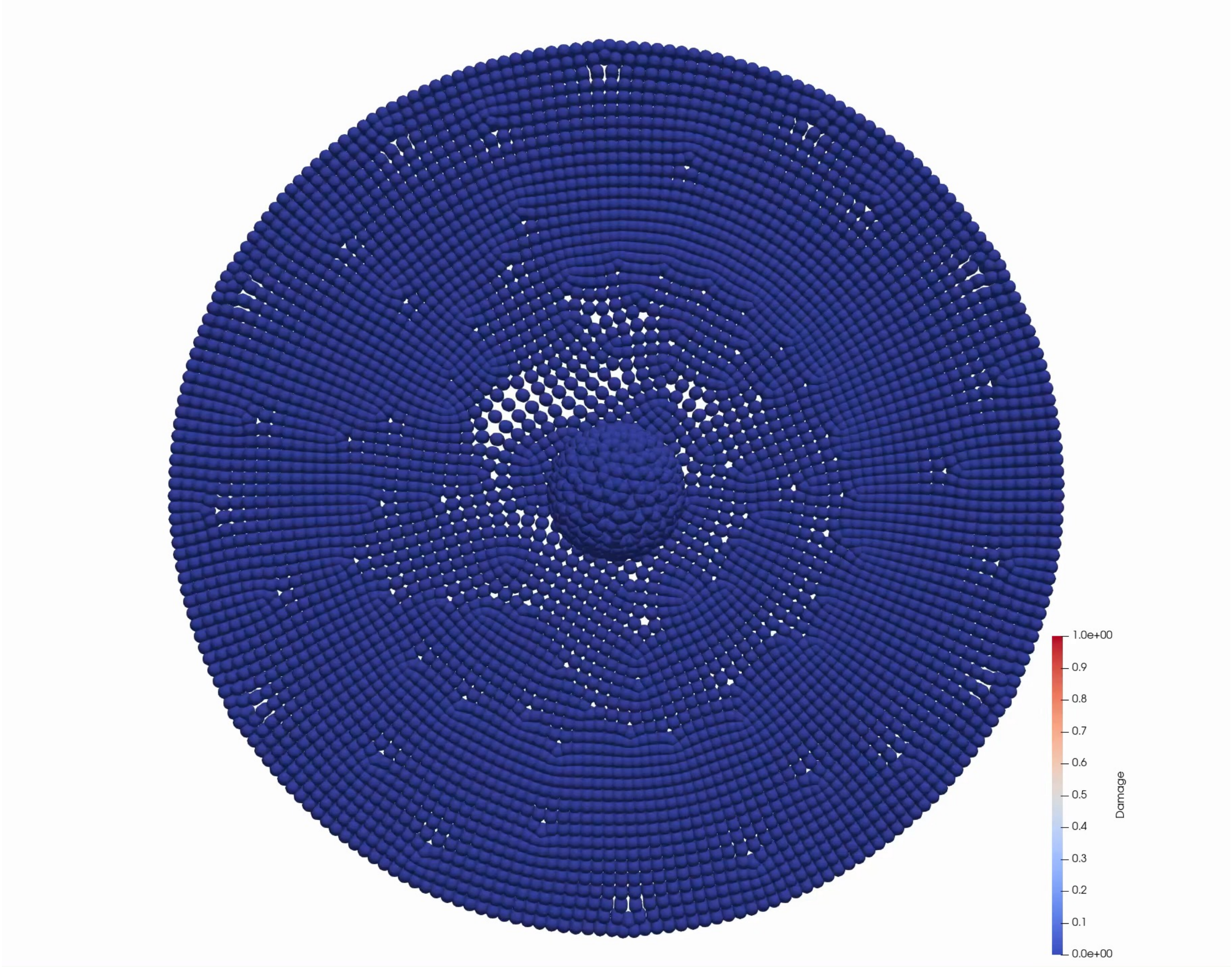
Augmentation from Loss of Weave Connectivity



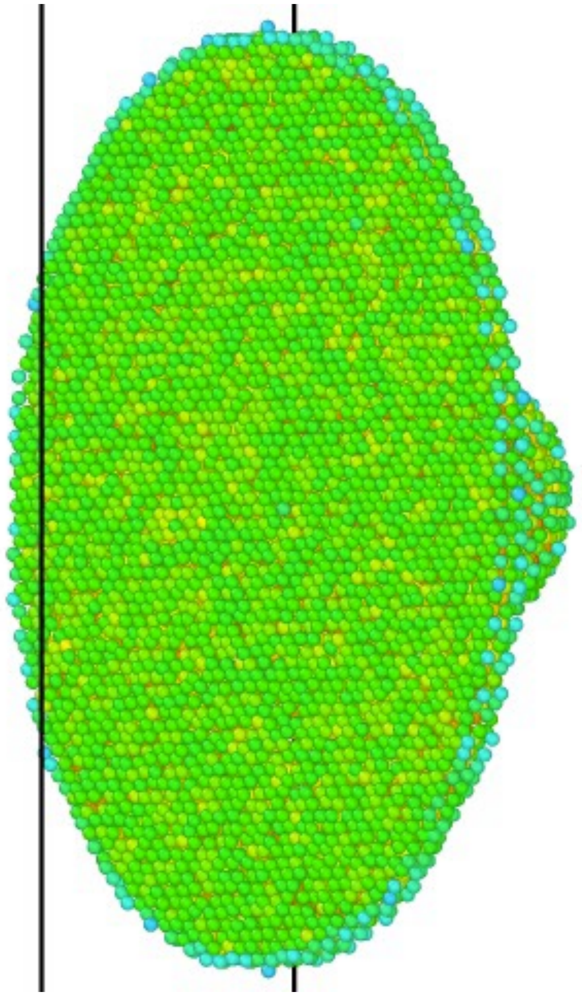
- Large portions of weft fibers ablate at a high rate due to the 3D, layered weave
- Enhancement from disconnection of weaves is found to be roughly 47%



Mass Loss Through Impact



Peridynamics simulation of a disk sample. Color correspond to damage.

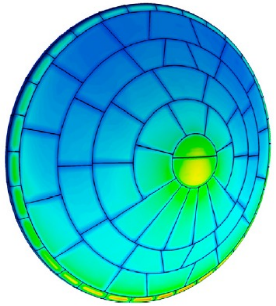


Bonded particle model

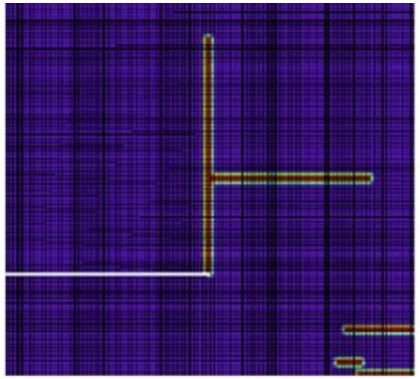
Continuum Approaches to Solving Thermo-Mechanical Response

- Material response codes model many entry-relevant physics on the continuum scale
- Finite element methods accurately capture solid mechanics but require *apriori* knowledge of cracks
- Peridynamics is a mesh-free solid mechanics technique, developed for fracture by inherently capturing discontinuities, and successfully modeled TPS

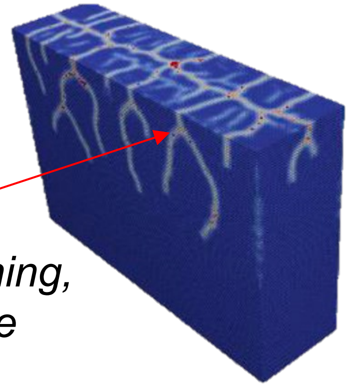
Material Response:
Heat shield recession



