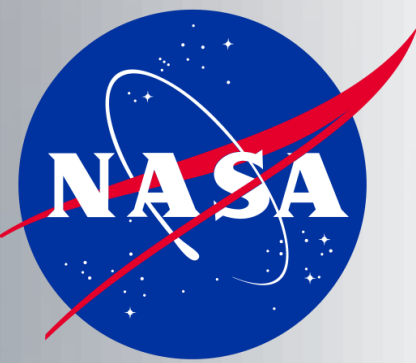




Natural Fiber Simulations and Analysis for Composites

Elizabeth M. Suehr¹, Melanie Chavez Rodriguez², Frederic Strommen², Lauren J. Abbott³ and **Andrew P. Santos**³

¹*NASA Postdoctoral Program, Oak Ridge Associated Universities, Thermal Protection Materials Branch NASA Ames Research Center, Moffett Field, CA, USA*

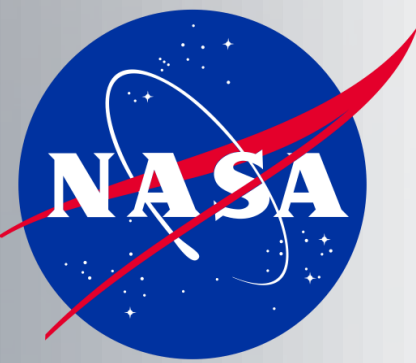
²*NASA Chabot High School Learning Experience, Oakland, CA, USA*

³*Thermal Protection Materials Branch NASA Ames Research Center, Moffett Field, CA, USA*



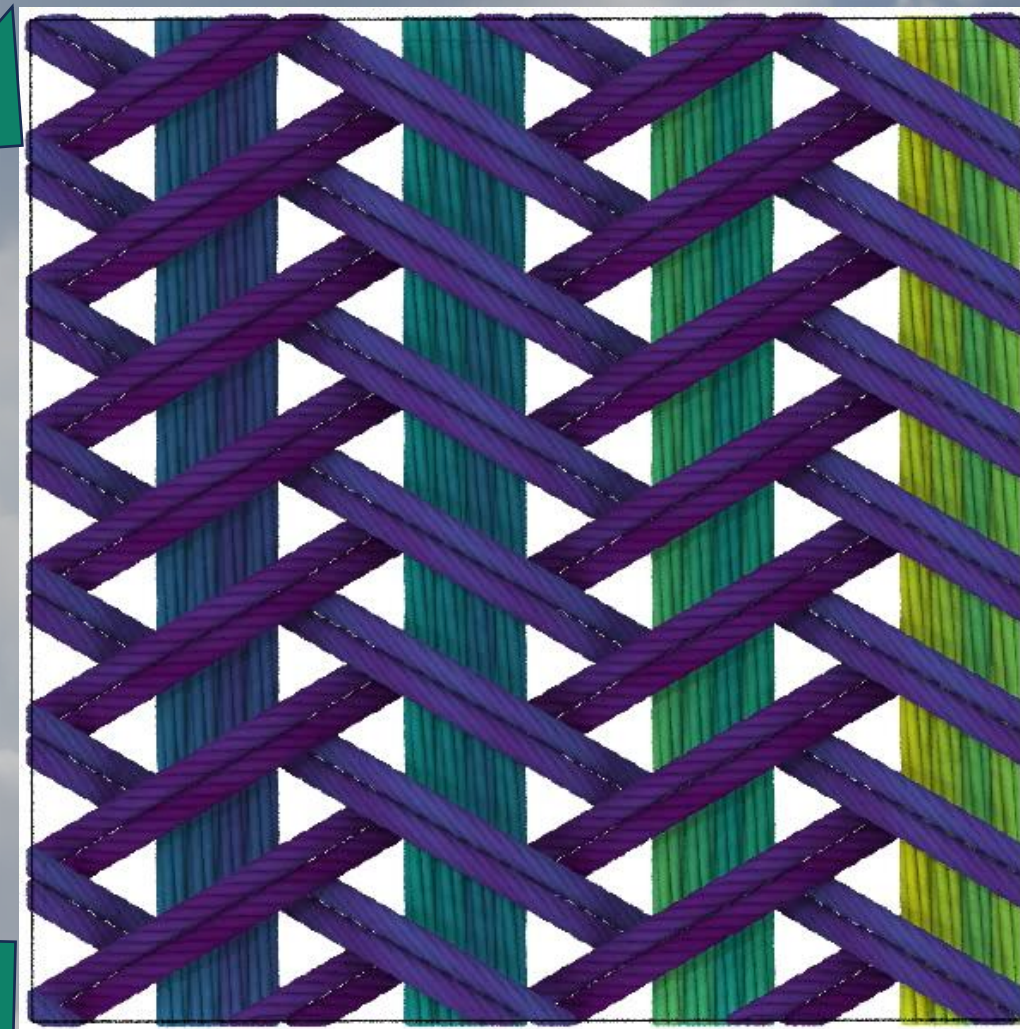
Meeting Series on Emerging Composite Technologies

June 16th, 2026

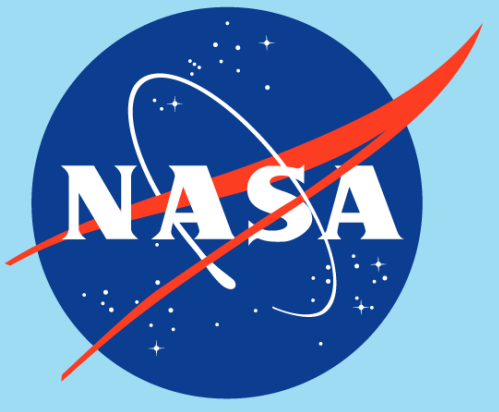


Concept: Infuse bio-based thermoplastics into weave or braid **flax** or **hemp fibers** for aircraft components.

This work: design and diagnose by simulating microstructure and physics of composite components.

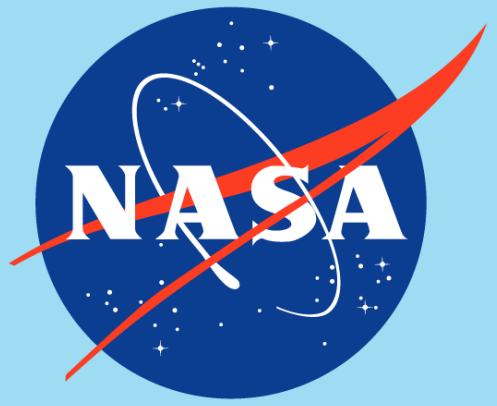


Benefits of SUMAC composites



- Aircraft are typically made of materials like aluminum and carbon fiber composites
- SUMAC aims to introduce more sustainable methods of constructing aircraft material, including natural fibers and resins
 - Life cycle impact on environment is much lower
 - Biodegradable and high recyclability
- Natural fibers have beneficial properties
 - Vibration dampening
 - Mechanical properties can compete with glass fibers
 - Radio frequency transparency

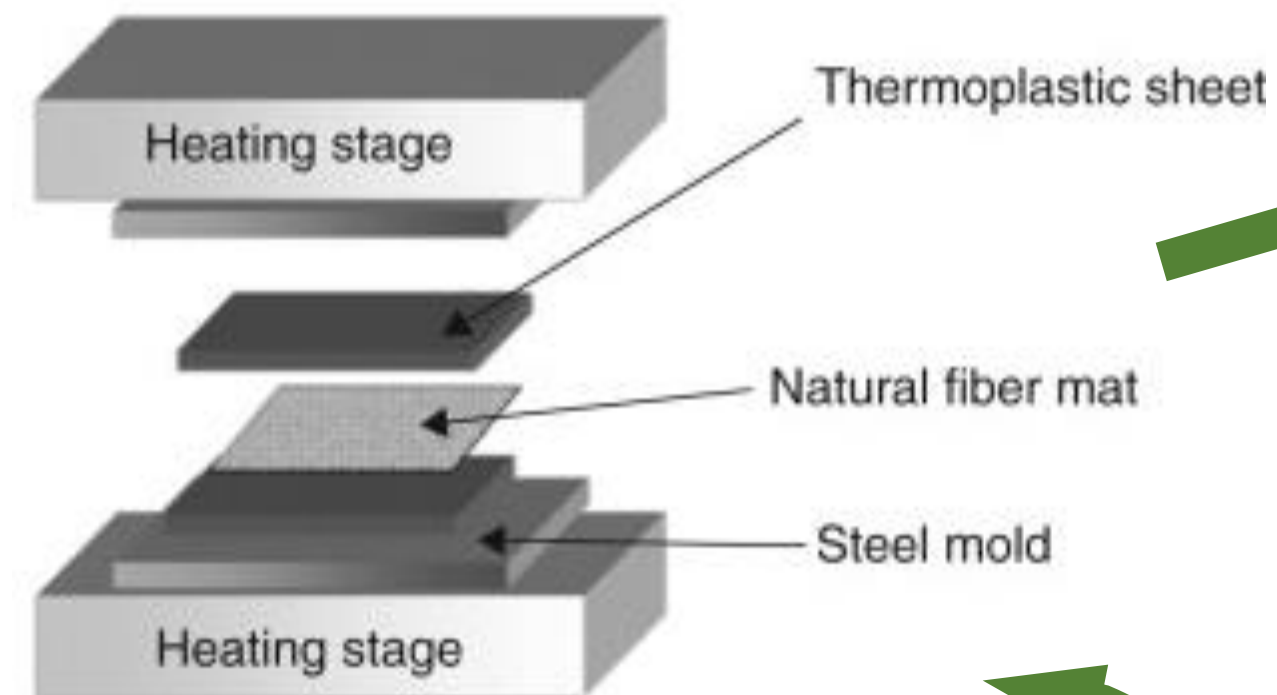
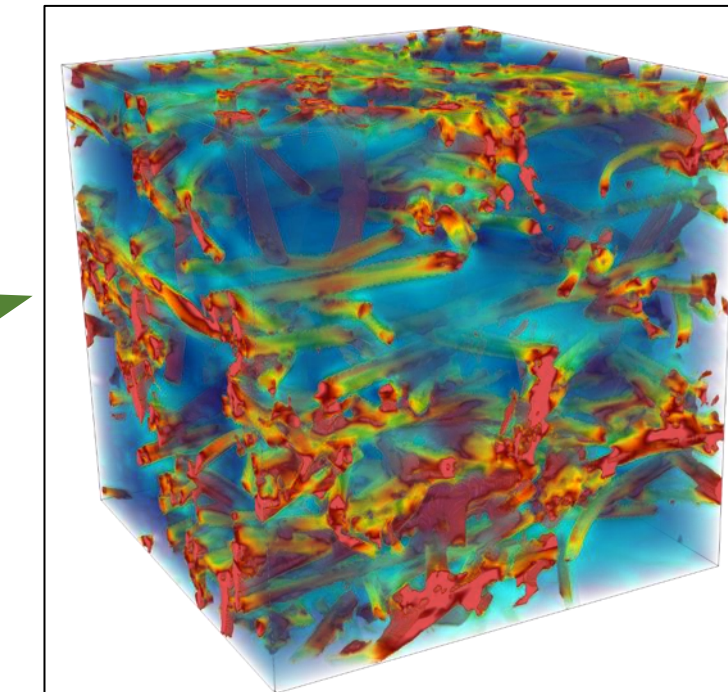
Project Approach to Composite Development



bioresin
(Mango PHB, Pond PLA,
Arkema PA11)



Manufacturing (GRC)



Modeling (ARC)



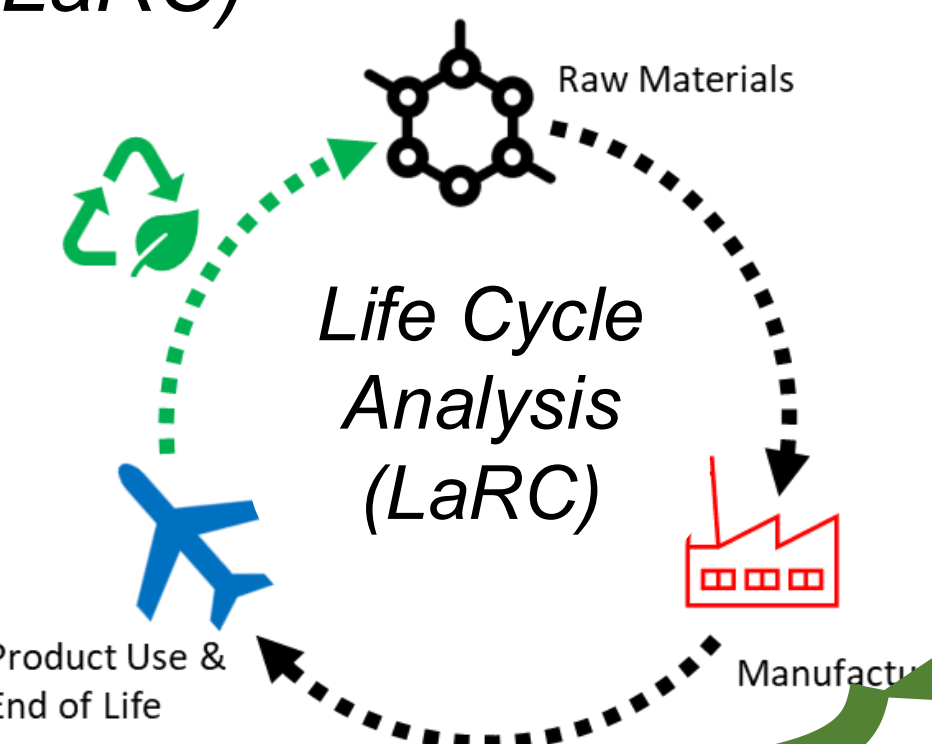
Sensors (LaRC)

Testing

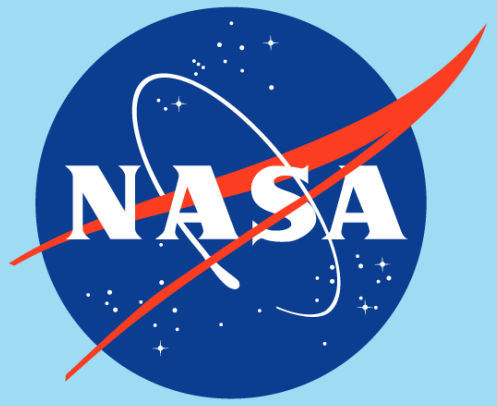


Flax (Bcomp, Terre de lin)
Hemp (EnviroTextiles)

*Weavers (Bcomp,
EnviroTextiles, AnP)*



Project Team

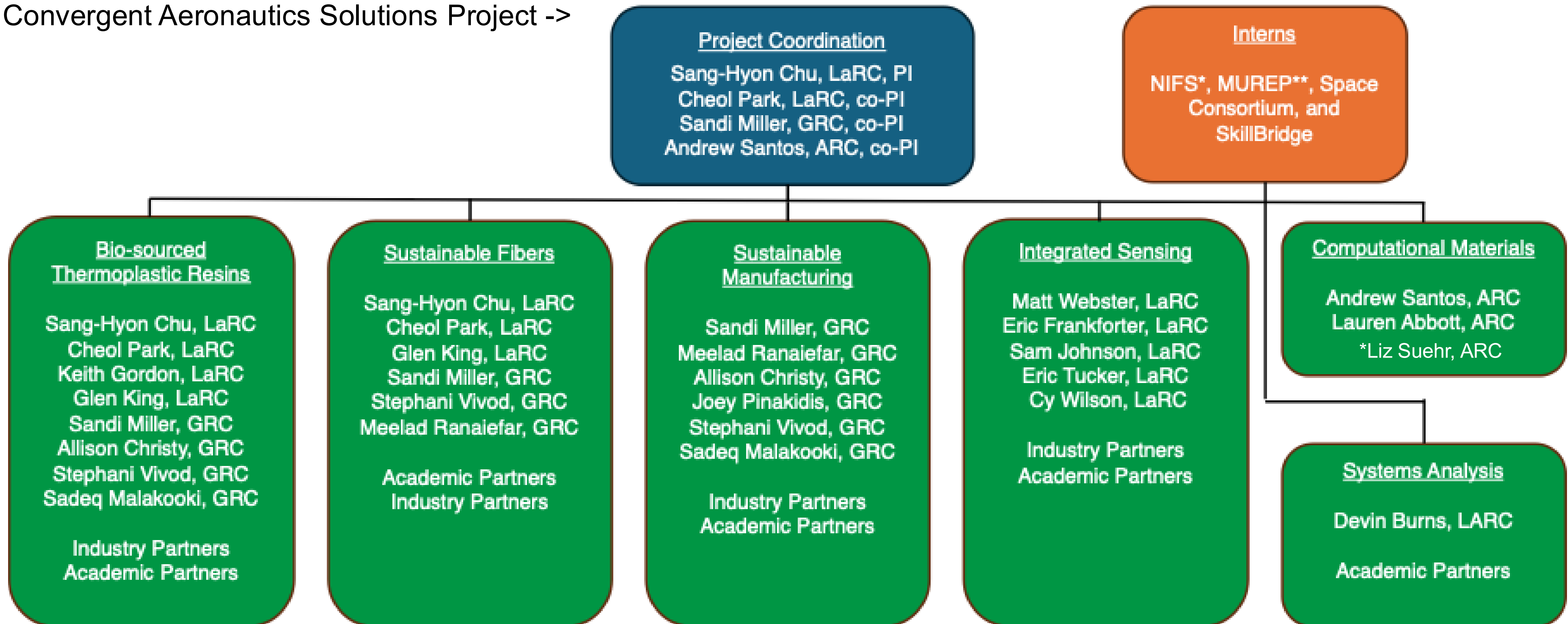


NASA ->

Aeronautics Research Mission Directorate ->

Transformative Aeronautics Concepts Program ->

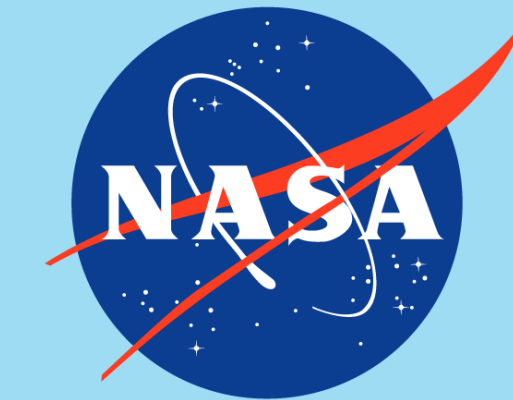
Convergent Aeronautics Solutions Project ->