FVM, FEM:
Crack path in a square mesh



Peridynamics:
Fracture of charring ablator



Mixed mode, branching, cracks do not require apriori knowledge

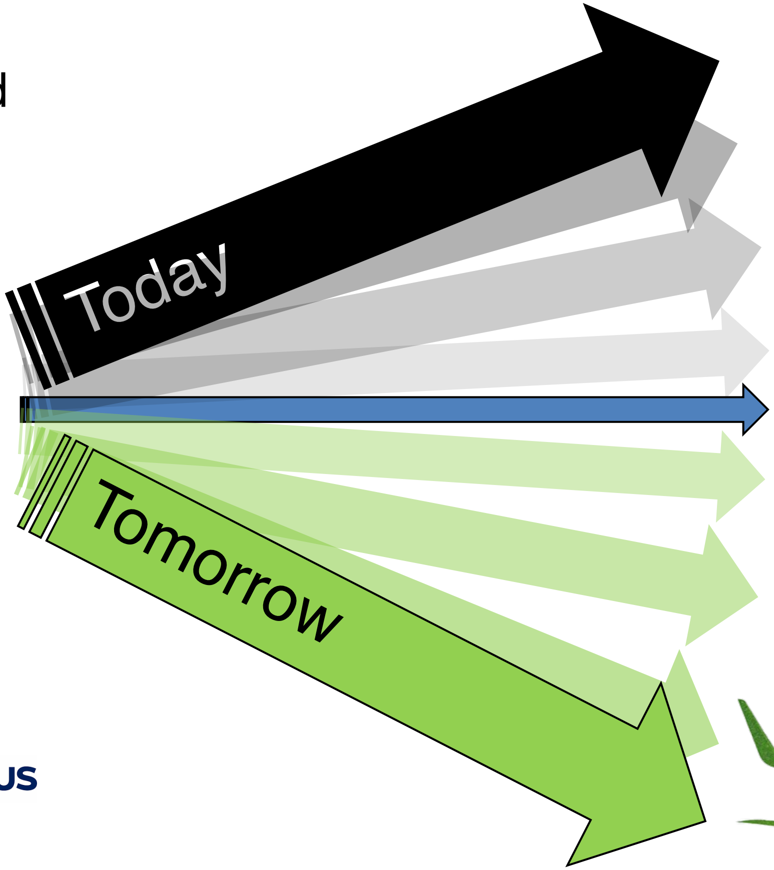
Coupled material response and peridynamics can simulate cracking due to thermo-chemical induced strain

R. Fu, S. McDaniel, *et al.*, in *AIAA Scitech 2021 Forum* (2021).
J. B. E. Meurisse, *et al.*, *Aerosp. Sci. Technol*. **76**, 497 (2018).
C. Luo and P. E. DesJardin, *Compos. Sci. Technol*. **67**, 1475 (2007).
Zhang, Y.; Behera, D.; Madenci, E. *Eng. Comput.* 40 343-365 (2023).

Sustainable Manufacturing of Aviation Composites (SUMAC)

SUMAC was asked the question, "What can NASA do to have the greatest impact on sustainability in aviation?"

State-of-the-art Materials and Manufacturing



Airplane Graveyard

Partners

Joby, Boeing, Airbus, pond, Mango Materials, Arkema, Bcomp, A&P Technology, ELI, Virginia Tech, Missouri S&T, Oak Ridge National Laboratory, Federal Aviation Administration, CSIRO

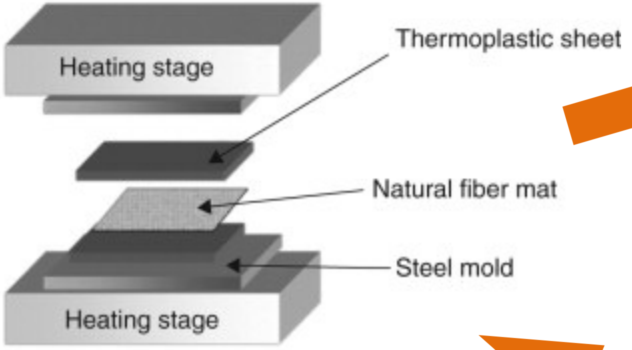
Sustainable Manufacturing of Aviation Composites (SUMAC)

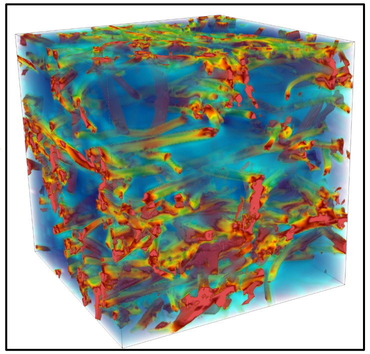
Established, change = disruption	**Supply Chain**	Nascent, change = inevitable
Rigid schedule/long lifetime	**Maintenance Cycle/Part Lifetime**	Flexible schedule/variable lifetime
Harsh conditions, high altitude	**Flight Profile and Operational Environment**	Moderate conditions, lower altitude

Focus Groups

bioresin (Mango PHB, Pond PLA, Arkema PA11)

Manufacturing (GRC)

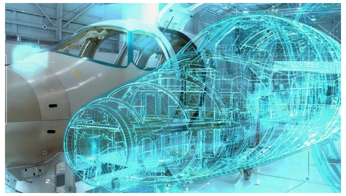




Modeling (ARC)

Flax (Bcomp, Terre de lin) Hemp (EnviroTextiles)

Weavers (Bcomp, EnviroTextiles, AnP



Sensors (LaRC)

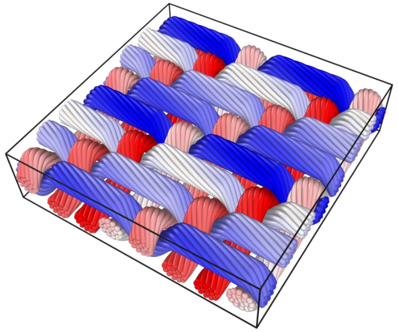
Testing

Life Cycle Analysis (LaRC)

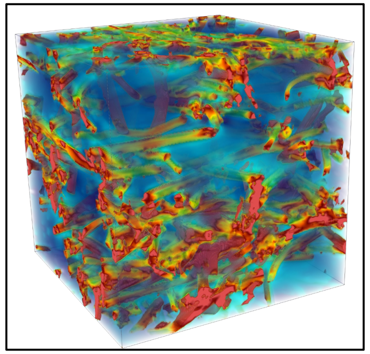
Modeling Woven Composites Overview

Support fiber, resin, and manufacturing efforts with simulations

Computational Screening



Composite Development



Narrow material design scope

Physics-based insights

Improved composite mechanical properties

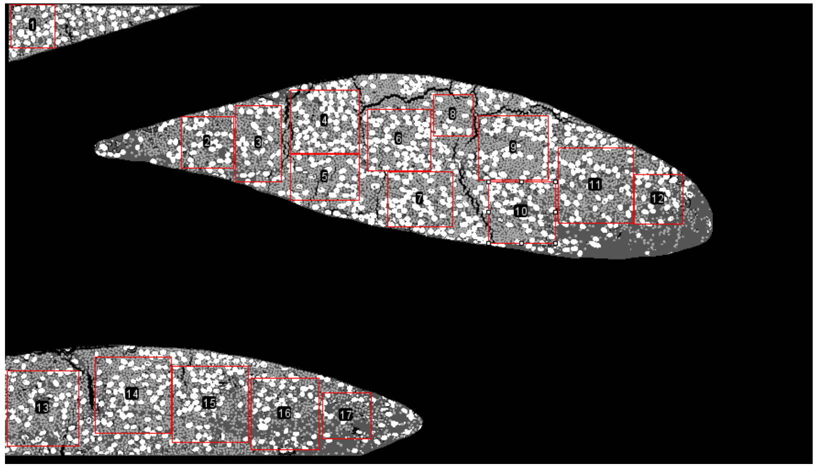
Scope
- Develop components and composites with improved properties
- Connect component behavior with composite properties to interpret experimental results

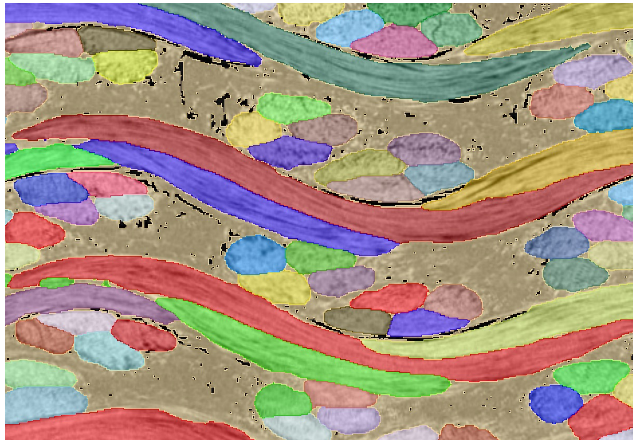
Benefit
- Reduce experimental needs and costs
- Narrow material design scope

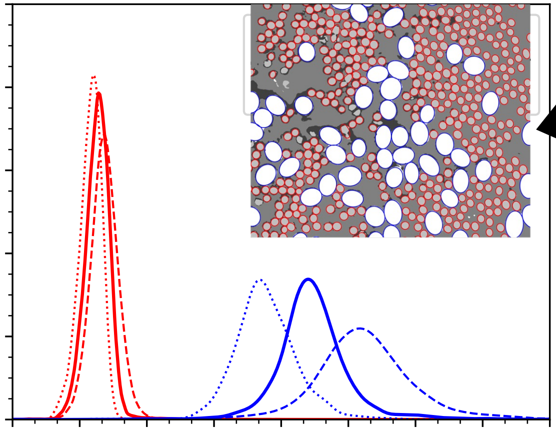
Approach
- Verify computational inputs and methodology with experiments
- Vary components and interactions with micro-scale simulations
- Calculate material properties from simulations and analysis

Modeling Woven Composites

Woven composites' inherent variability requires tools that can capture the influence of manufacturing



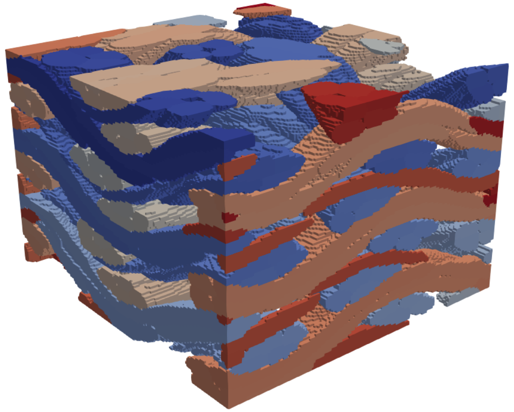




Fiber characteristics, *eg* fiber size and shape distribution

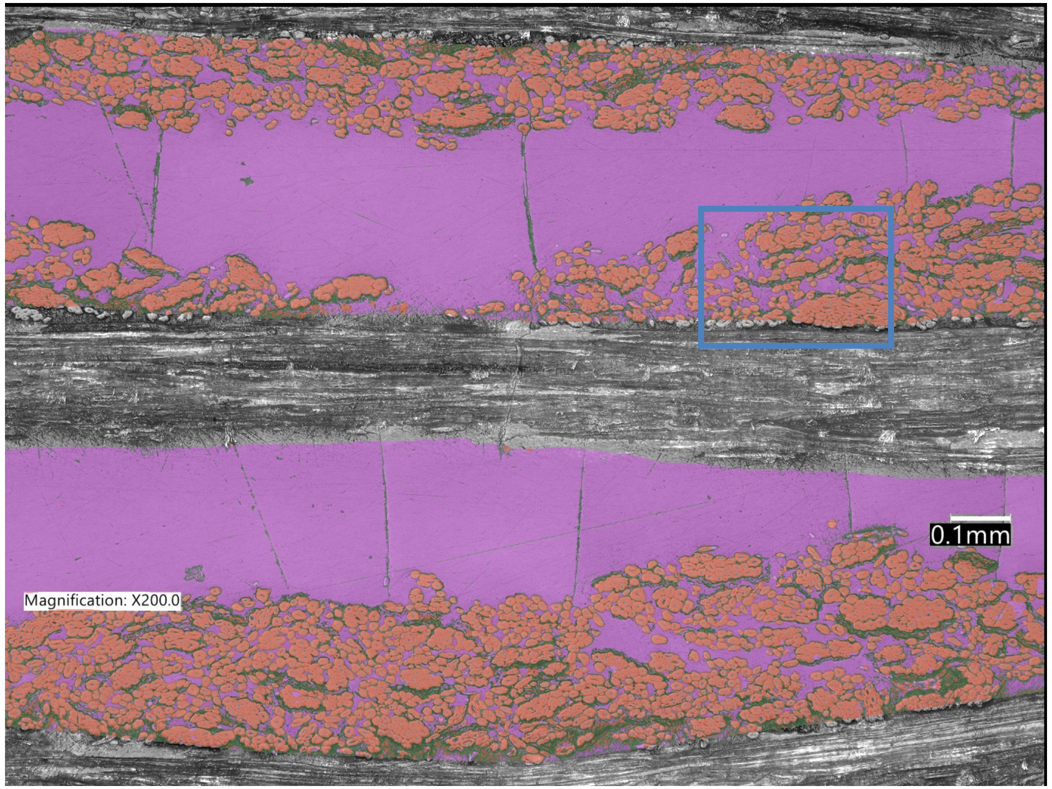
Single- or multi-ply yarns with twisting

Populate yarn paths

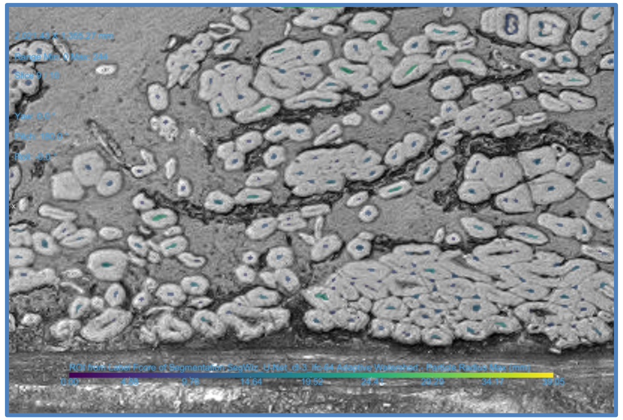


Yarn paths for model configurations that capture variability, voids

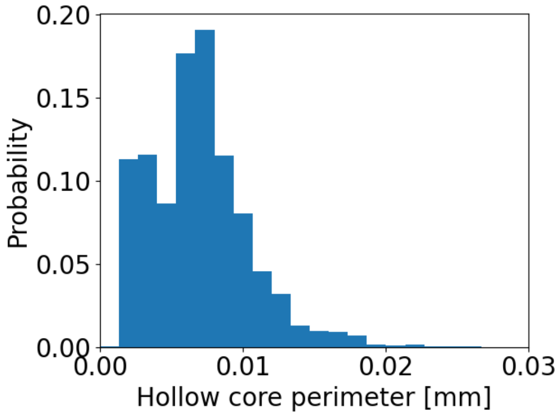
Extracting Fiber-scale Properties from Images



Twill flax-pla OM segmented with ML by fiber (red), resin (purple), void (green) and fiber core (blue) (manufacturing and OM: Allison Christy)



Identification of ~3k hollow cores



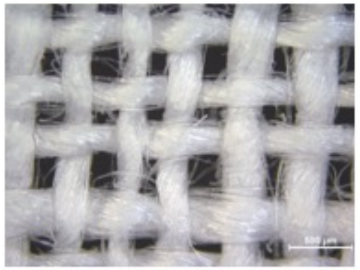
Hollow cores perimeter distribution

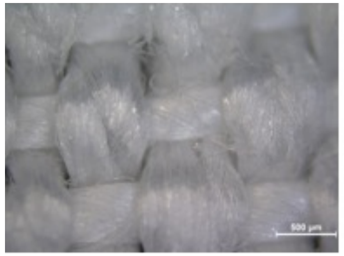
- A good test case for segmentation, but the manufacturing procedure has been optimized
- Distinguishes intra-yarn resin, cracks and hollow cores
- Hollow core size probability informs model generation and can verify manufacturer's data
- Cores enhance dampening and fiber packing density

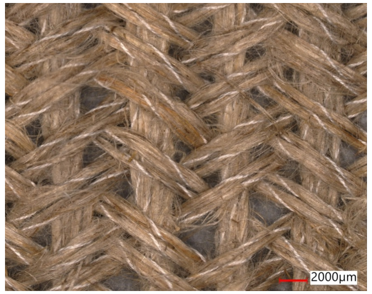
Future work: compare distributions in different fiber-resin composites

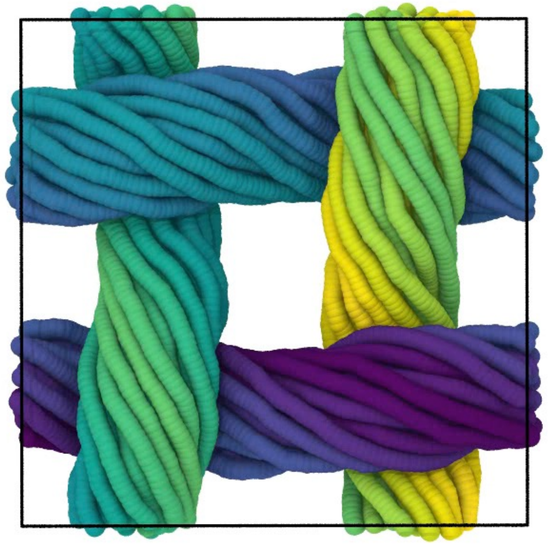
Matching Experimental Dry Weaves

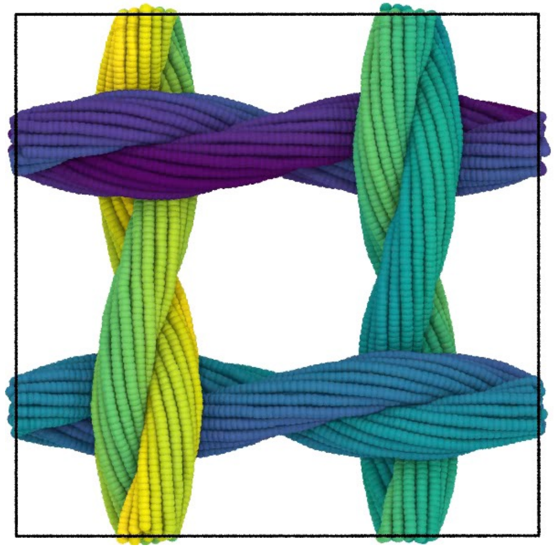
1-ply plain weave (B608)	2-ply plain weave (B601)	Twill weave (Bcomp)	Triaxial braid (AnP)