*NIFS: NASA Internships, Fellowships and Scholarships

*MUREP: Minority University Research & Education Project

Team Acknowledgment



Yarn Simulations

- Elizabeth Suehr
- Andrew Santos

Weave Simulations

- Andrew Santos

Optical Microscopy Analysis

- Frederic Strommen
- Melanie Rodriguez
- Lauren J. Abbott

Project Management

- Sang-Hyon Chu
- Lauren J. Abbott
- Andrew Santos

Fiber Properties

- Enoch Kim
- Francisco de Jesus
- Glenn King
- Cheol Park
- Sang-Hyon Chu

Composite Manufacturing and microscopy

- Change Long
- Tyler Klinchuch
- Sandi Miller
- Allison Christy

Partners:

Fiber/weave providers

Bcomp
Envirotextiles
A&P Technology
ELI

Resin providers

Mango Materials
Pond
Arkema

Aircraft

Joby
Airbus
Boeing

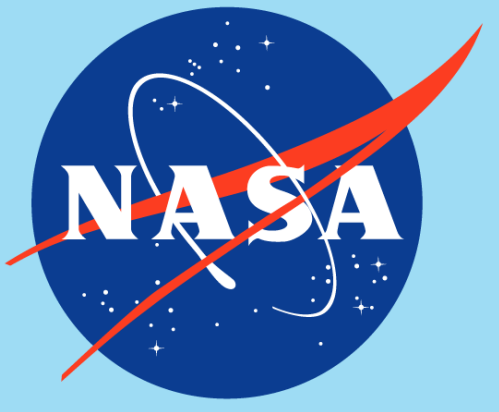
Agencies

FAA
Oak Ridge Nat. Lab

Universities

Virginia Tech
Missouri S&T

Team Acknowledgment



*Sang-Hyon Chu, Cheol Park, Keith Gordon, Glen King, Matthew Webster, William C. Wilson, Eric Z. Tucker, Samantha Johnson, Erik Frankforter, Devin Burns, Edward Glaessgen
Langley Research Center, Hampton, Virginia*

*Sandi Miller, Allison Christy, Meelad Ranaiefar, Sadeq Malakooti, Joseph Pinakidis, Stephanie Vivod
Glenn Research Center, Cleveland, Ohio*

*Andrew P. Santos, Lauren J. Abbott
Ames Research Center, Moffett Field, California*

Paula Heimann, Universities Space Research Association, Washington, District of Columbia

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Nerika Hernandez, University of Puerto Rico Río Piedras, San Juan, Puerto Rico

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Khadeejah Jenkins, William Paterson University, Wayne, New Jersey

Aliah Claire O. Colobong, Montclair State University, Montclair, New Jersey

Nour H. Hakim, University of Nevada, Las Vegas, Nevada

Luke D. Post, Iowa State University, Ames, Iowa

Gael Perez, University of Nebraska-Lincoln, Lincoln, Nebraska

Katie Blyler, The Pennsylvania State University, University Park, Pennsylvania

Chase Long, University of Idaho, Moscow, Idaho

Tyler Klinchuch, Boise State University, Boise, Idaho

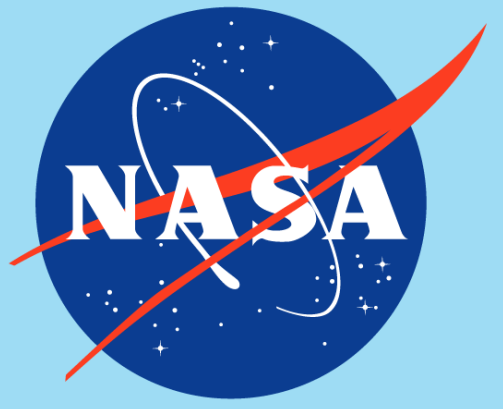
Julia Hand, Grand Canyon University, Phoenix, Arizona

Elizabeth M. Suehr, University of California Davis, Davis, California

Melanie Chavez Rodriguez, East Bay Innovation Academy, Oakland, California

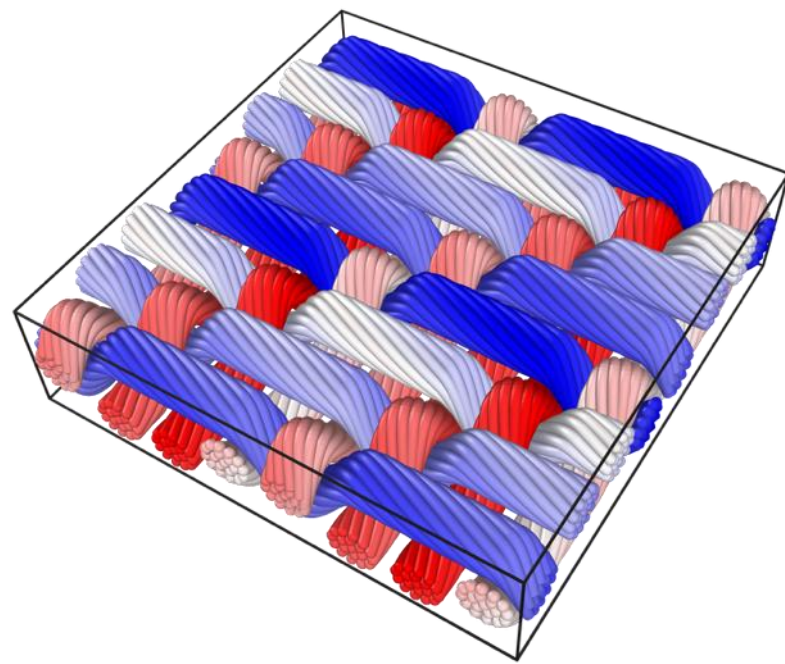
Frederic M. Strommen, East Bay Innovation Academy, Oakland, California

Computational Materials Overview

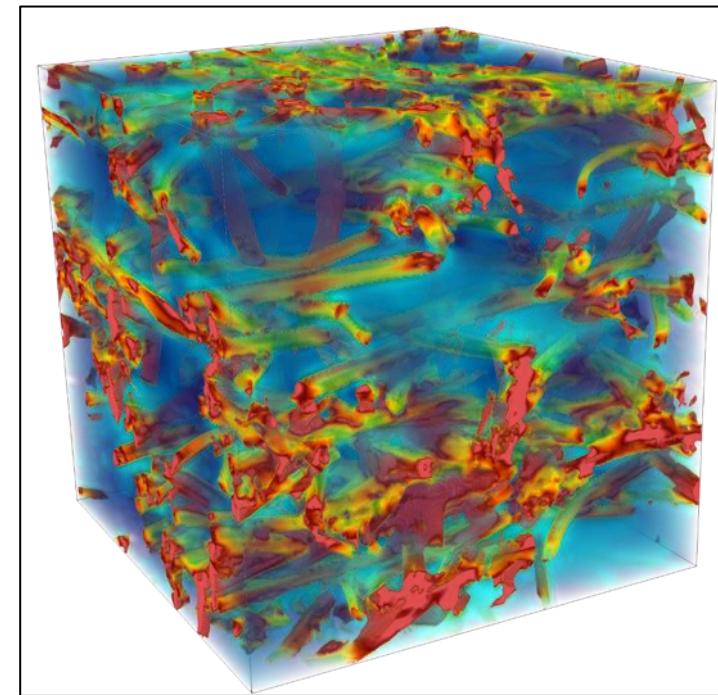


Support fiber, resin, and manufacturing efforts with simulations

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

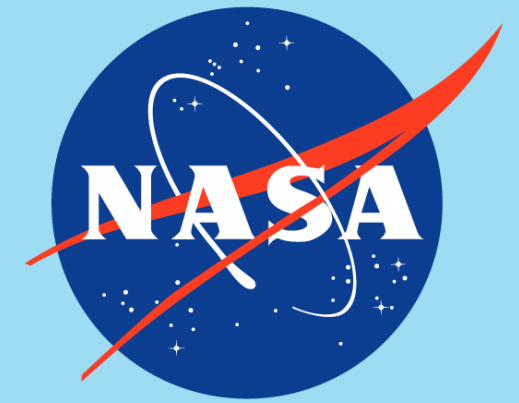
Benefit

- Reduce experimental needs and costs
- Narrow material design scope

Approach

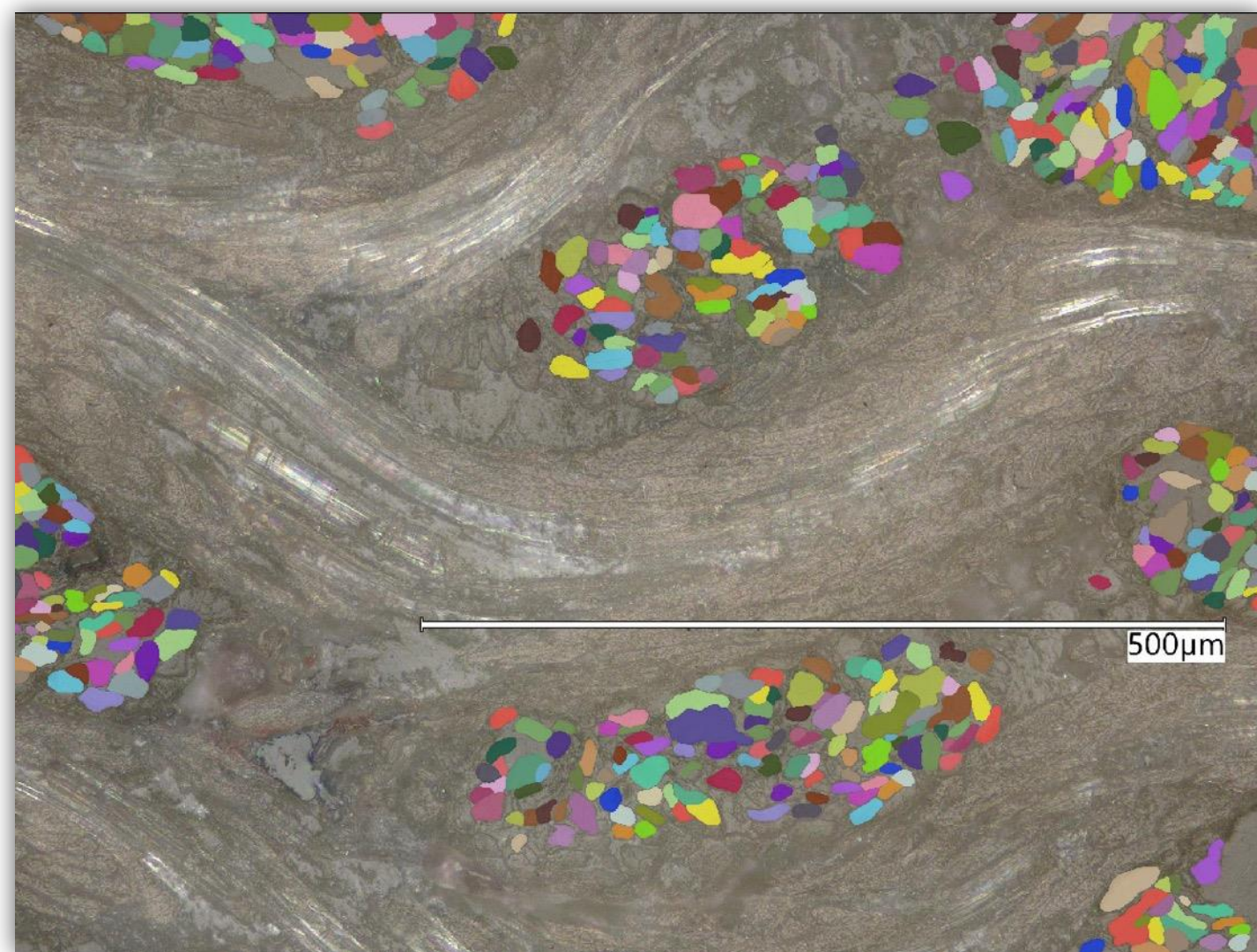
- Verify computational inputs and methodology with experiments
- Vary components and interactions with micro-scale simulations
- Calculate material properties from simulations and analysis