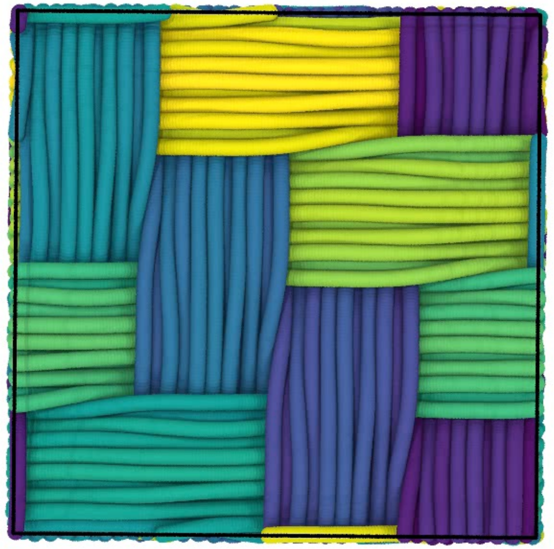


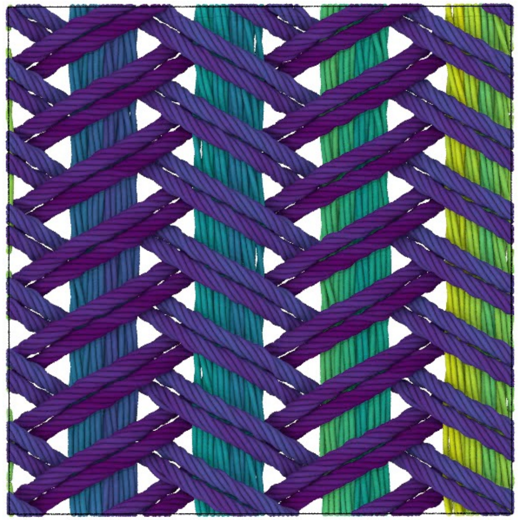






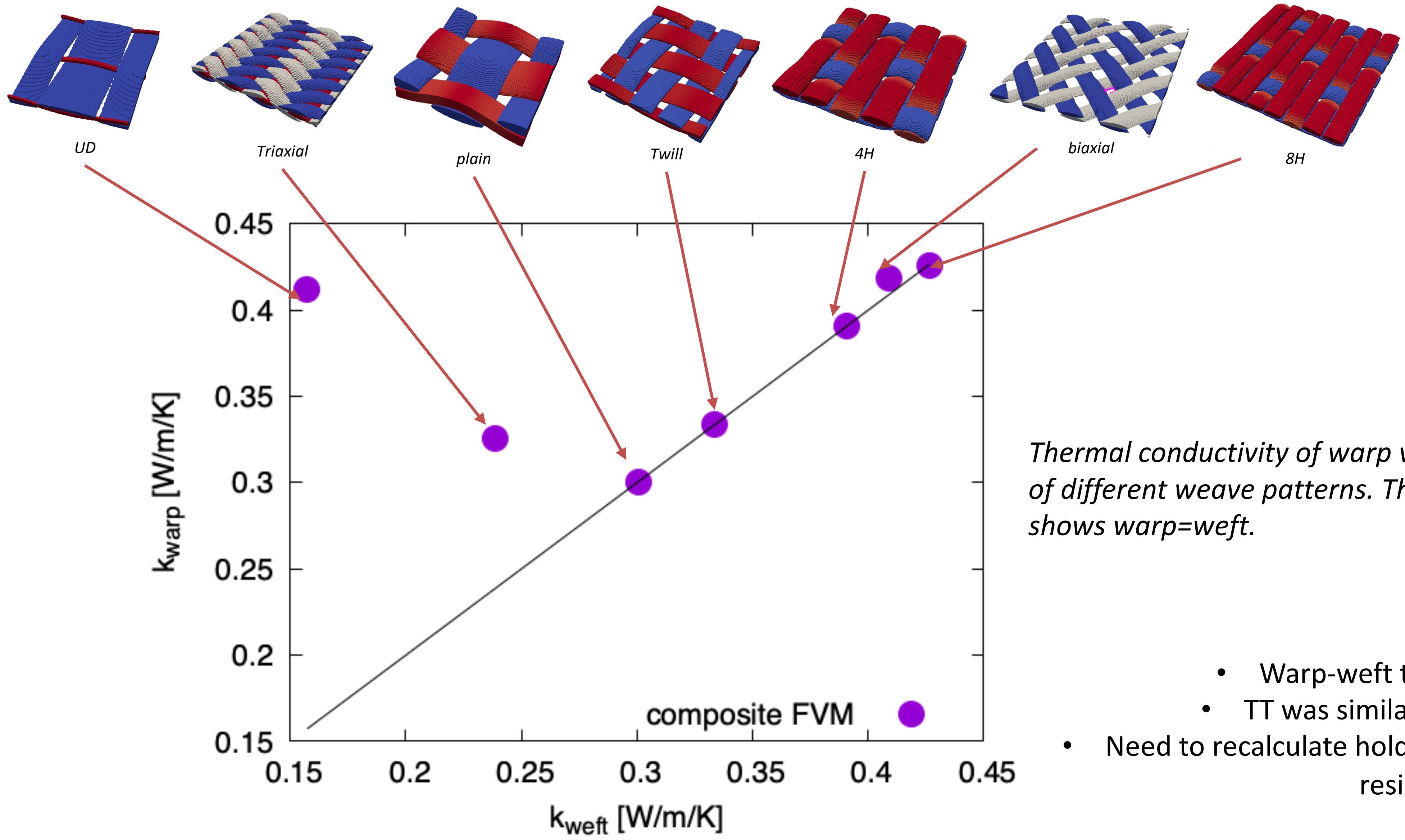






Bonded particle models capture twist, ply, yarn dimension and spacing

Thermal Conductivity of Different Patterns

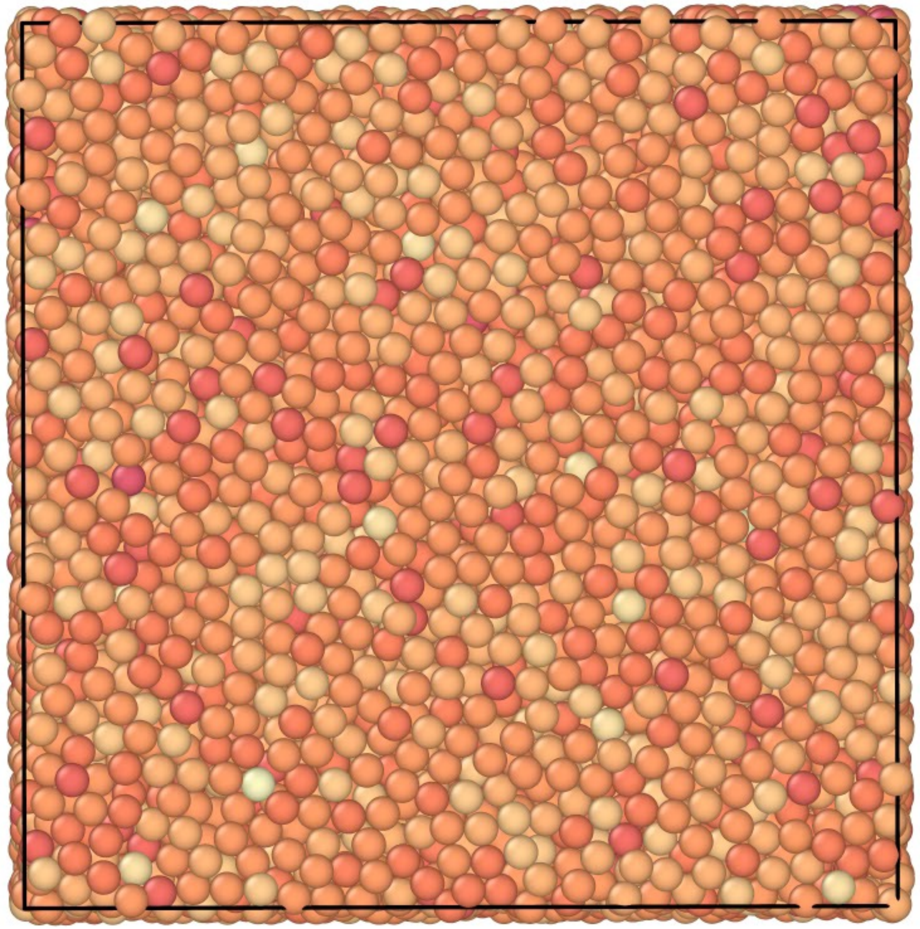


Component	Conductivity [W/mK]
PLA	0.1
Flax - axial	1.232
Flax - radial	0.17

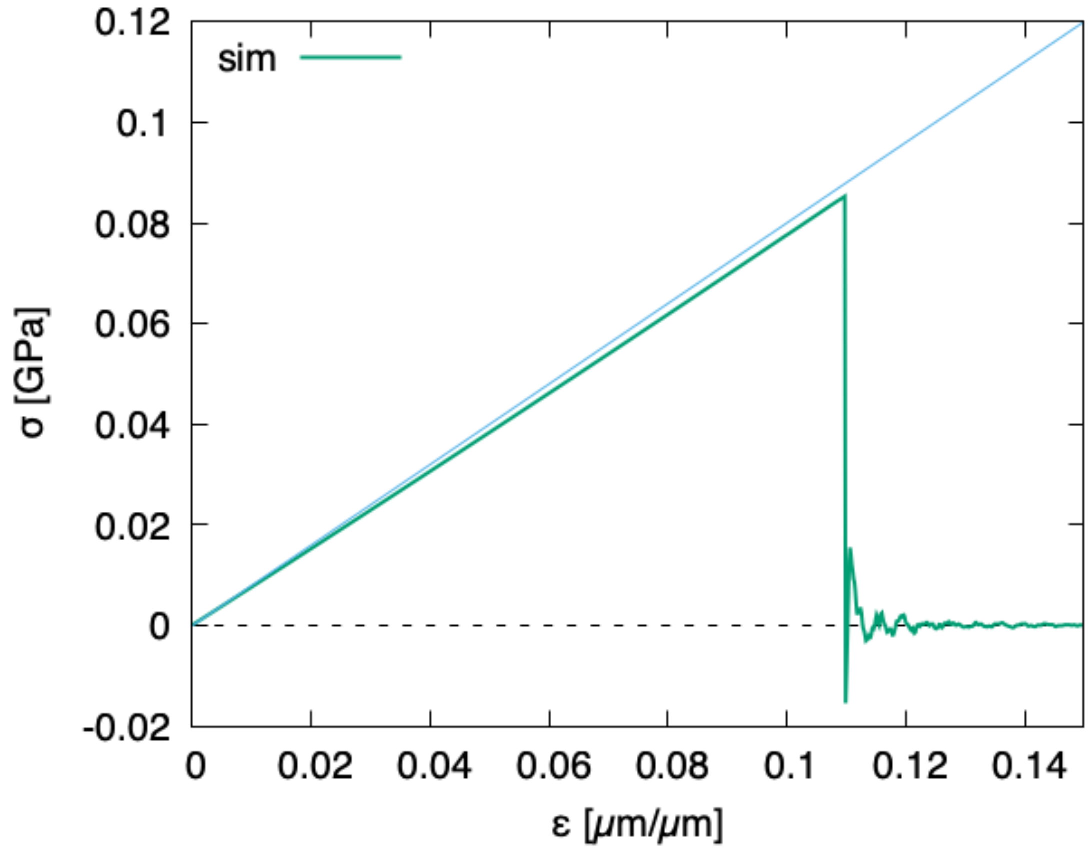
Thermal conductivity of warp vs weft of different weave patterns. The line shows warp=weft.

- Warp-weft trends as expected
- TT was similar 0.13-0.15 W/m/K
- Need to recalculate holding the the yarn area and vol% resin constant

Modeling Resin at the Fiber Scale



Pond pla resin bonded particle simulation tensile simulation, particles are colored by number of bonds (black:0 to orange:17)



Preliminary tensile stress strain

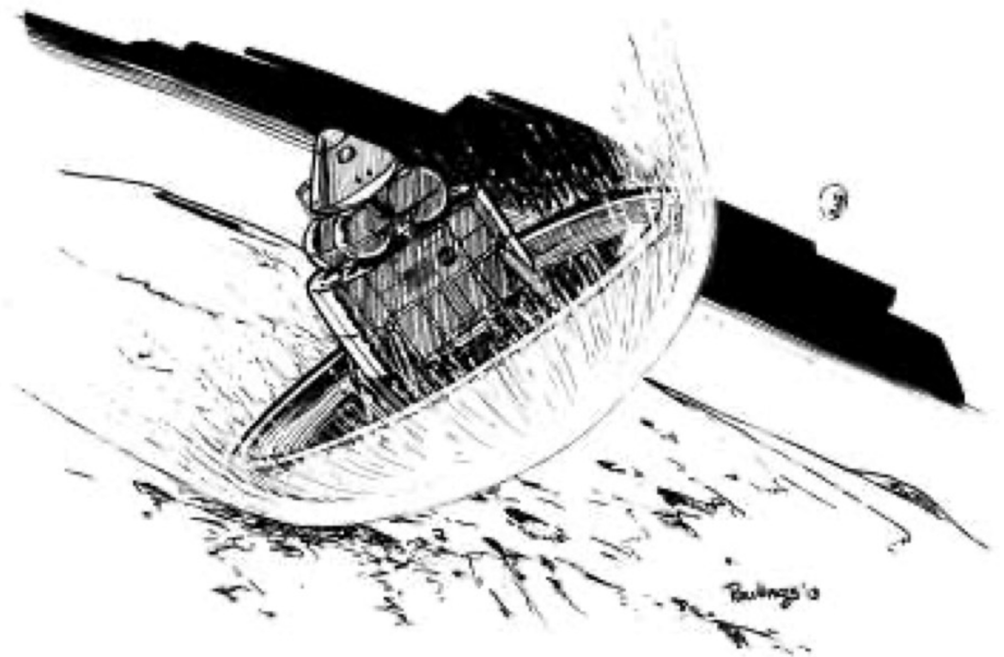
Resin-regolith Composites for Heat Shields

Regolith Derived Heat Shield for Planetary Body Entry and Descent System with In Situ Fabrication

NASA Innovative Advanced Concept (NIAC)

Final Report

November 13, 2012

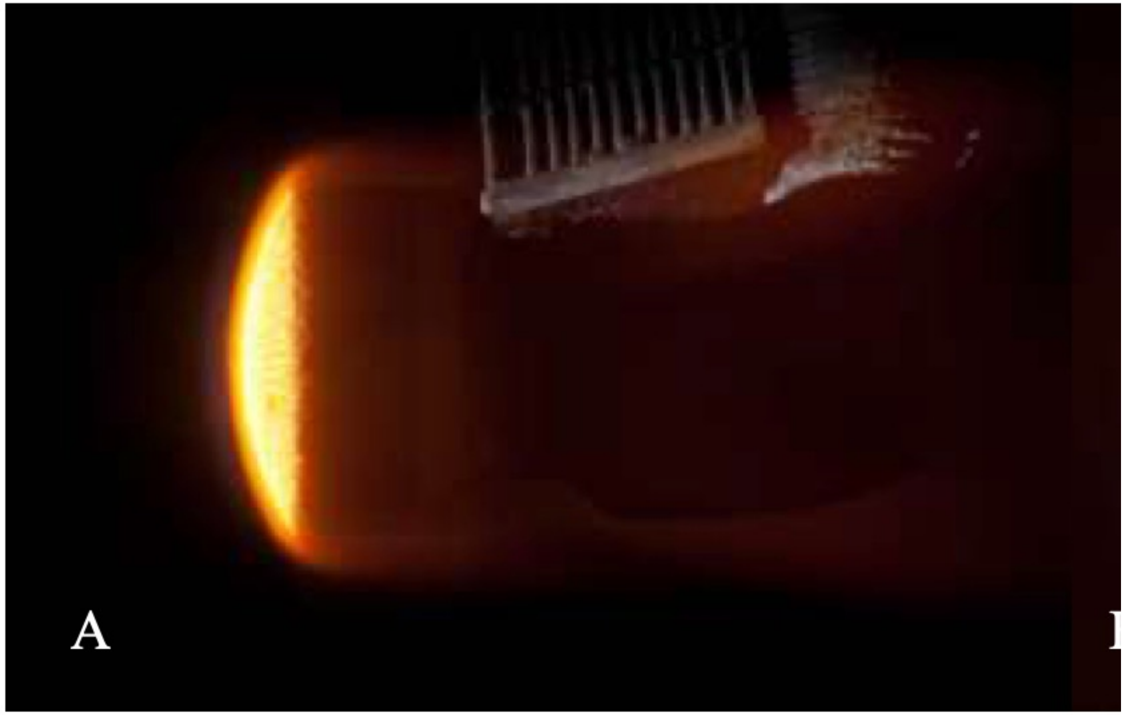


RTV-Simulant composite manufacture and Flame tests

Figure 17. Post-test photo of the front surfaces of the eight flame test samples. The two JSC-1AC Lunar sintered samples are on the left-most column. The remaining samples on the top row are: RTV/JSC-1 Mars, RTV/JSC-1A Lunar, RTV/JSC-1 Mars. On the bottom row: RTV/JSC-1A Lunar, RTV/JSC-1 Mars, RTV/JSC-1A Lunar

Regolith-Derived heat Shield in the Arc Jet

Martian regolith-RTV in the Arc Jet

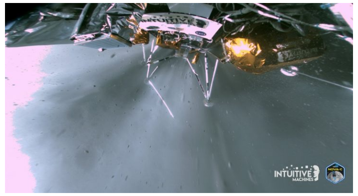


Lunar regolith-RTV in the Arc Jet

Can we make the resin with in-situ resources? For Landing?