Outline



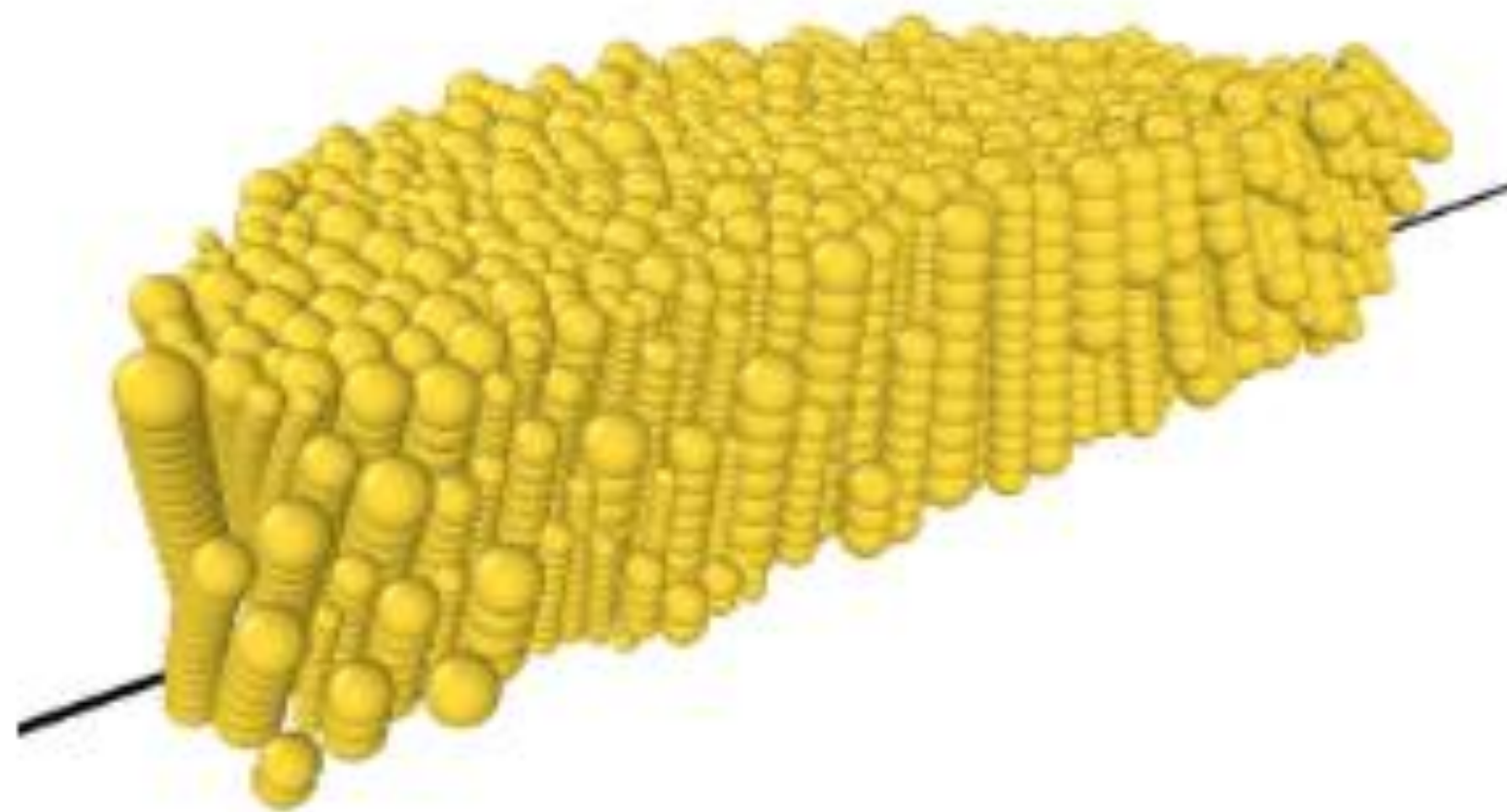
Part I

**Fiber characterization from
image segmentation**



Part II

Yarn-scale simulations

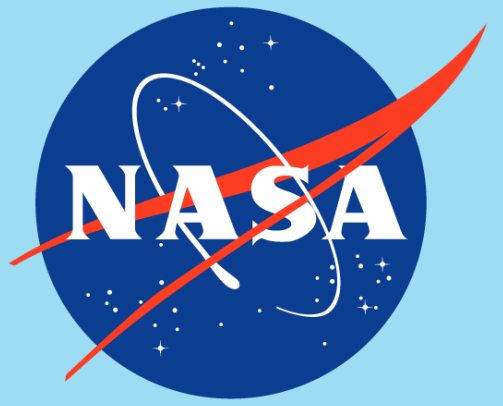


Part III

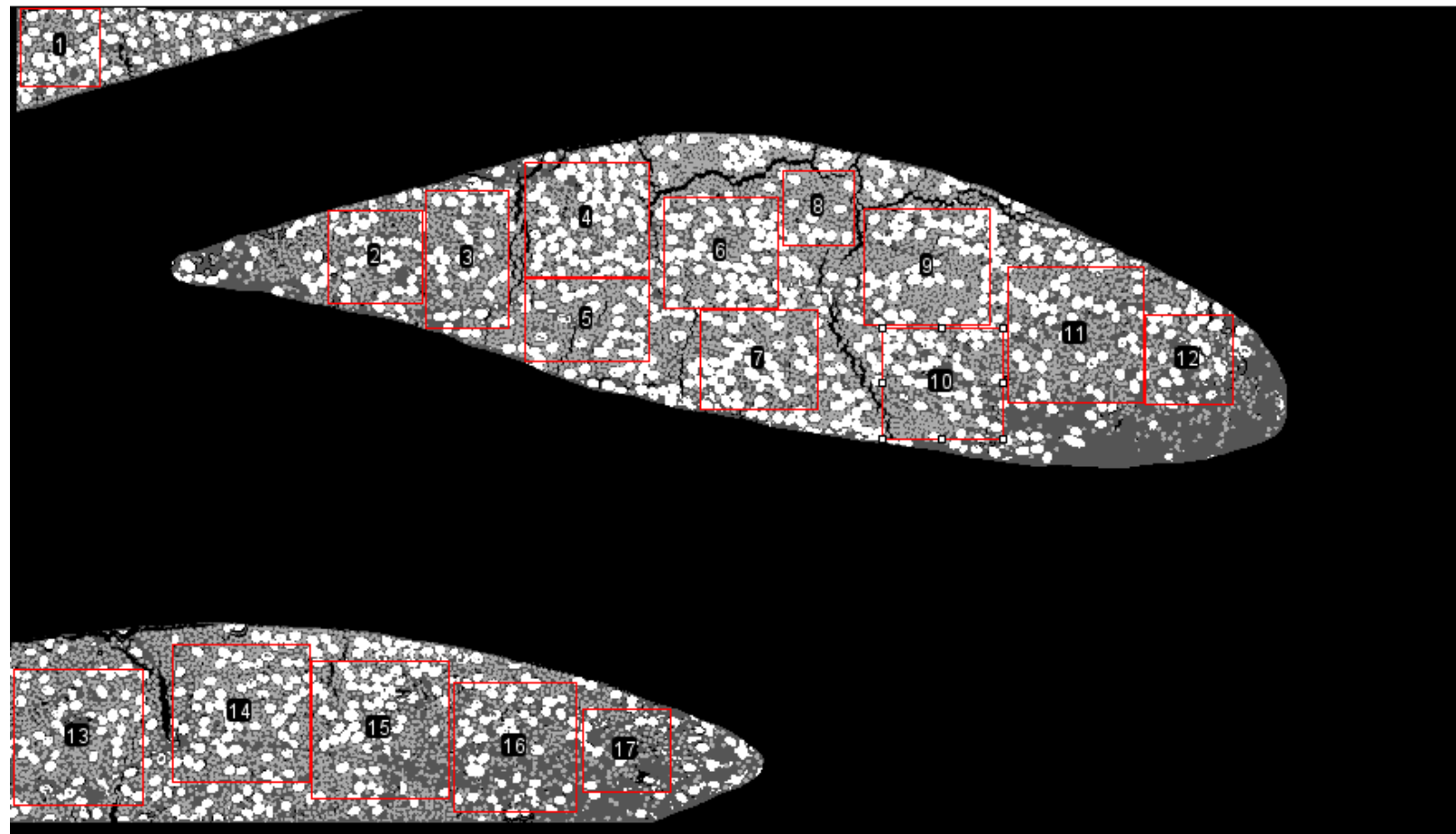
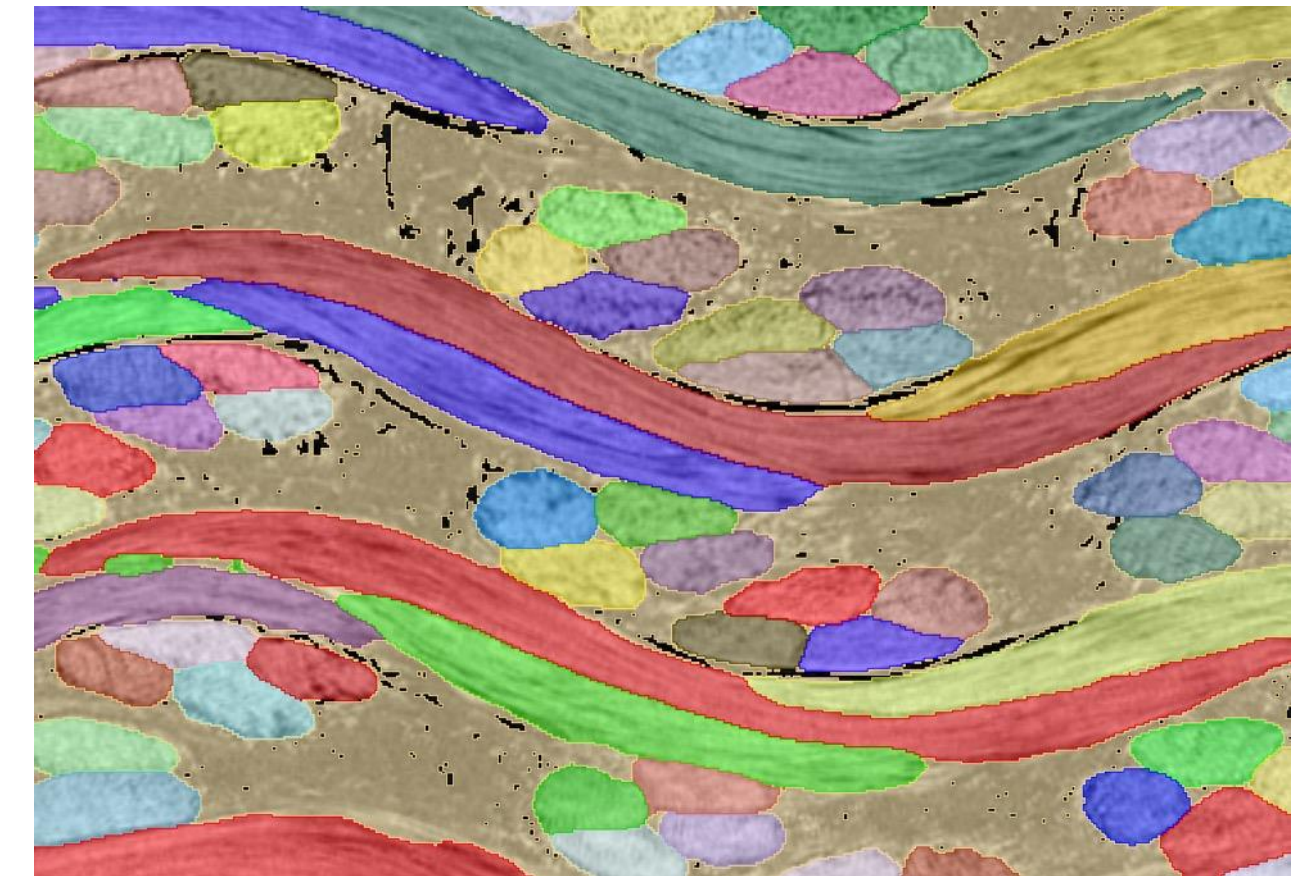
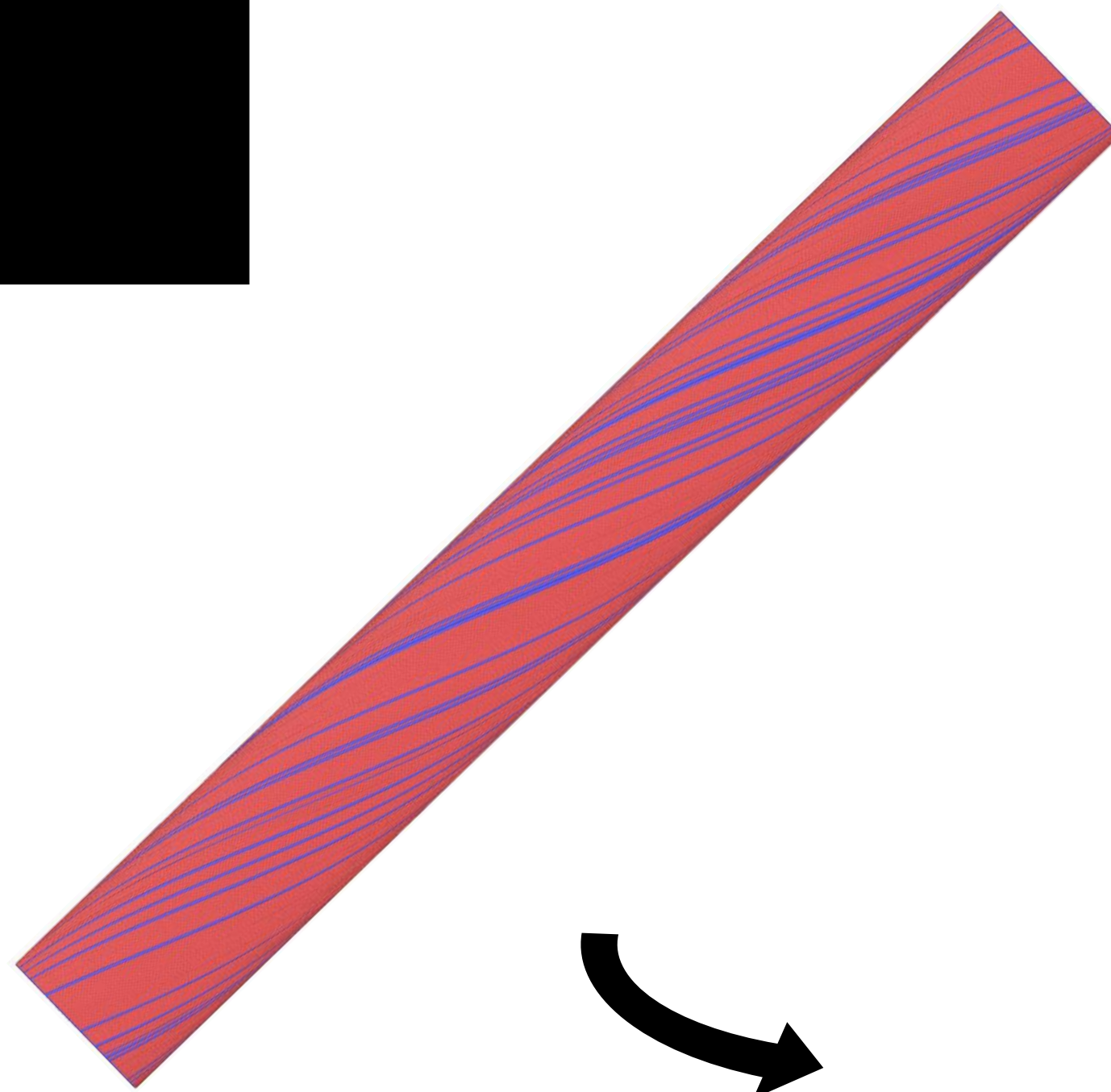
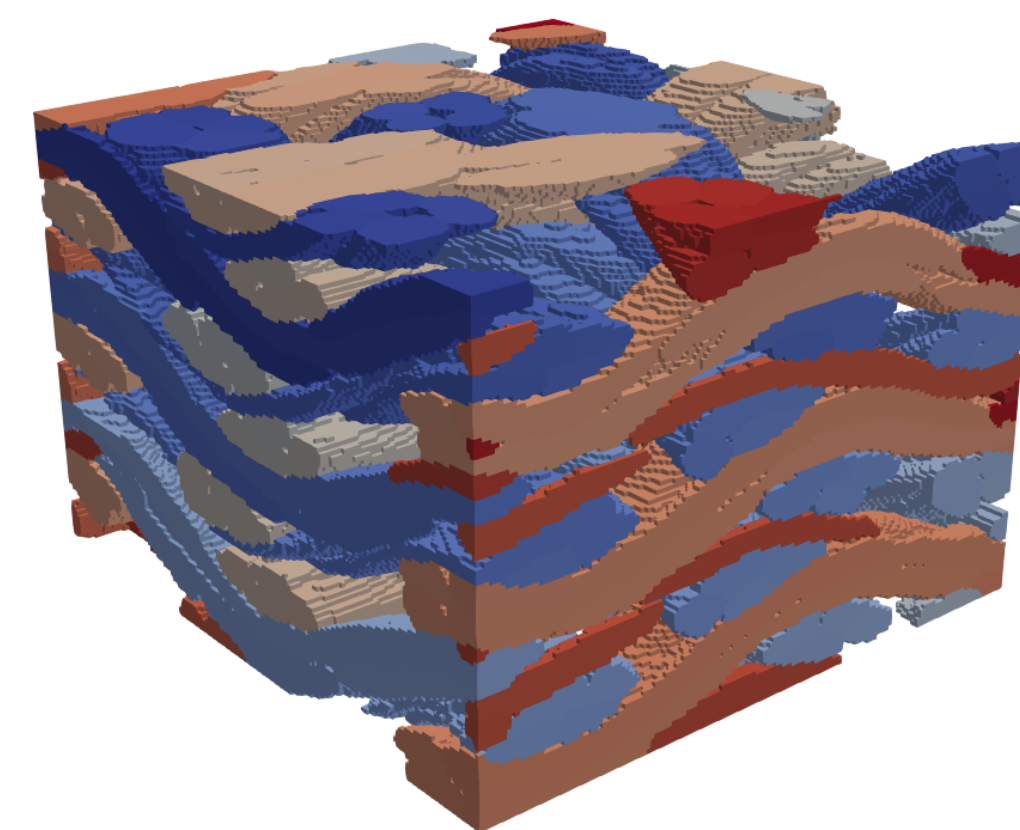
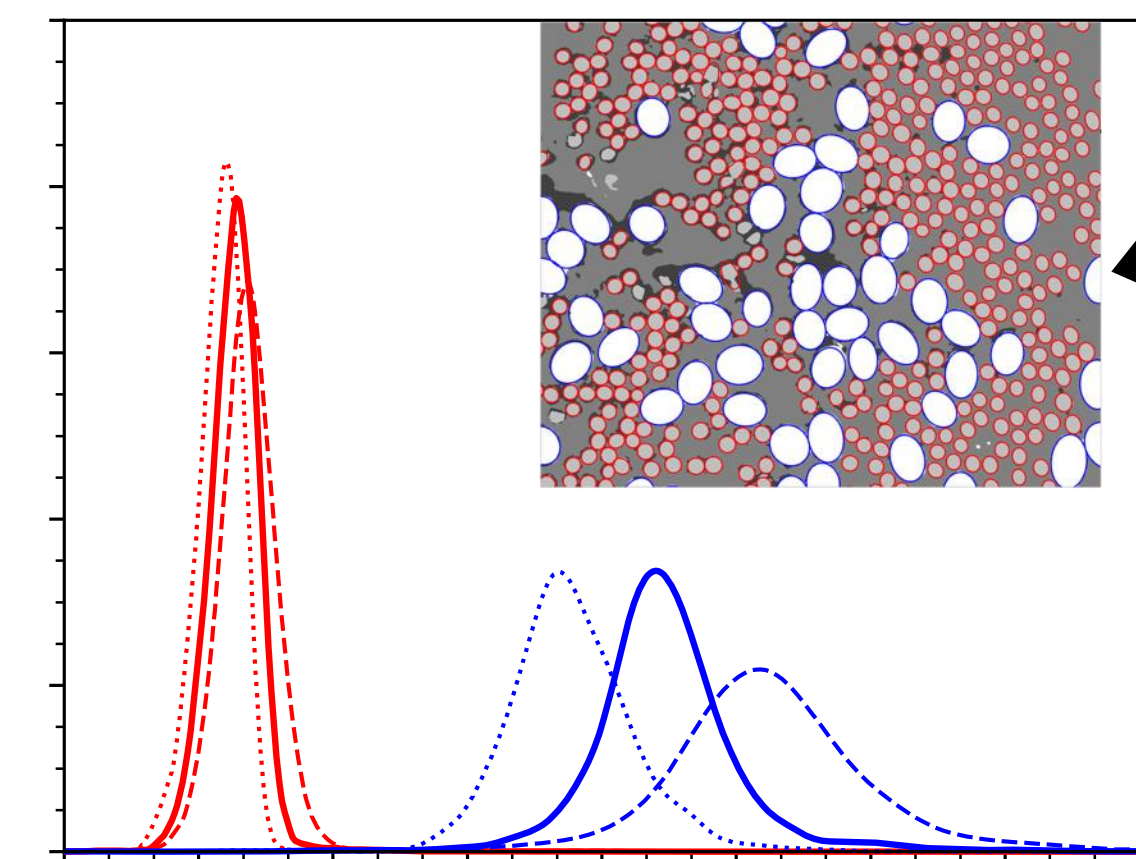
Weave-scale simulations