Capability Need/Knowledge Gap:

Cratering of regolith during Mars and Moon landings needs to be mitigated to protect craft and habitats. Landing pads that withstand the extreme off-world and landing environments. In-situ resources must be utilized.



IM (CLPS) kicking up Lunar regolith.

Objectives: Design regolith UV-curable polymer composites for landing pads with material response modeling.

Technology State-of-the-Art:

Resin-regolith composite showed promise for heat shields and landing pads in ground testing with ArcJet (NIAC) and rocket engine plumes (ACO). CIF25 UV-curable resin composite is also very promising. These have not been optimized and characterized for landing pads. Material response modeling for TPS can be leveraged.

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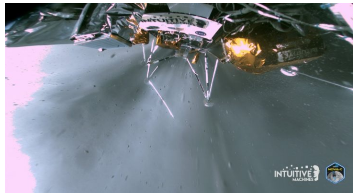

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Technical Approach:

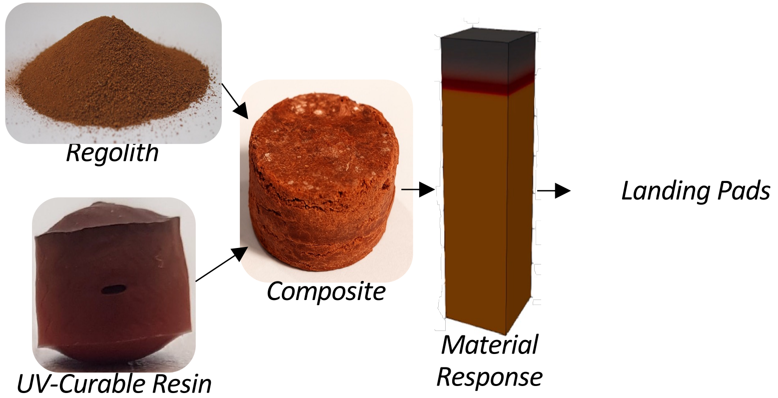
Advance UV-curing resin system developed for CIF25 and utilize tools and characterization techniques for heat shield sizing to:

•Maximize regolith simulant loading in composite

•Develop material model with experimental mechanical, optical, thermal and environmental property characterization

•Inform PSI simulations and design by simulate landing with adjusted modeling methodology

Figure 3: Schematic of methodology



Partnerships:

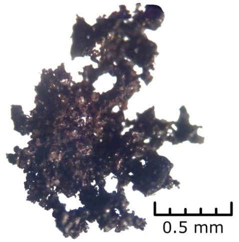
Organization: Kennedy Space Center
Org Role: Regolith and composites samples, construction

Organization: UI - Chicago
Org Role: Recycled resin-regolith composite properties

Organization: Glenn Research Center
Org Role: Biopolymer-regolith composite properties

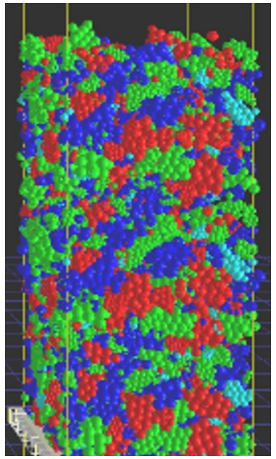
Accurate Regolith Modeling into Composite Model

Generate grain configurations, calculate porosity, vary gravity and compaction with DEM simulations



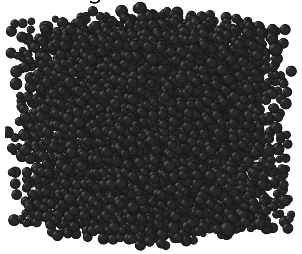
Example of lunar regolith shape (no erosion on the moon means very non spherical and open

Interactions and shapes



Apply 1 and 0.1g

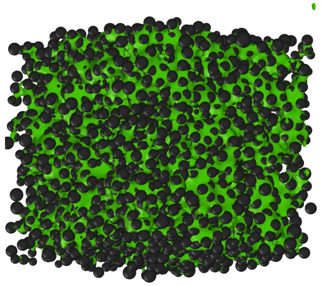
*"unprocessed" Lunar regolith model**



*"processed" Lunar regolith model**

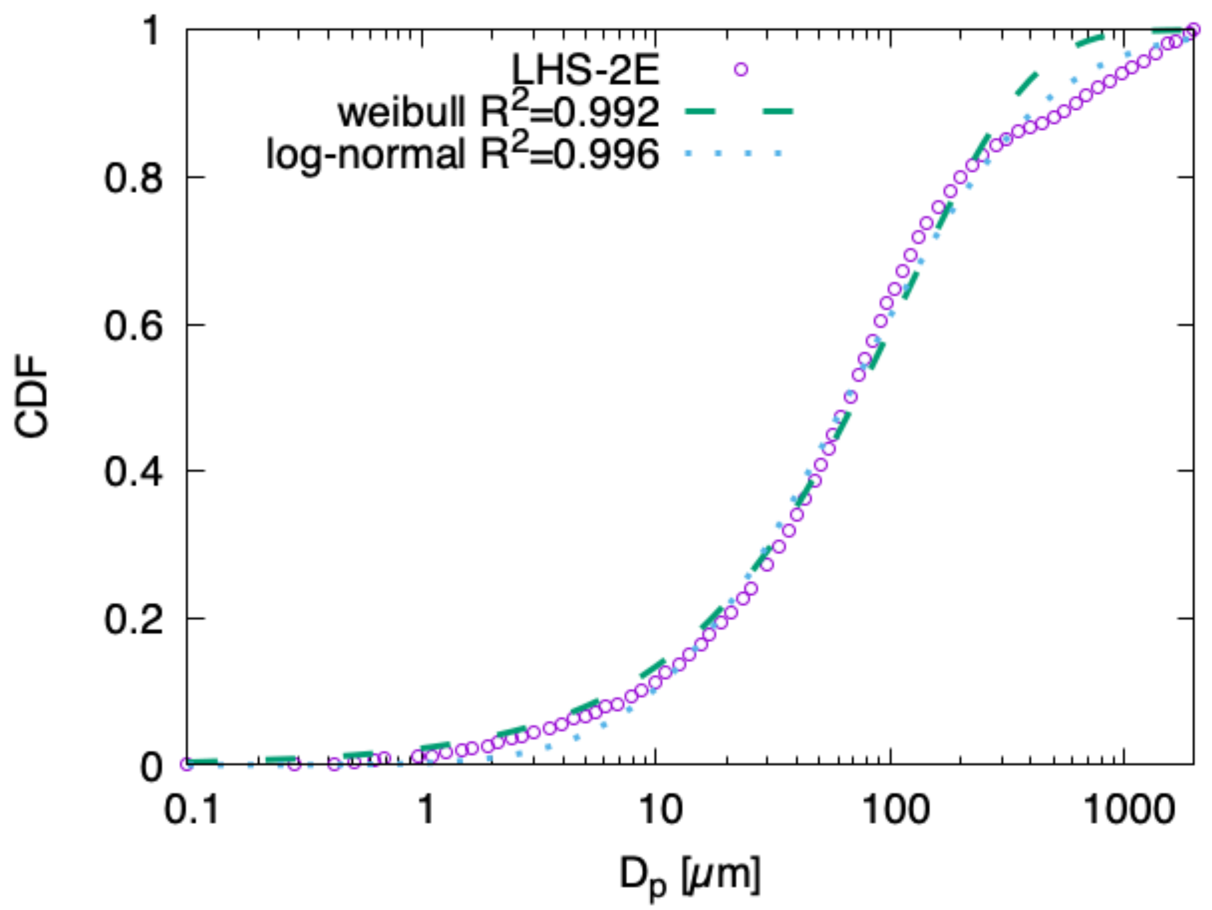
Regolith configurations to puma mesh and assume full polymer infusion