Modeling Woven Composites



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

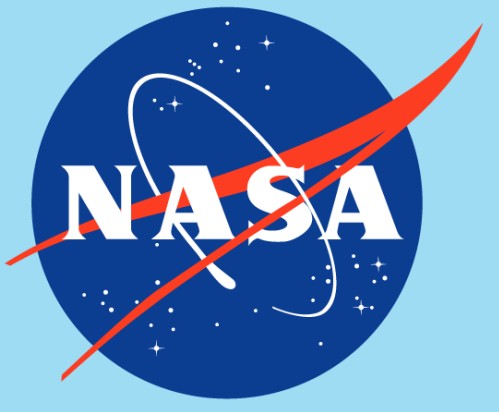


Fiber characteristics, e.g. fiber size and shape distribution

Yarn simulations that resolve every fiber

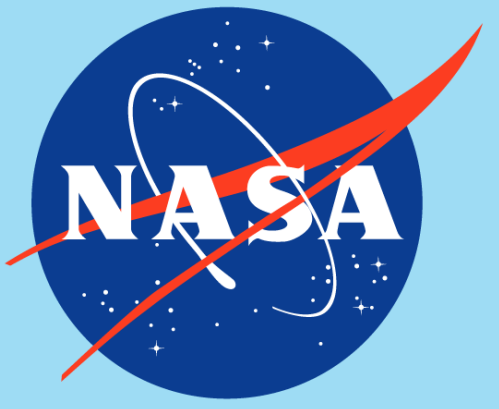
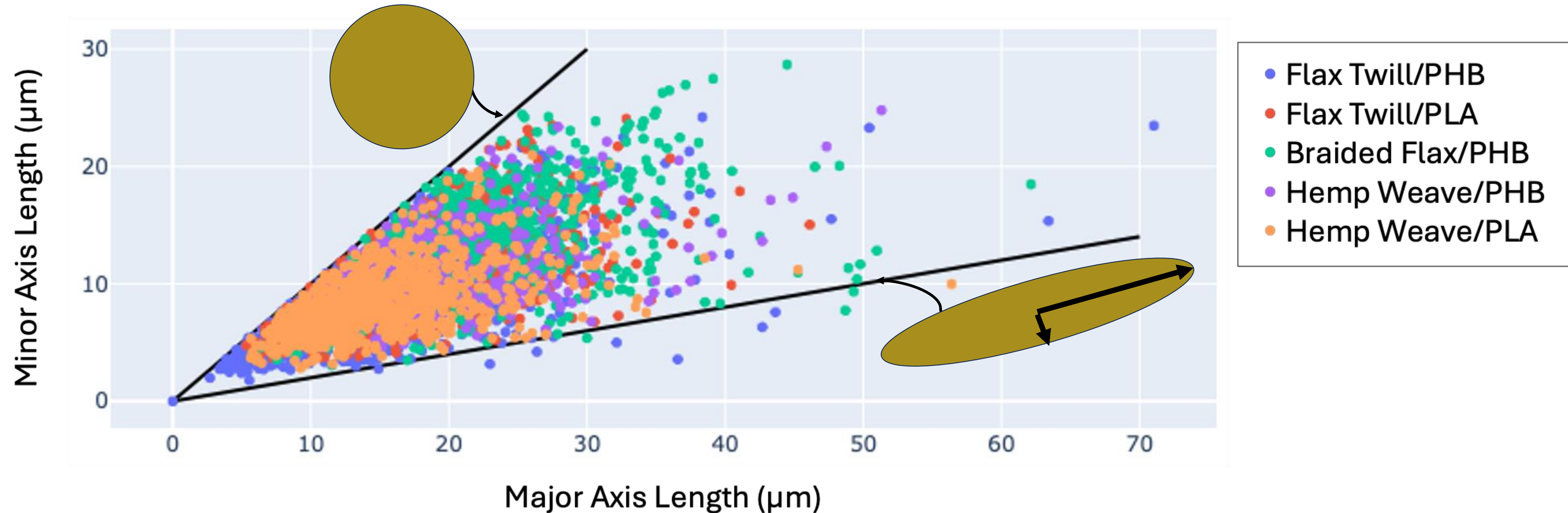
Weave simulations that many "coarse" fibers per yarn

Example Segmentation



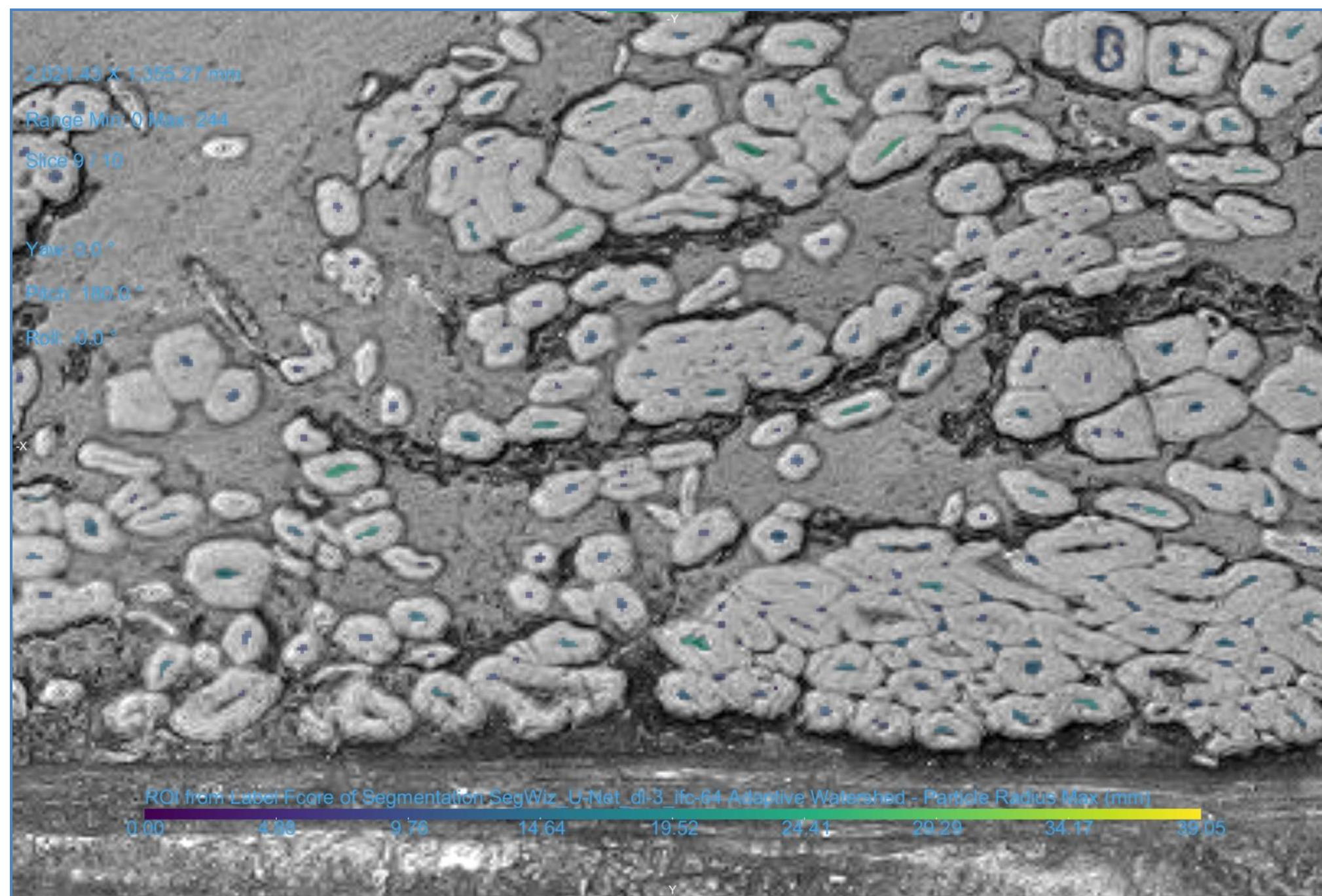
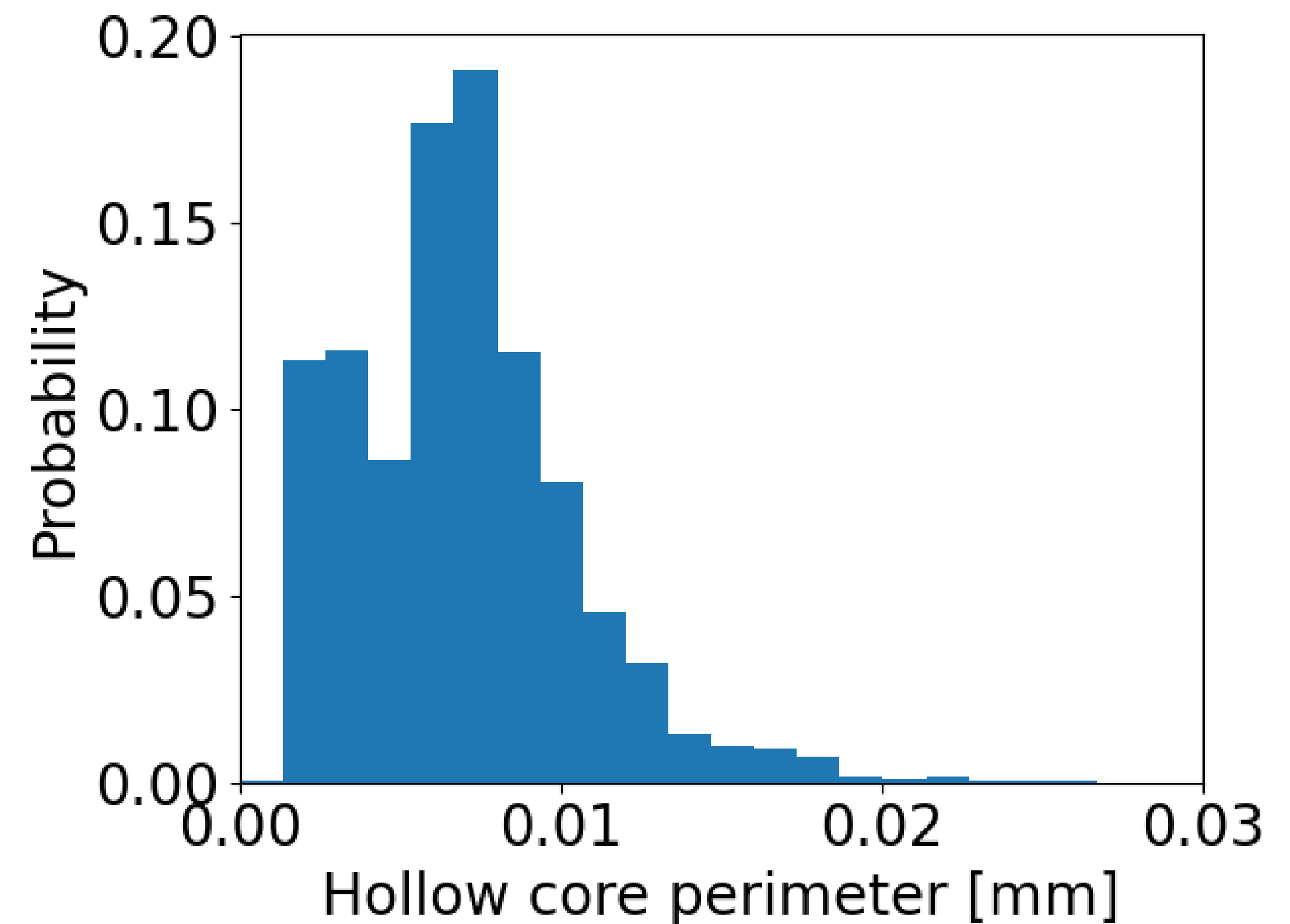
Optical microscopy of Hemp Weave/PLA composite at $400\times$ magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

Fiber Shape Anisotropy



Fiber shapes range from flattened, aspect ratios $R_{\text{long}}/R_{\text{short}}$ up to 5, to round, $R_{\text{long}}/R_{\text{short}}=1$

Fiber Hollowness Variation

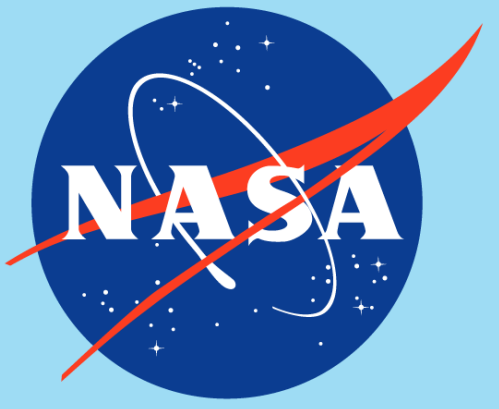


Close-up of Flax fibers in a Flax Twill-PLA optical microscopy showing hollow core segmentation. About 3000 cores were segmented

Probability distribution of hollow core perimeter lengths.

Larger hollow cores likely correlate with larger, less circular, and **more deformed fibers**.
 Fiber wall thickness seems to have a wide distribution.

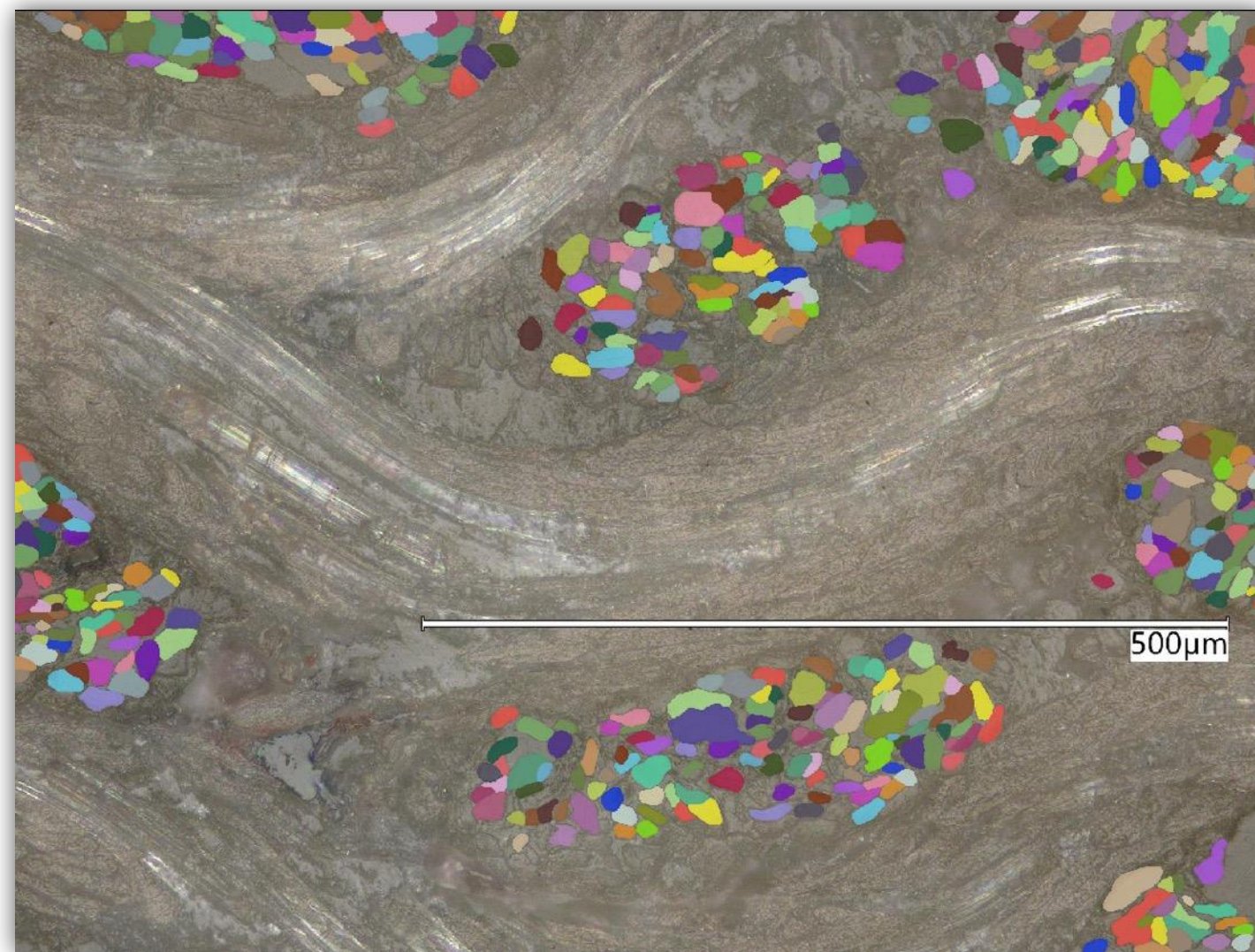
Yarn-Scale Simulations



Fiber cross sectional properties were calculated by optical microscopy segmentation to quantify microstructure variation and influence of manufacturing.

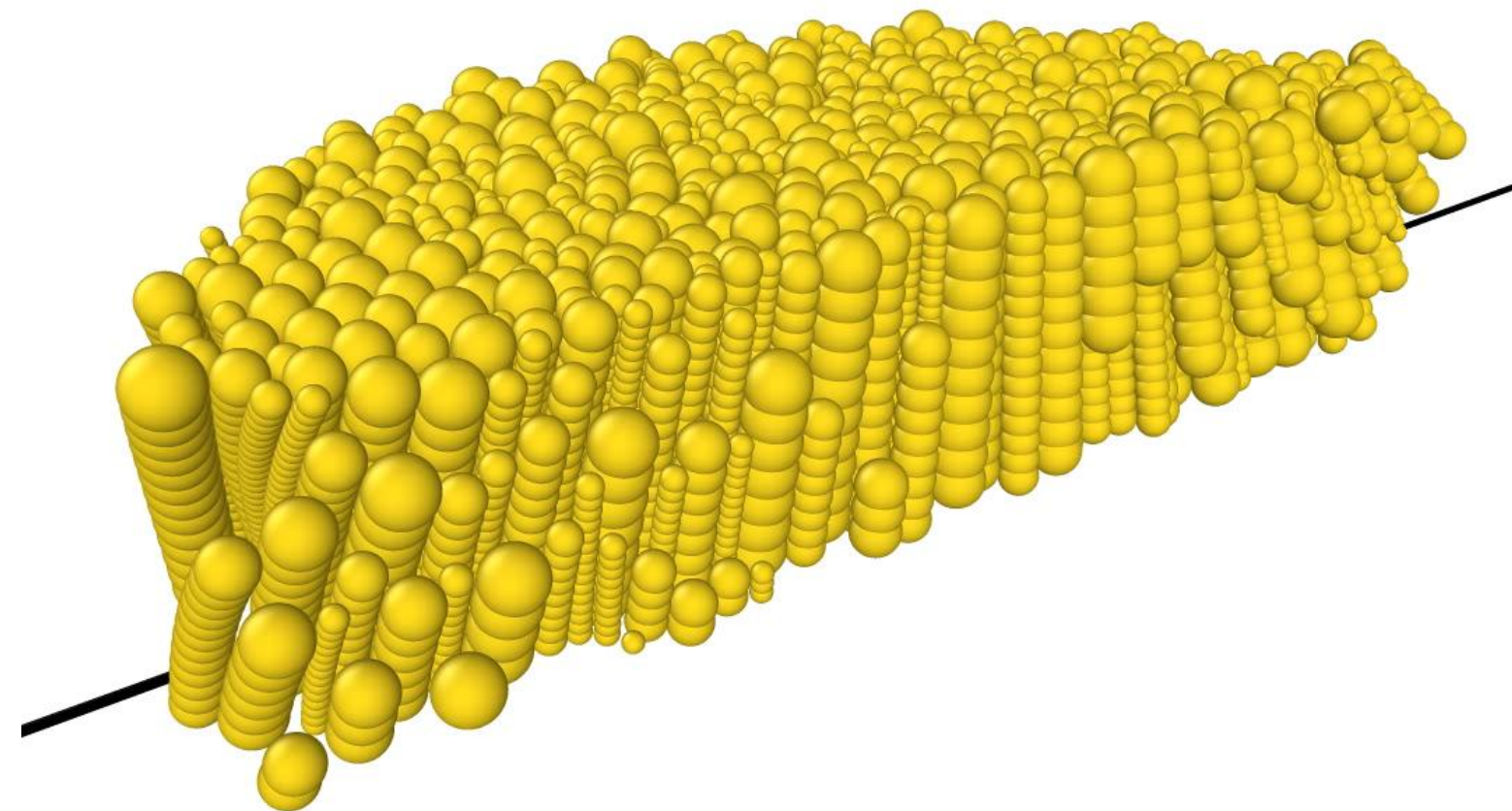
Part I

Fiber characterization from
image segmentation



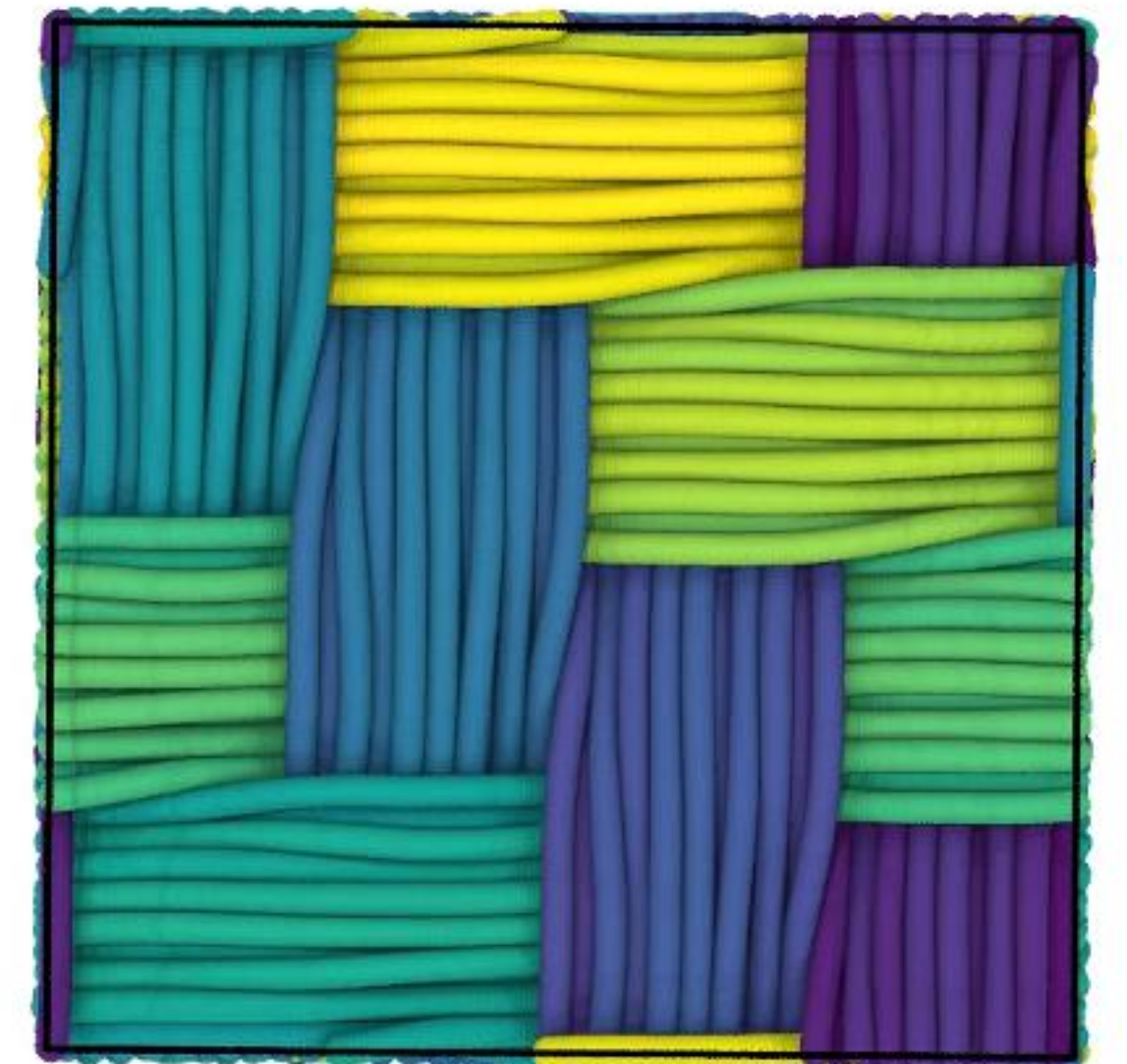
Part II

Yarn-scale simulations



Part III

Weave-scale simulations



DEM

Simulation technique for particle motions

- Based on Newtons' second law

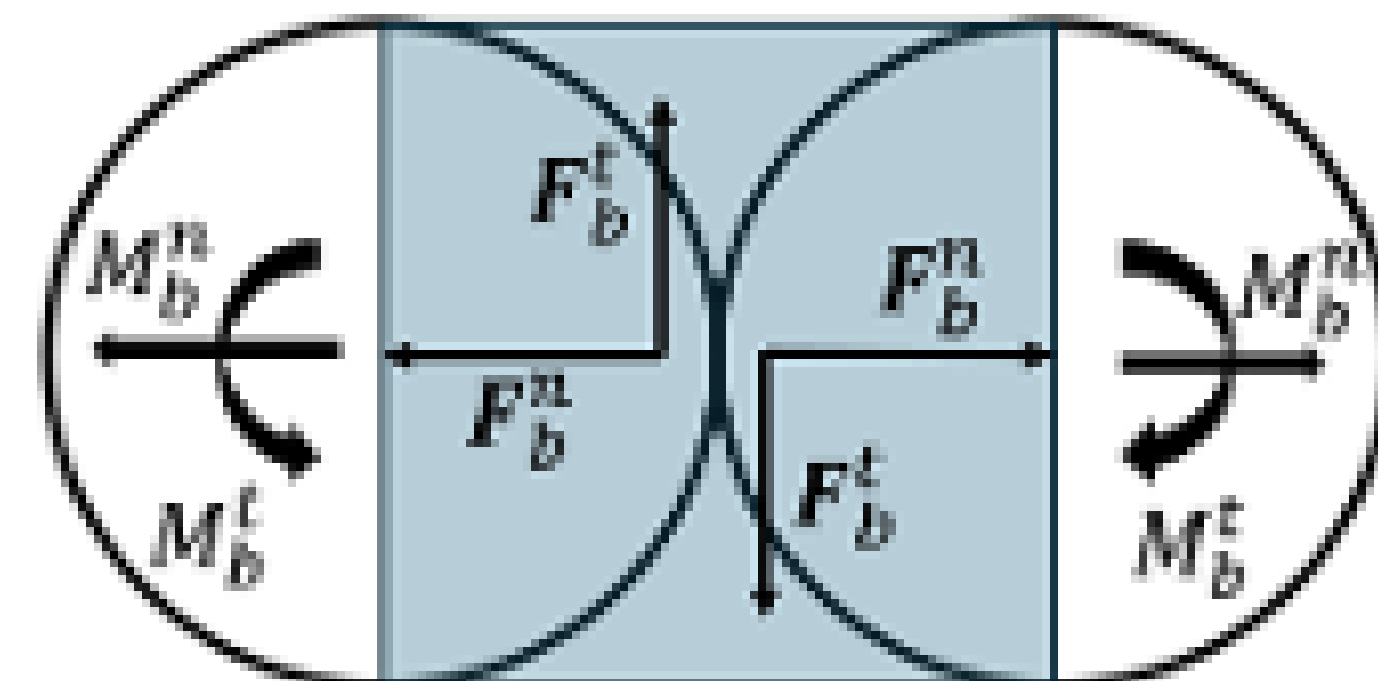
$$m_i \frac{d\mathbf{u}_i}{dt} = \mathbf{F}_i \quad I_i \frac{d\boldsymbol{\omega}_i}{dt} = \mathbf{M}_i$$

- Forces come from contact models
- Pros: access to trajectories, positions, or forces of each particle
- Cons: computationally expensive
 - Scales with number of particles $O(N \log(N))$ with optimizations

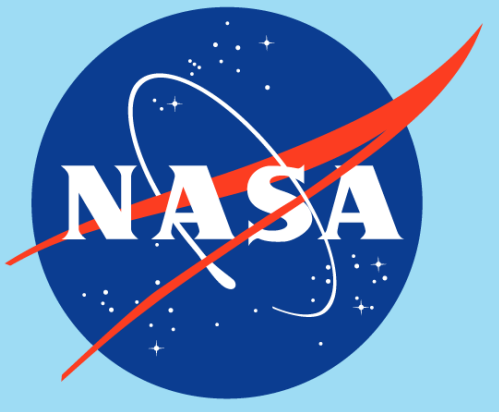
BPM

Creates a bond between to spheres, as if there was solid material filling the cylinder between the two spheres

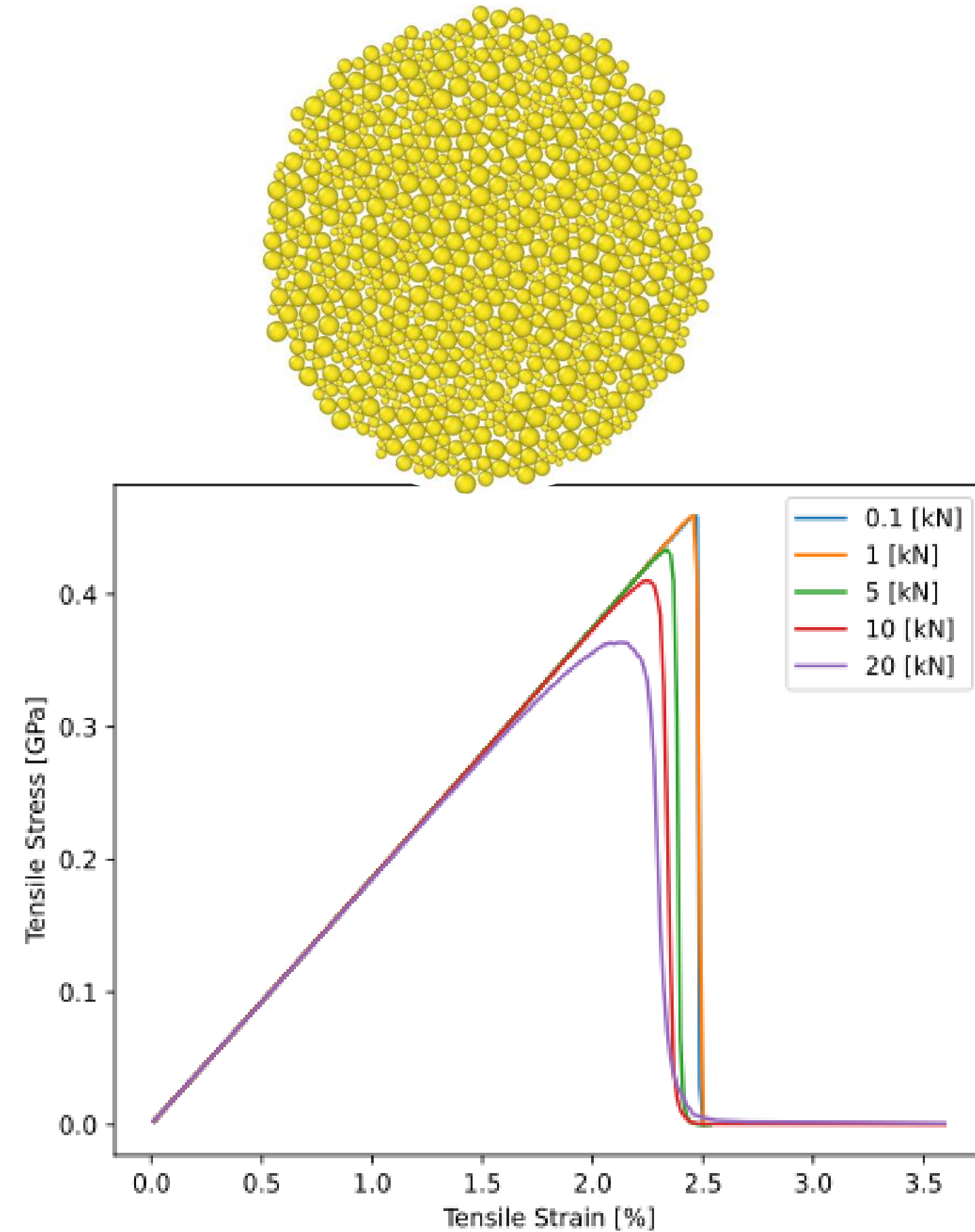
- Bonds keep track of compression/extension, torque, twisting, bending
- Bonds break after a max Force and Moments are exceeded



What is Required to Simulate Yarn Mechanics

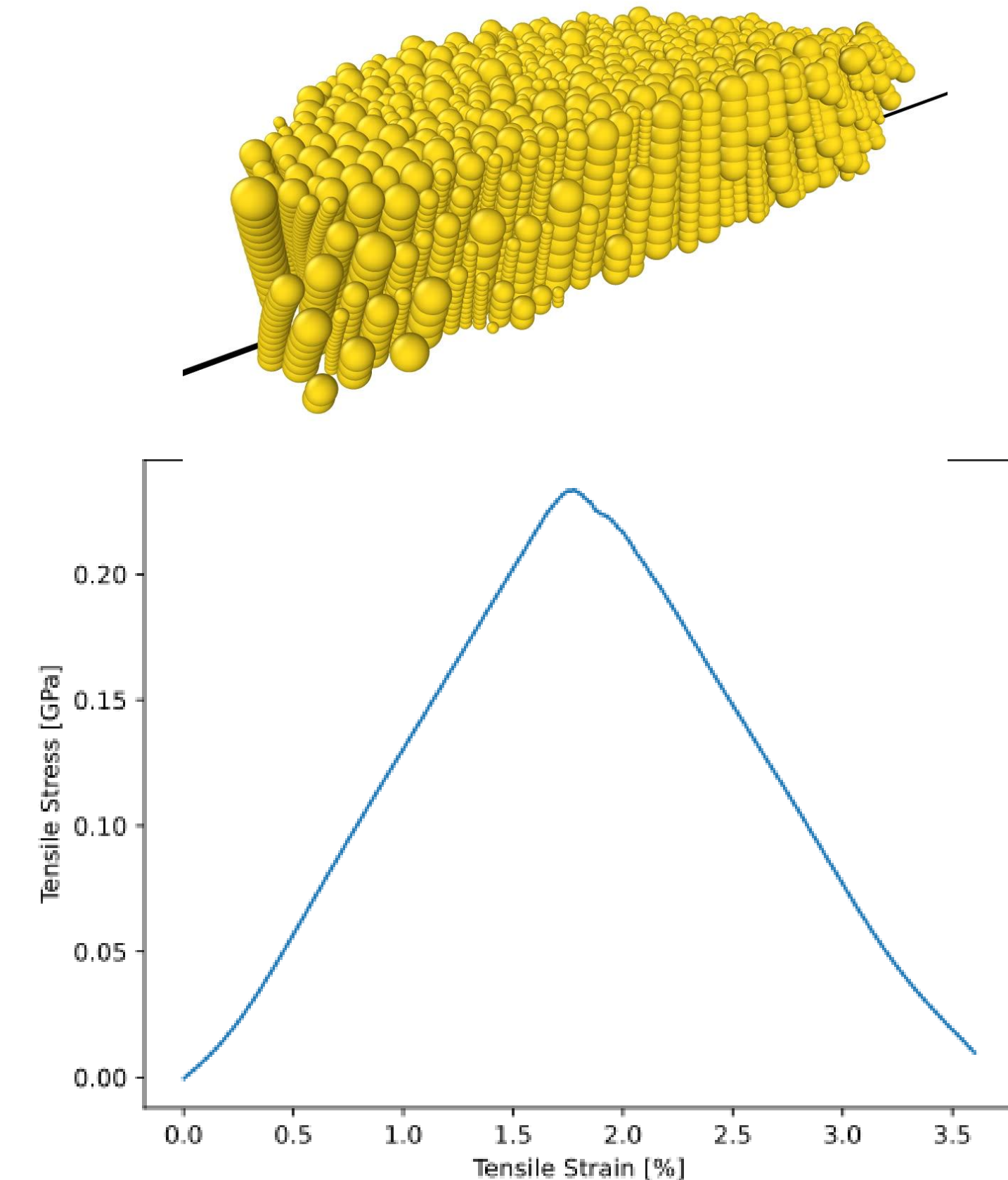


2D



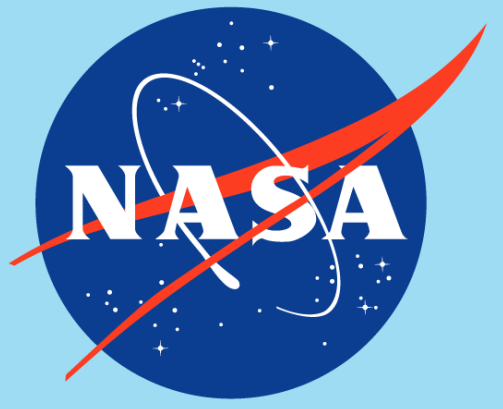
- Similar to a volume-fraction averaged model