Regolith

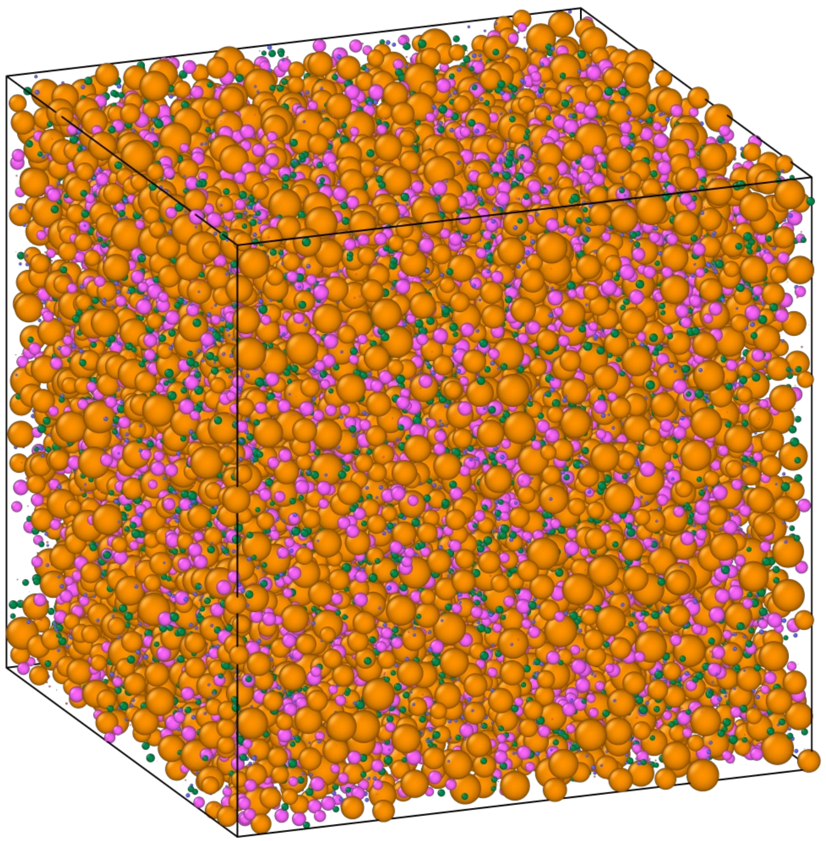


polymer

Spherical Approach



Cumulative distribution function CDF *of particle diameter* D_p *for the LHS-2E simulant (similar to JSC-1). Weibull and log-normal distribution fits are shown as lines and used to initialize particle simulations.*

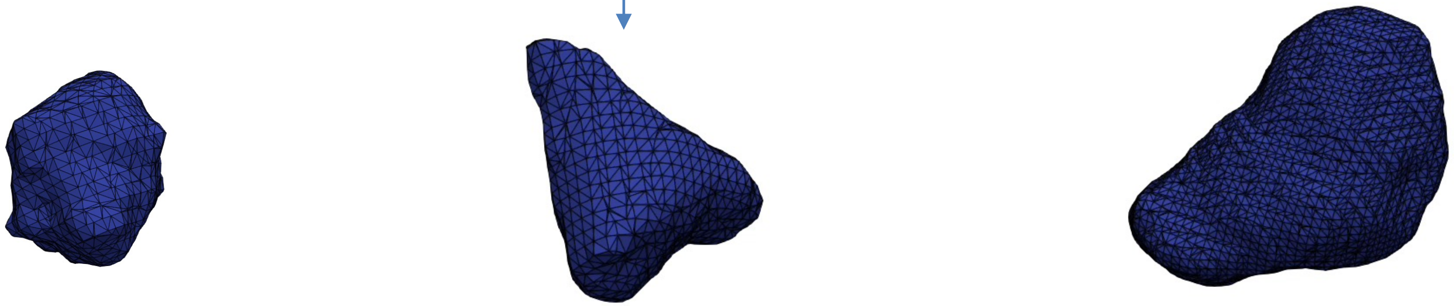


Initial particle representation sampling the experimental LHS-2E particle diameter distribution. Colors represent diameter ranges.

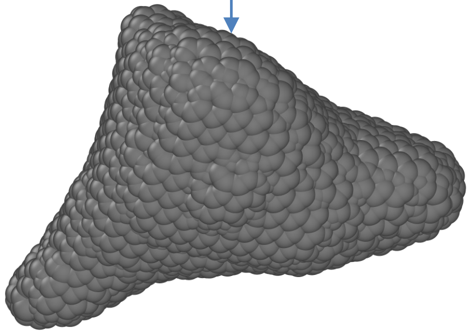
Shape-resolved Approach

From NIST: https://data.nist.gov/od/id/mds2-3043
Of Appollo 10, 14 Sample returns and JSC-1A