Quasi 2D

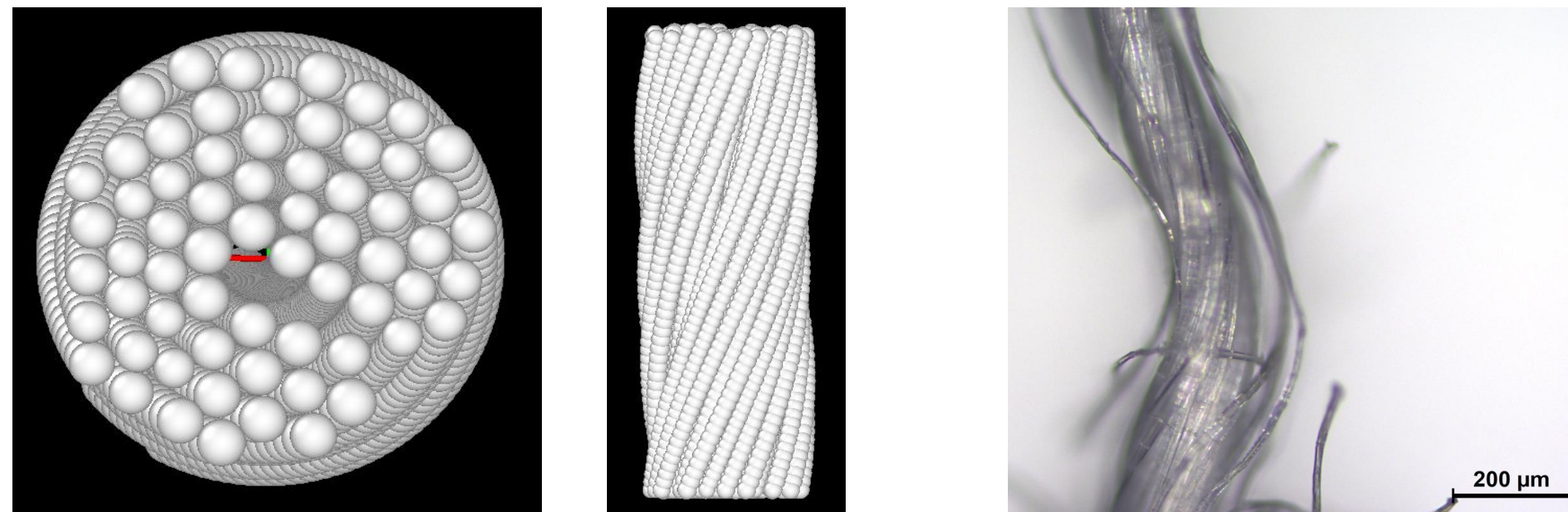


- Captures strain-hardening seen in experimental yarn tests
- Can capture twist effects at low angle
- But strength is still a challenge

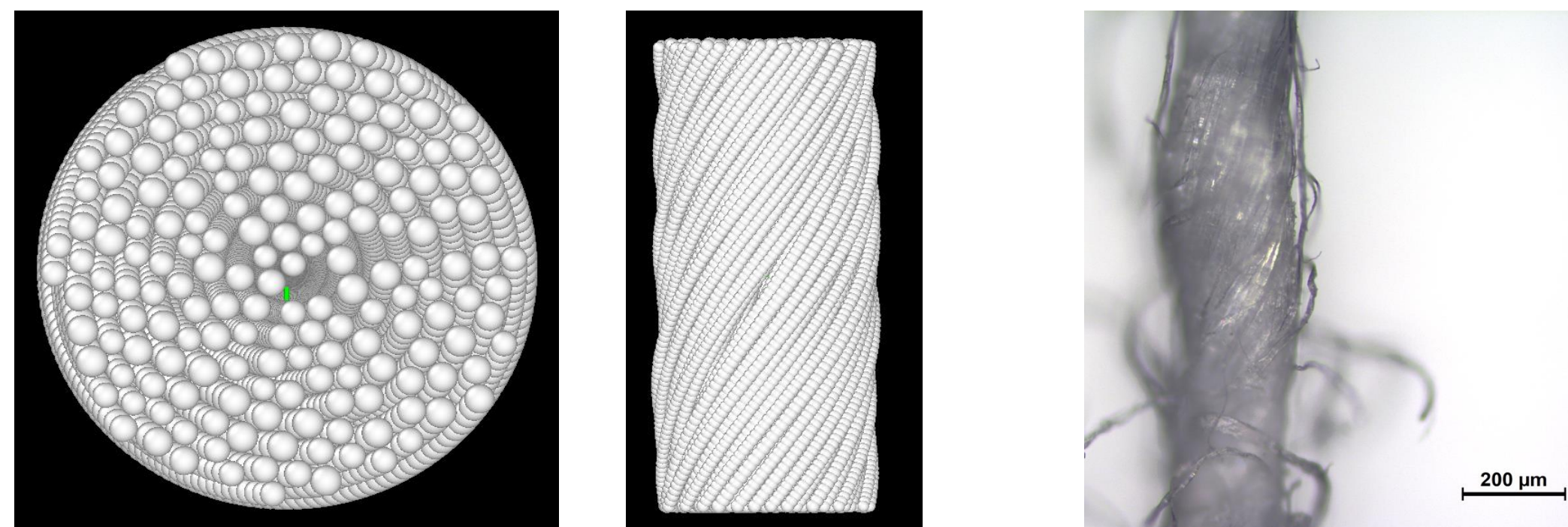
Hemp Yarn Validation



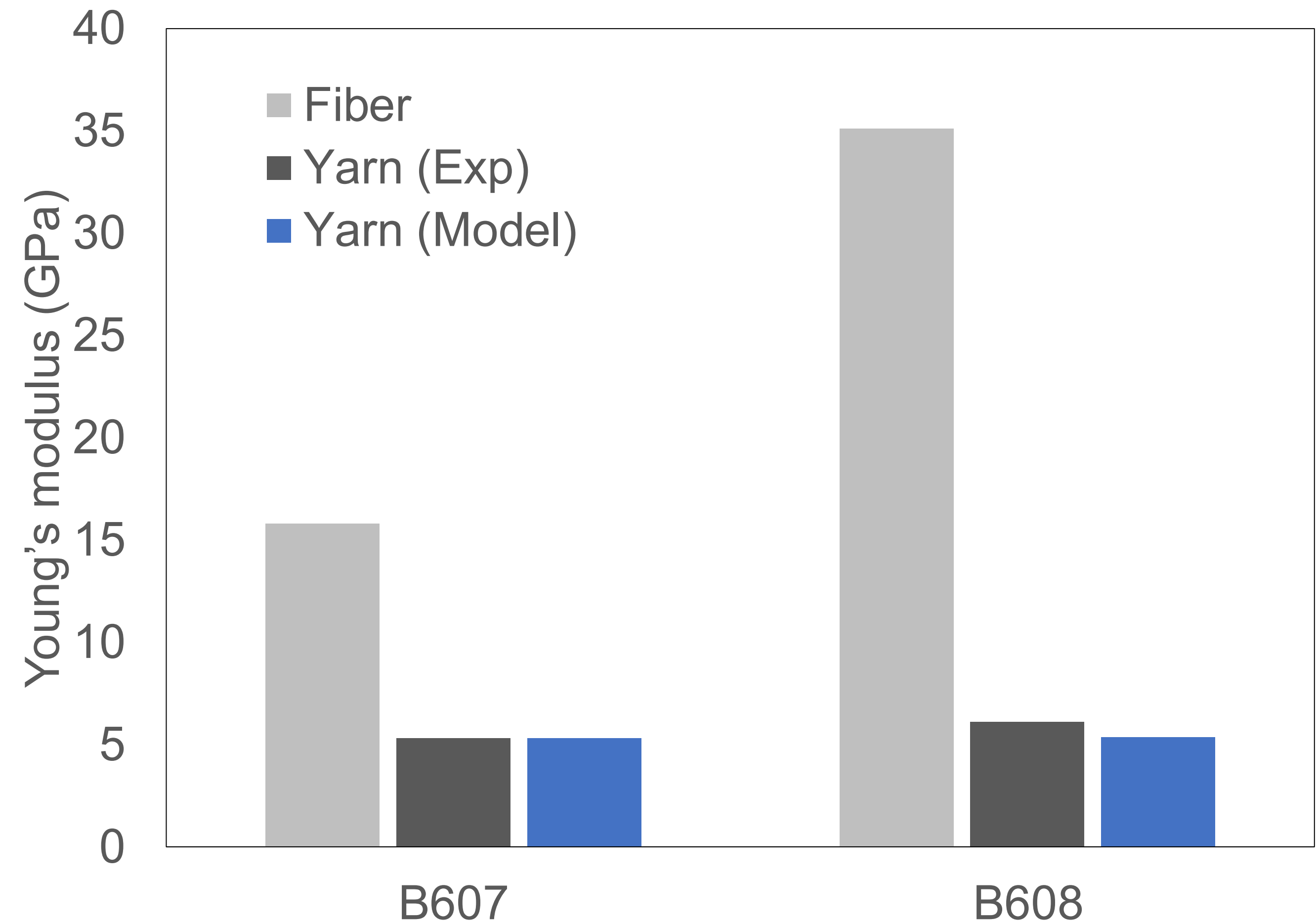
Models agree well with experimental Young's modulus for very different hemp yarns



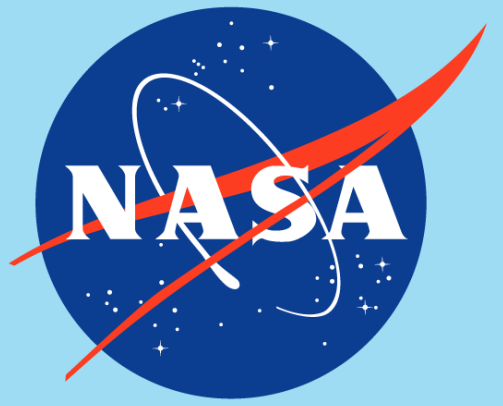
B607 yarn model (left) and micrograph (right)



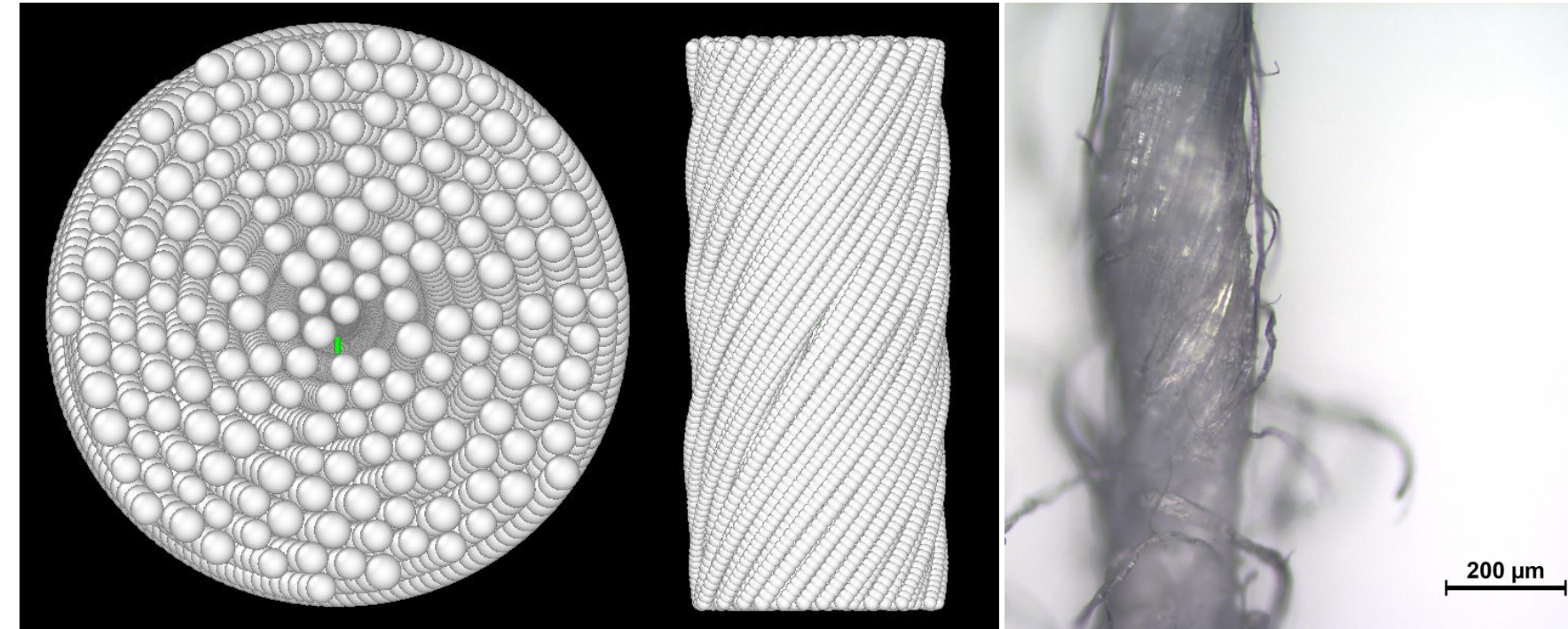
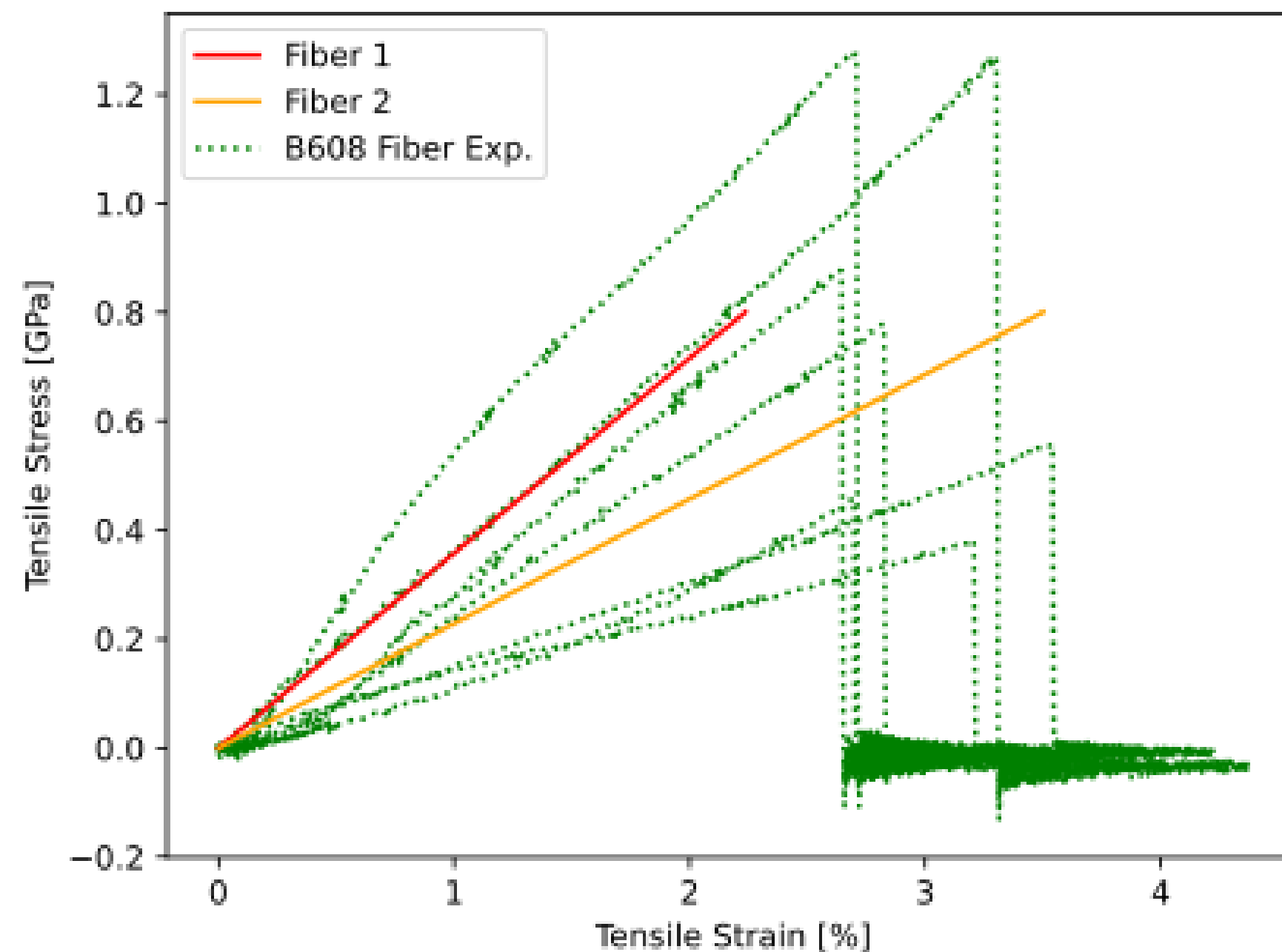
B608 yarn model (left) and micrograph (right)



Validation with Hemp B608

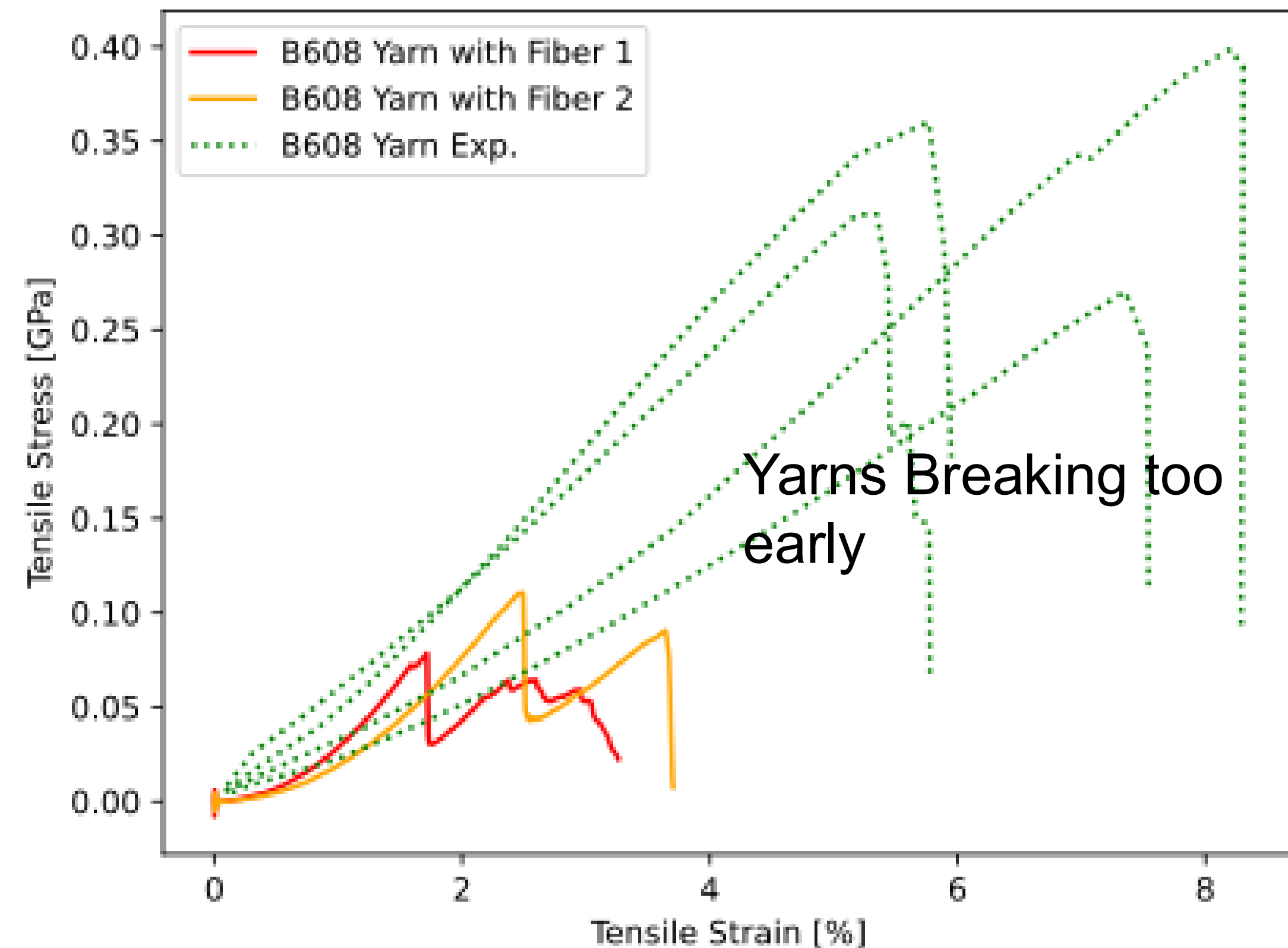


Hemp
B608



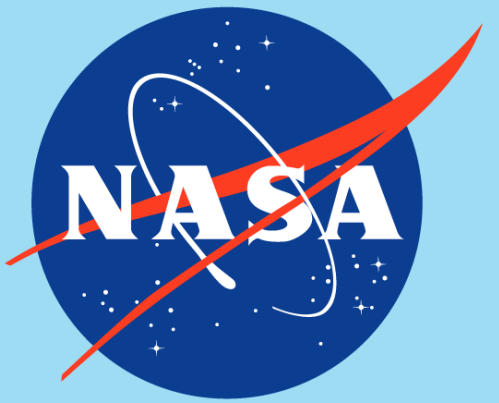
*Simulation fiber properties compared
to fiber experimental data*

Fiber 1: Average YM and average strength
Fiber 2: Highest strain and Average strength

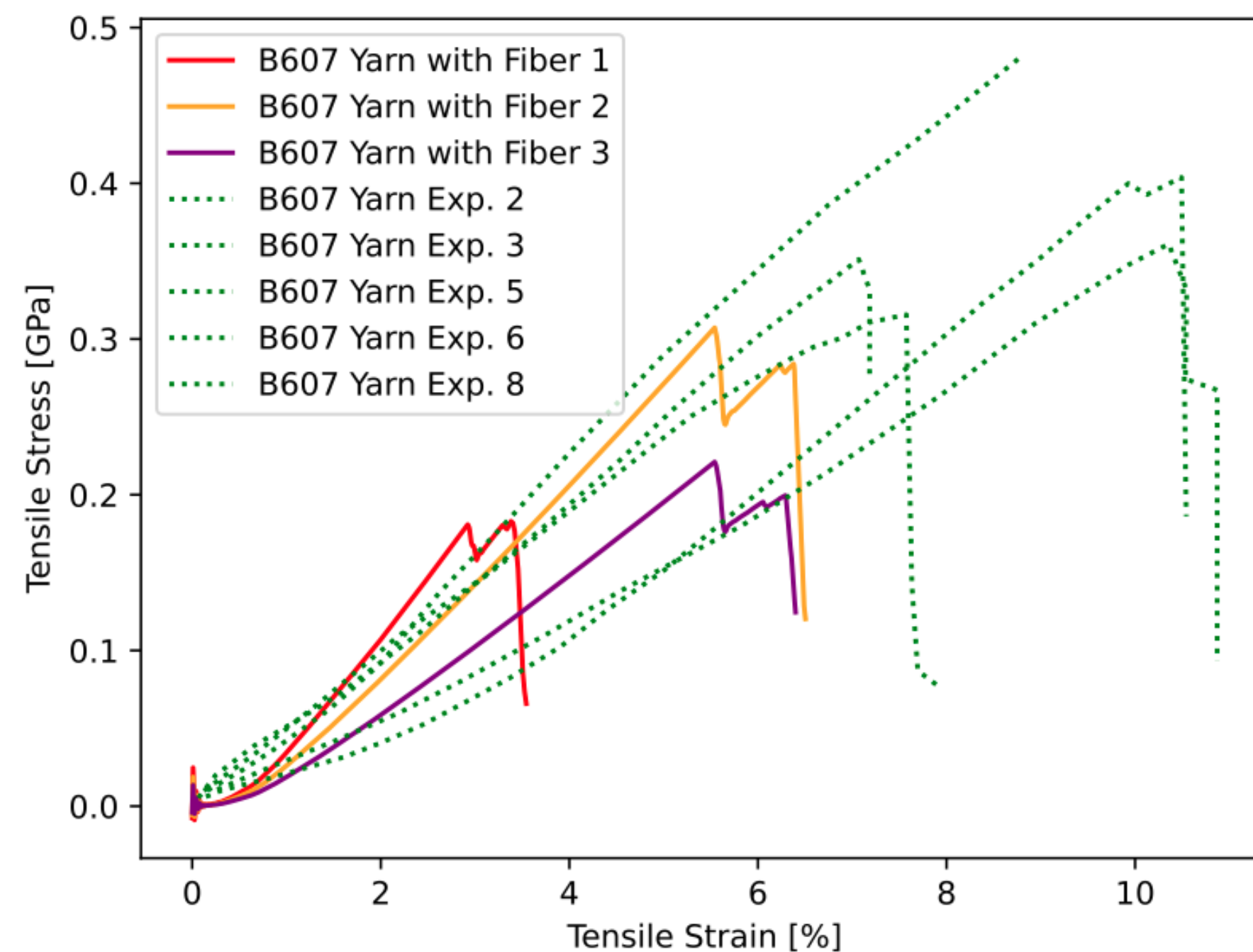


*Simulation fiber properties ran in yarn structure
compared to yarn experimental data*

Key Factors in Yarn Breakage

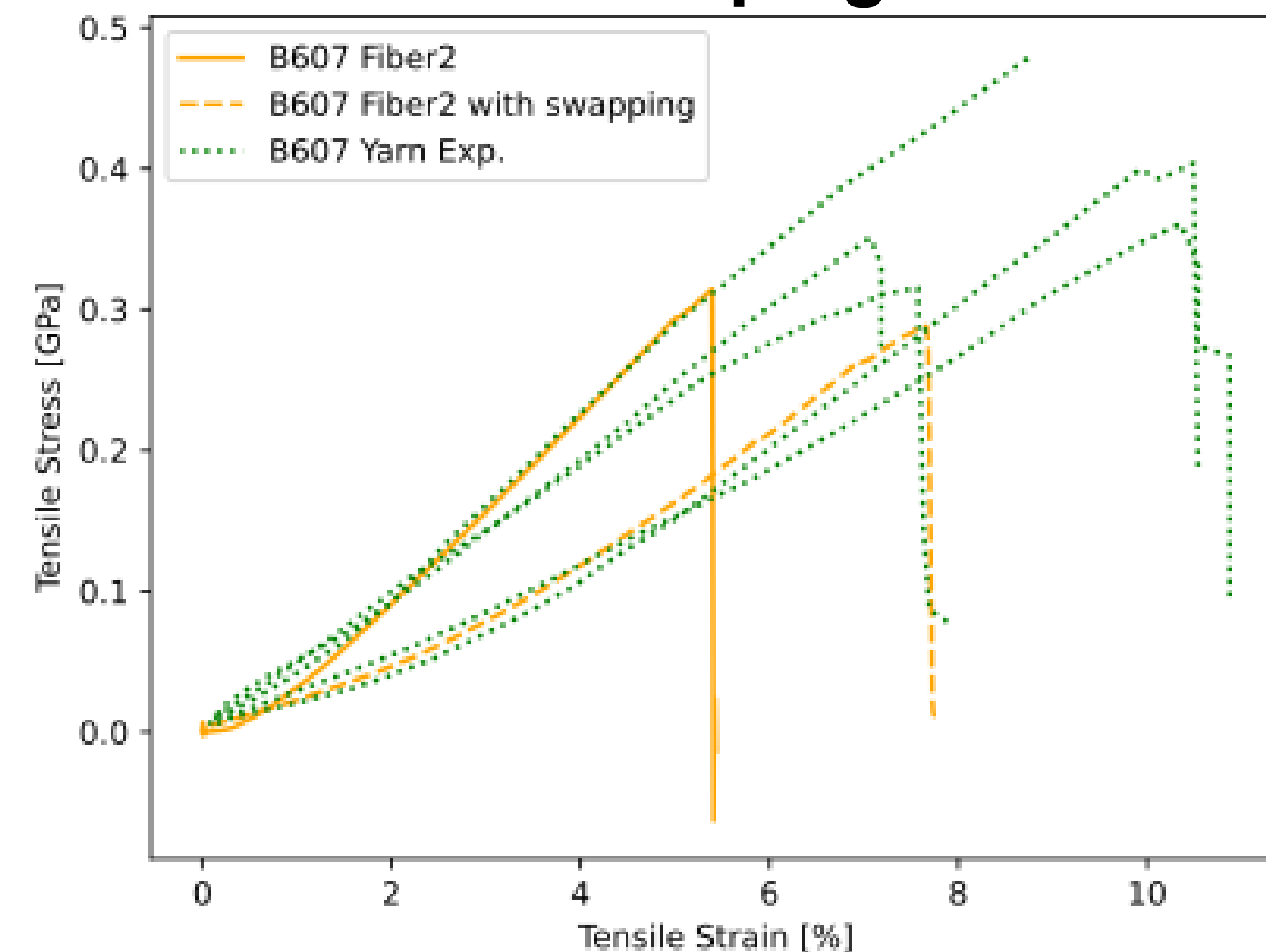


Friction

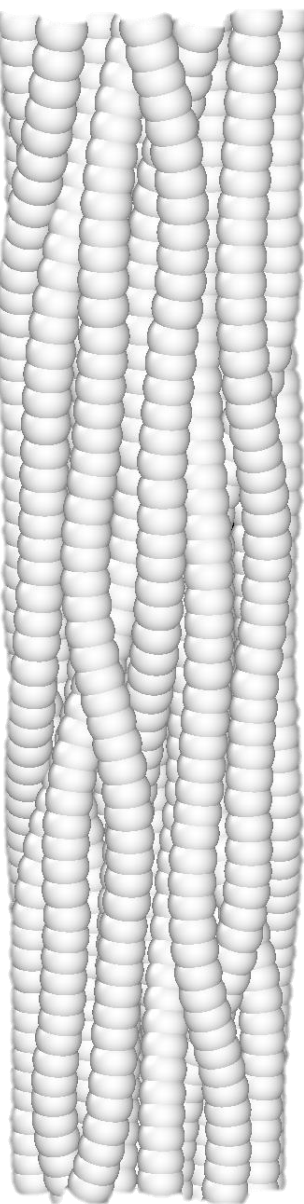


- **Decreasing Friction** leads to initial center fiber breakage which does not cause the whole yarn to fail

Crimping



- **Increasing tortuosity** can lead to **higher percent strain at breakage**. We lack experimental data