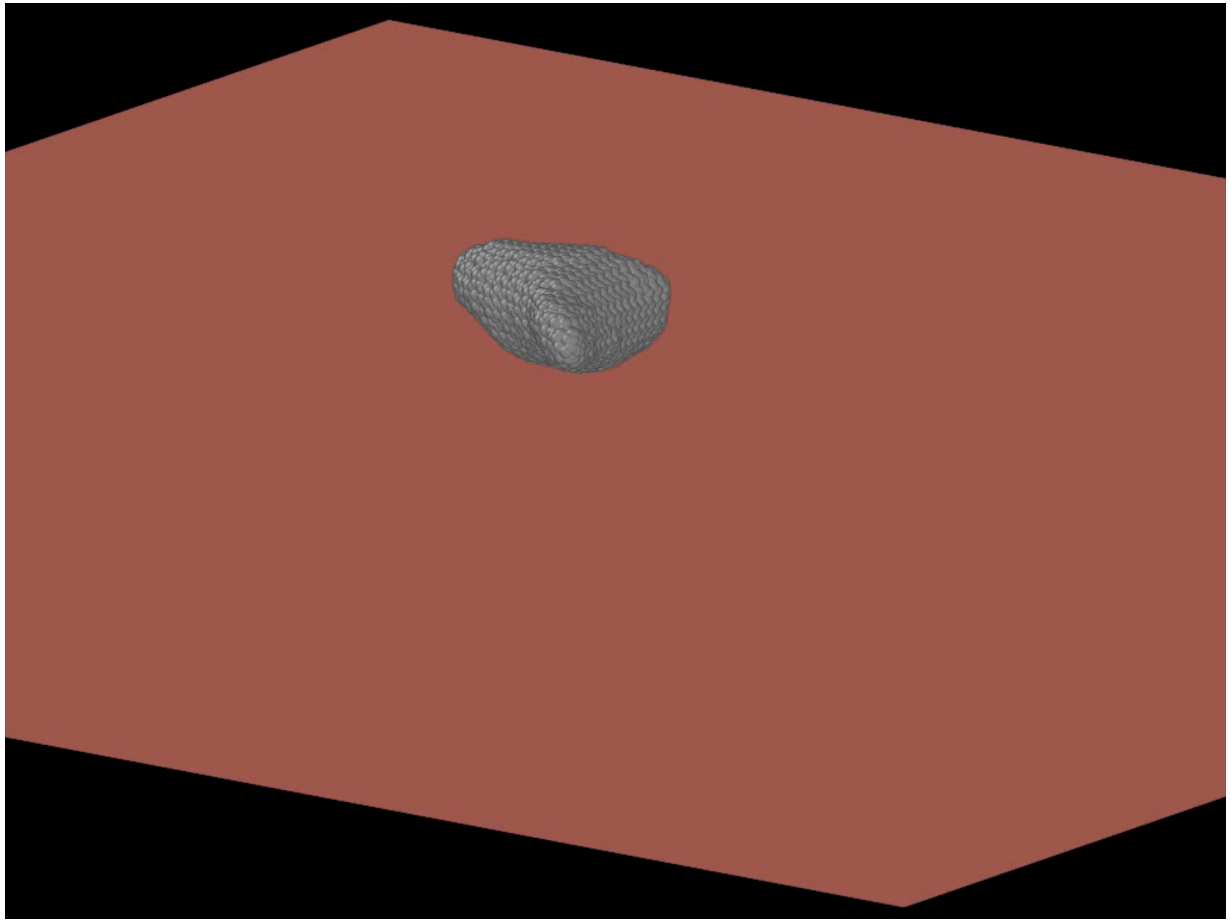
CT Scans converted to a surface mesh



Convert surface mesh to Discrete element model

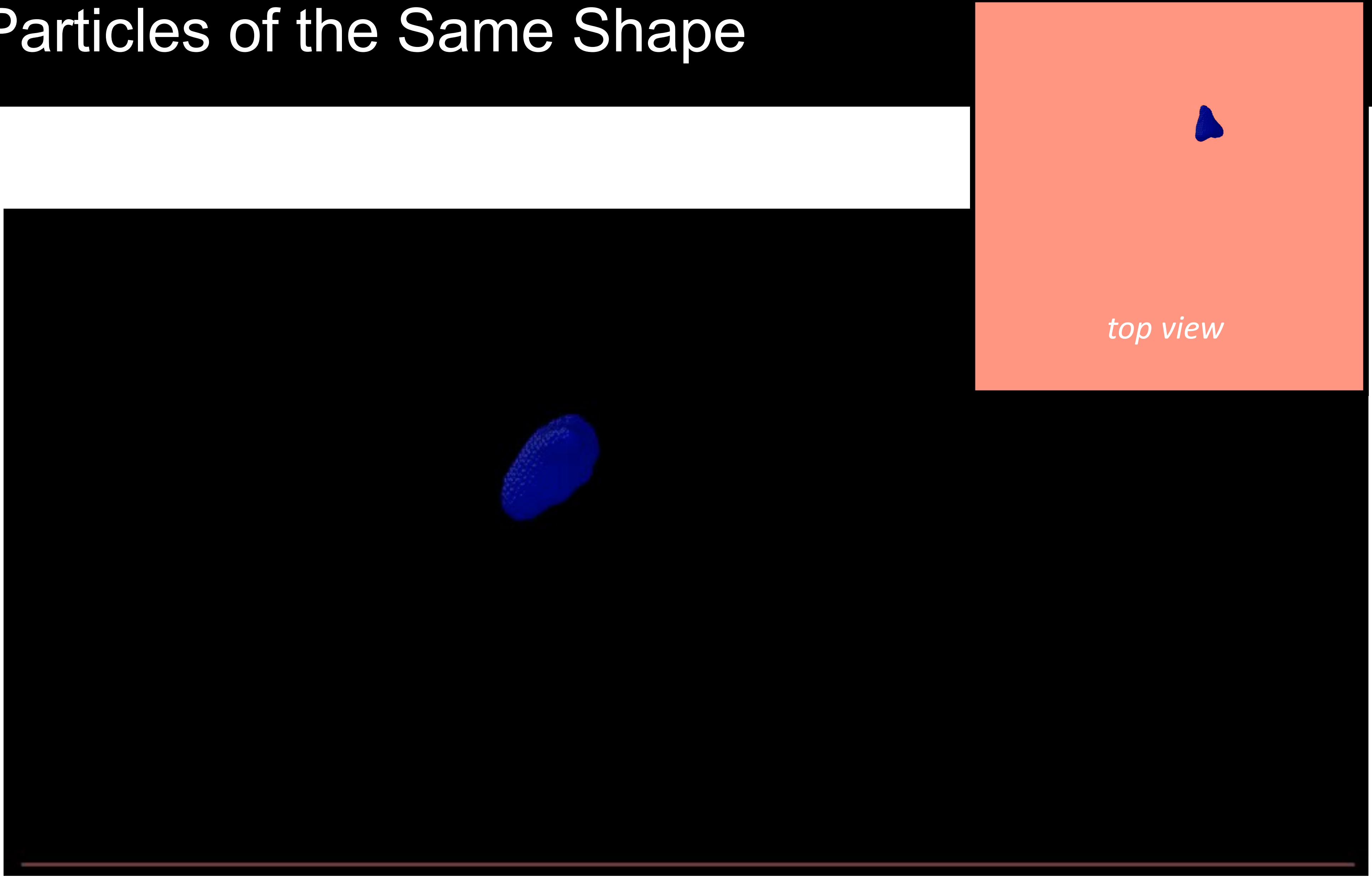


Single-particle on a smooth surface



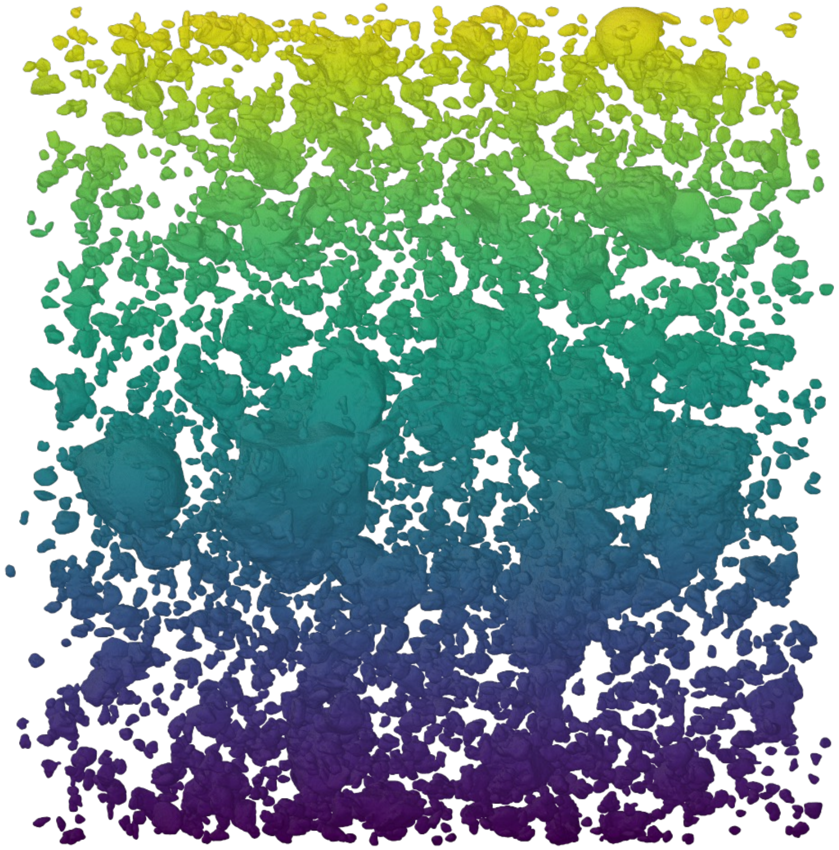
LAMMPS discrete element method simulation of a single grain from the Appollo 10 returned sample on a smooth plane.

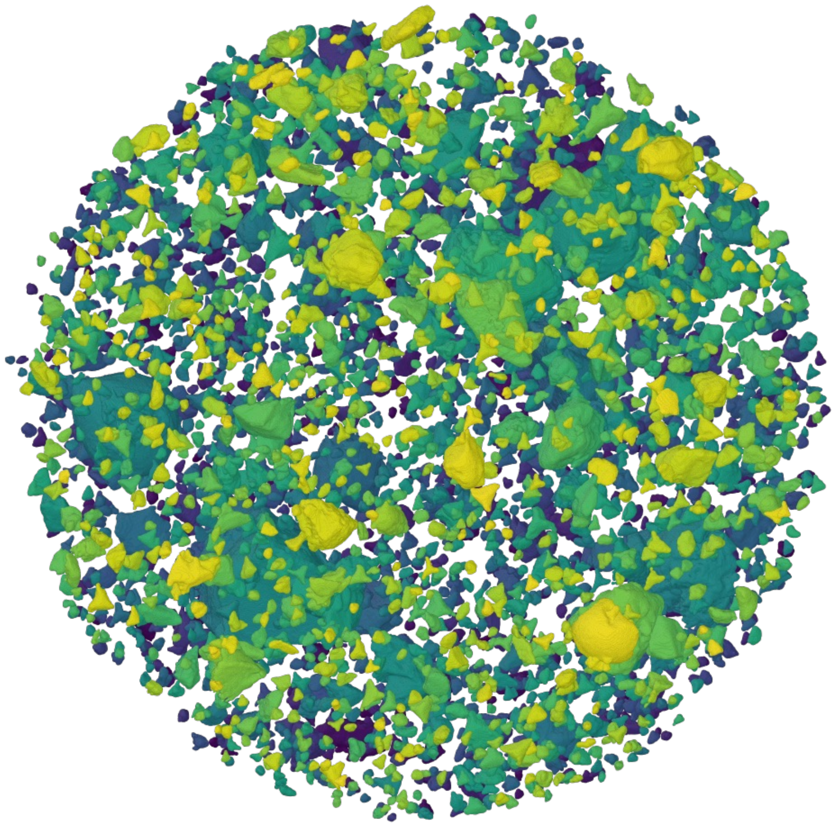
Many Particles of the Same Shape



Pouring simulation of 300 frictional regolith particles (generated from an Apollo 10 scan) onto a surface with periodic boundary conditions.

Next, simulate packing of full sample





Particle representation of ~4000 regolith grains (14 million particles) from the side (left) and top (right).

In-progress, Proposed and Future Regolith Work

- CIF25: preliminary experimental development of a UV-curable resin and resin-regolith composite
- MISSE-23: Early next year the CIF25 composite will go into space!
- CIF26: Assess resin-regolith composites for off-world landing pads with material response
    - Including resins from CIF25, UIC, and Glenn Research Center (PHB, Allison Christy)
- CIF26: Improve sintered and melted regolith processing with a metal AM modeling framework
- NIAC phase I: Experimental and computational maturation of CIF25 material
- Industrial proposals: SpaceX – manufacturing scale up. Blue Alchemist ACO?

Thank you, Questions?