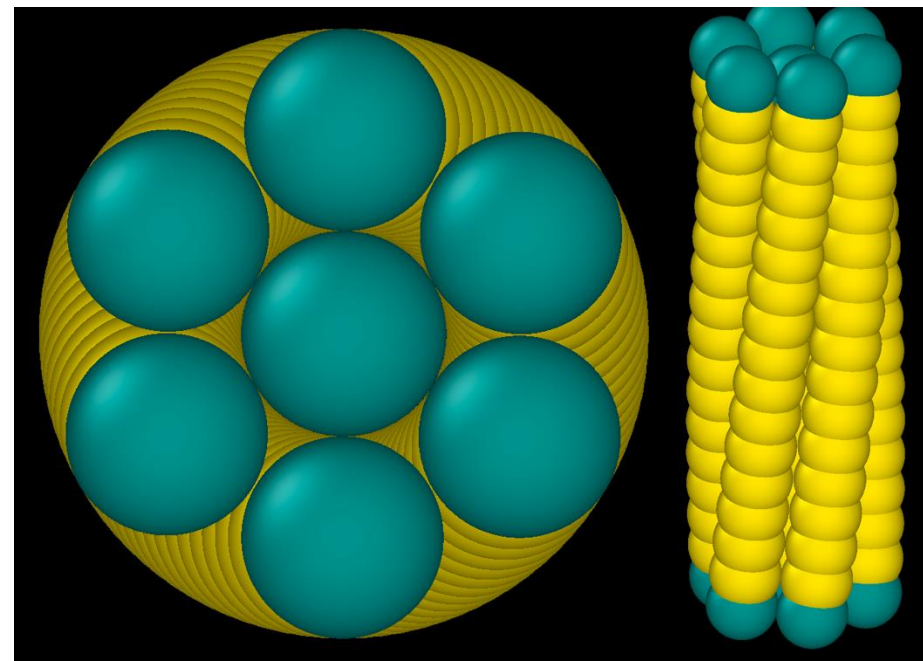
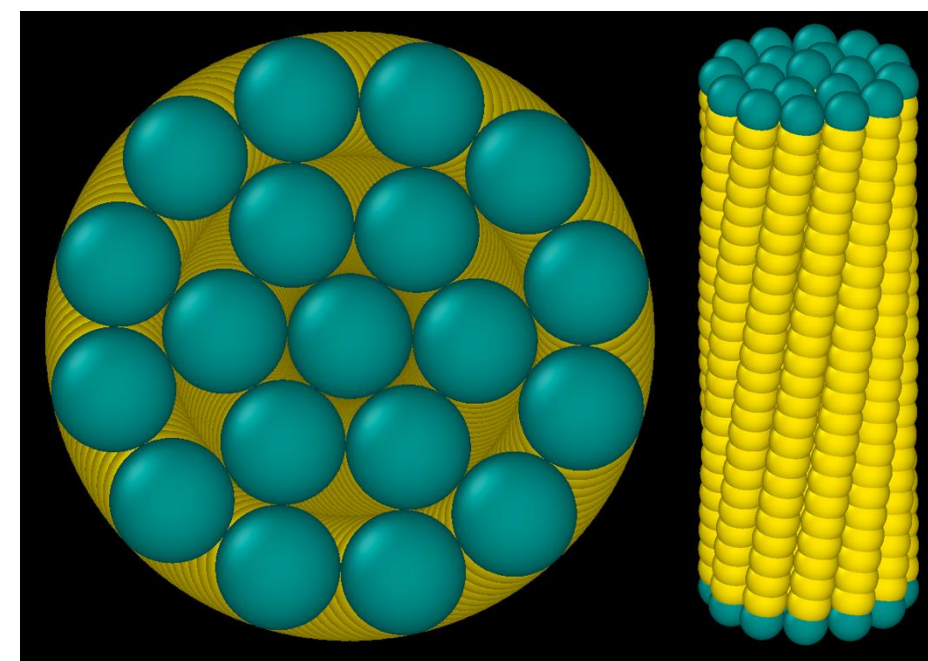
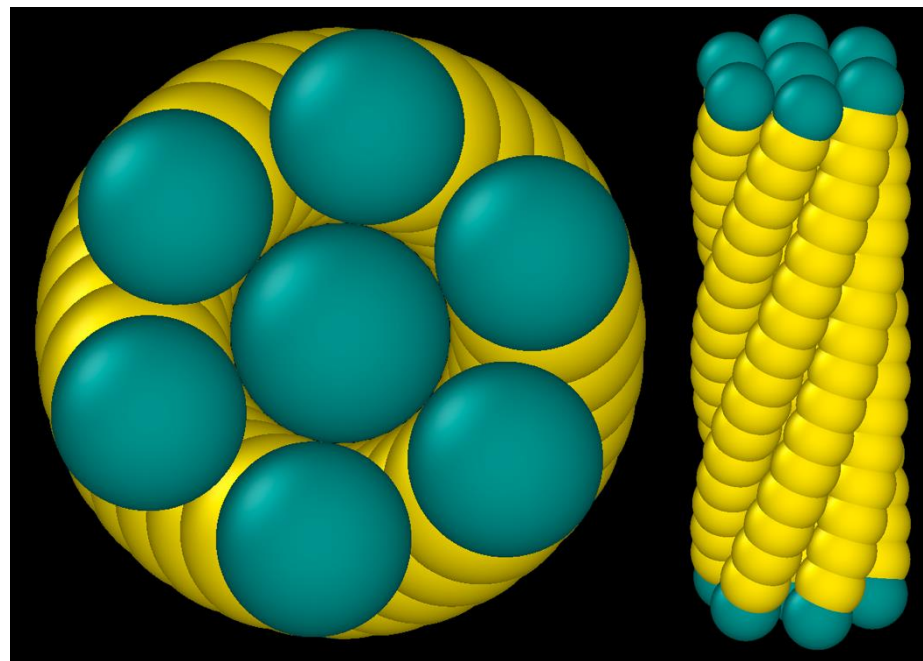
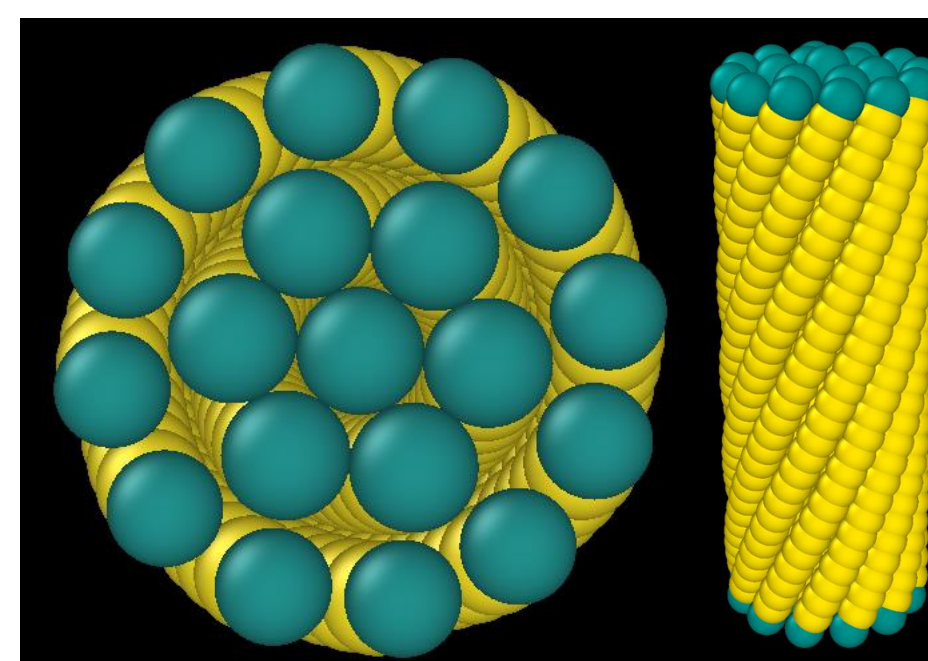
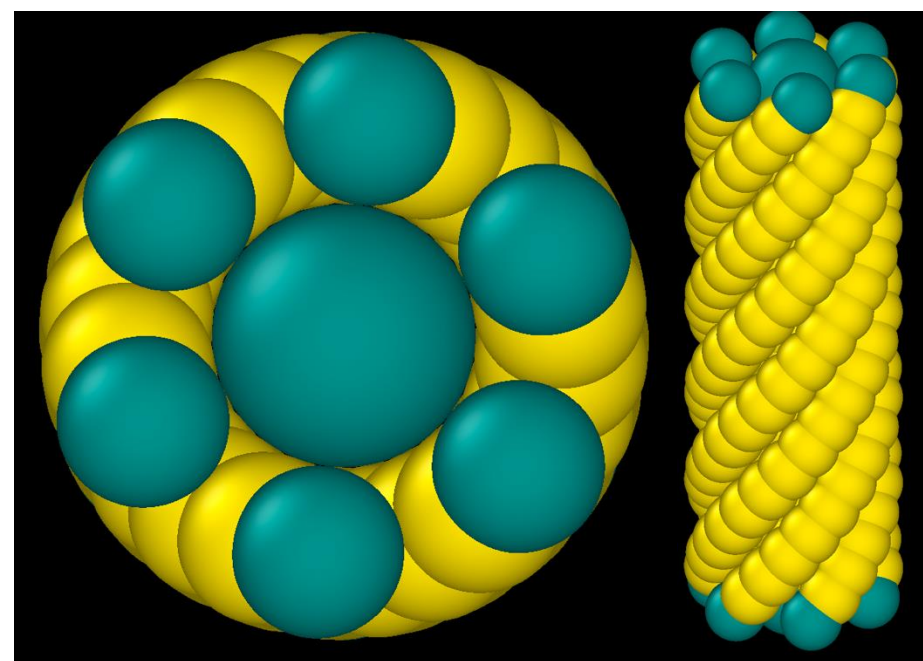
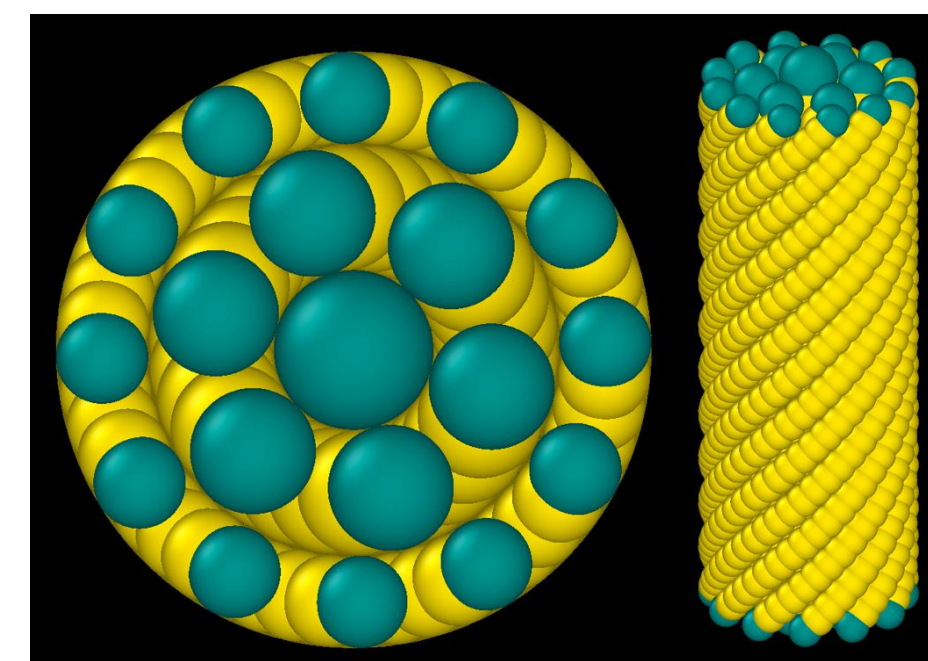
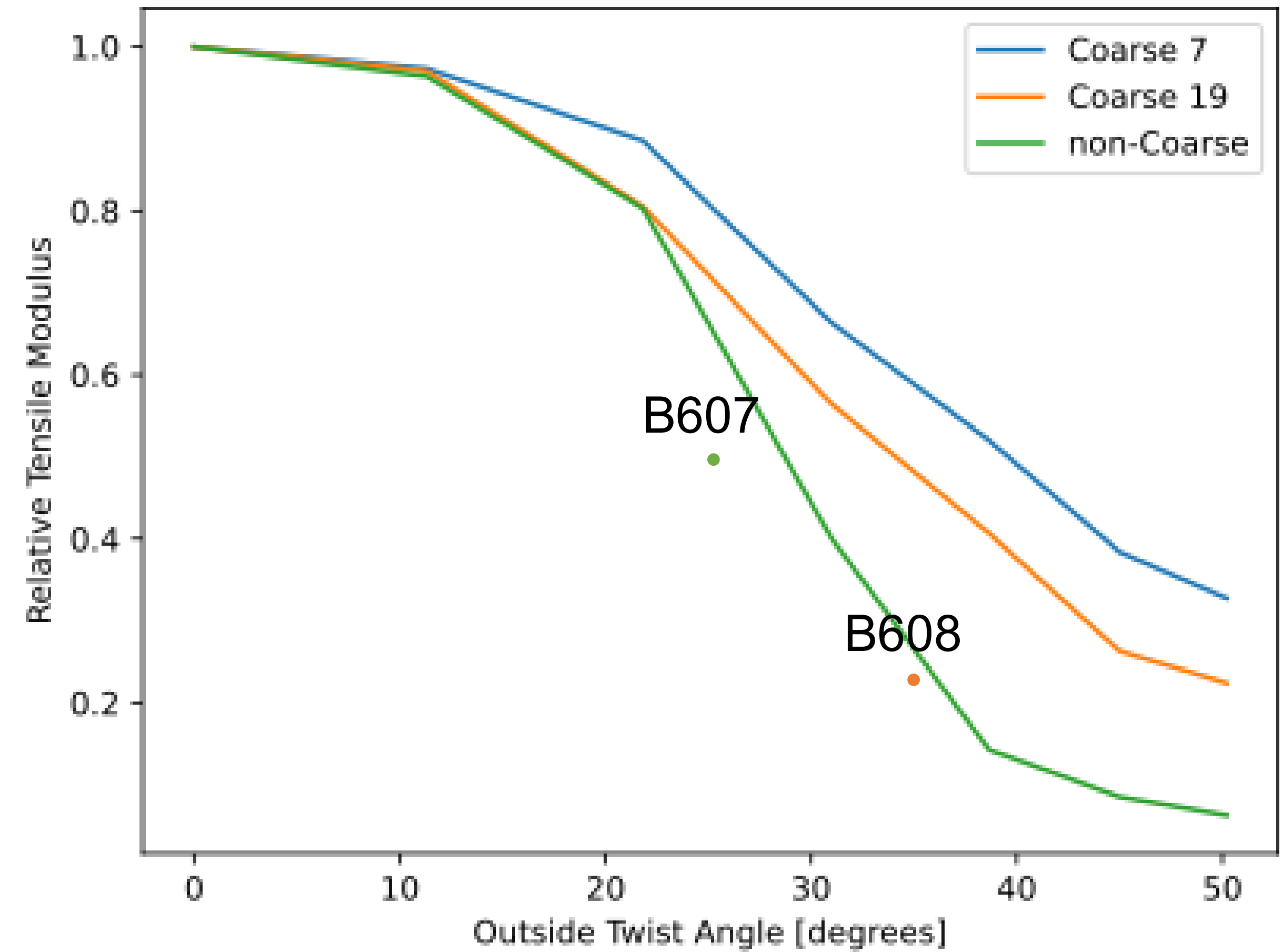


Coarse Graining and Twist

Coarse 7

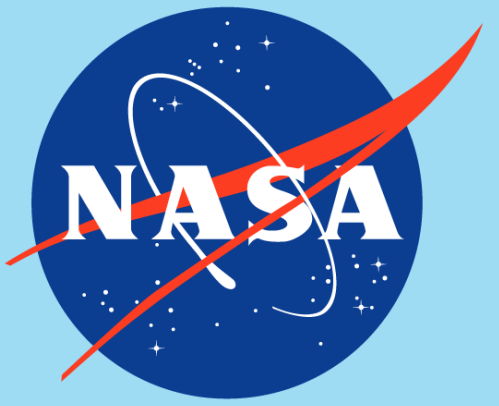
Coarse 19

Rotation
↓



- At high twist, coarse grained yarns overestimate modulus

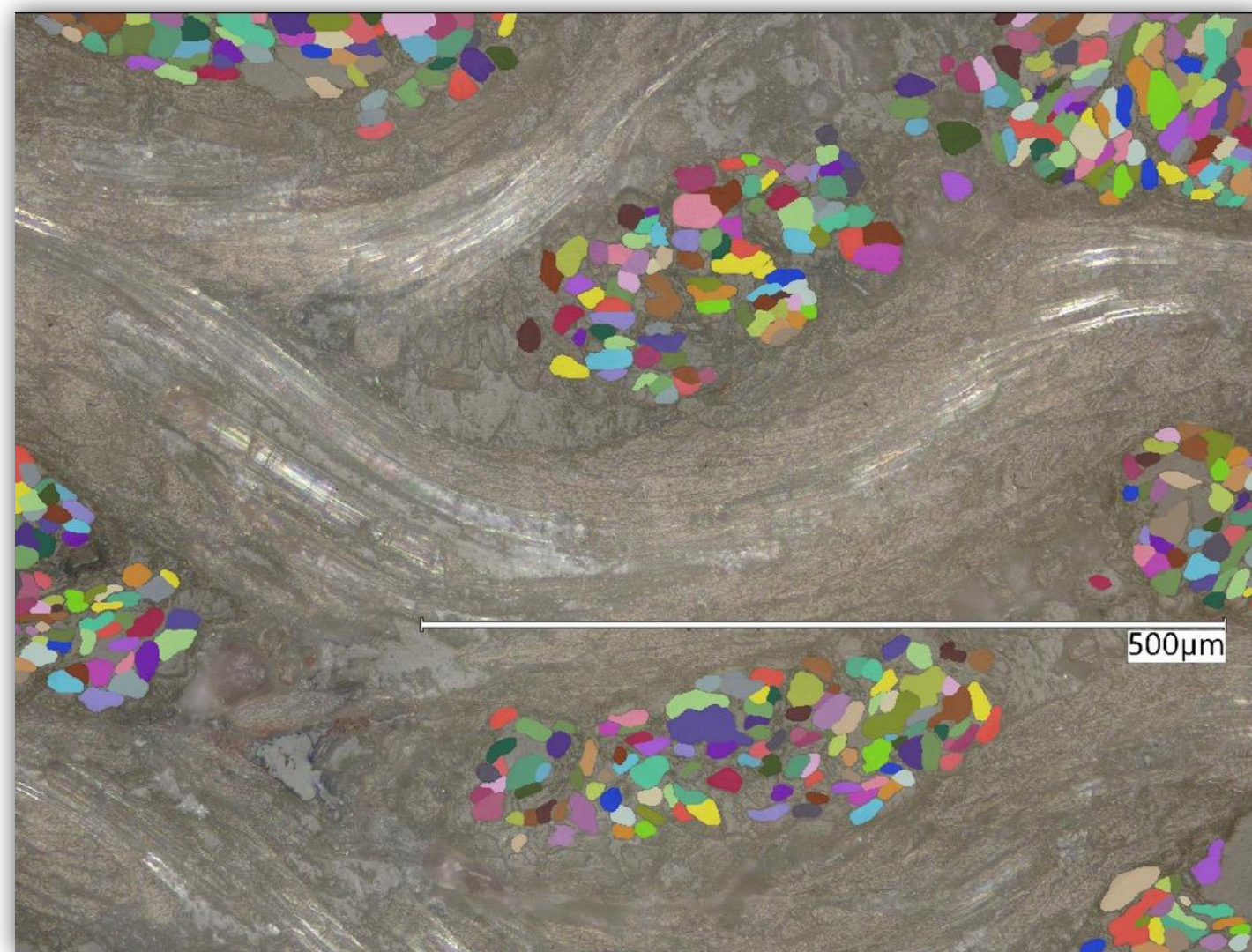
Weave-Scale Simulations



Explicit-fiber yarn simulations, parameterized from single-fiber measurements, resolved and identified slack as a cause for yarn strain-hardening tensile behavior.

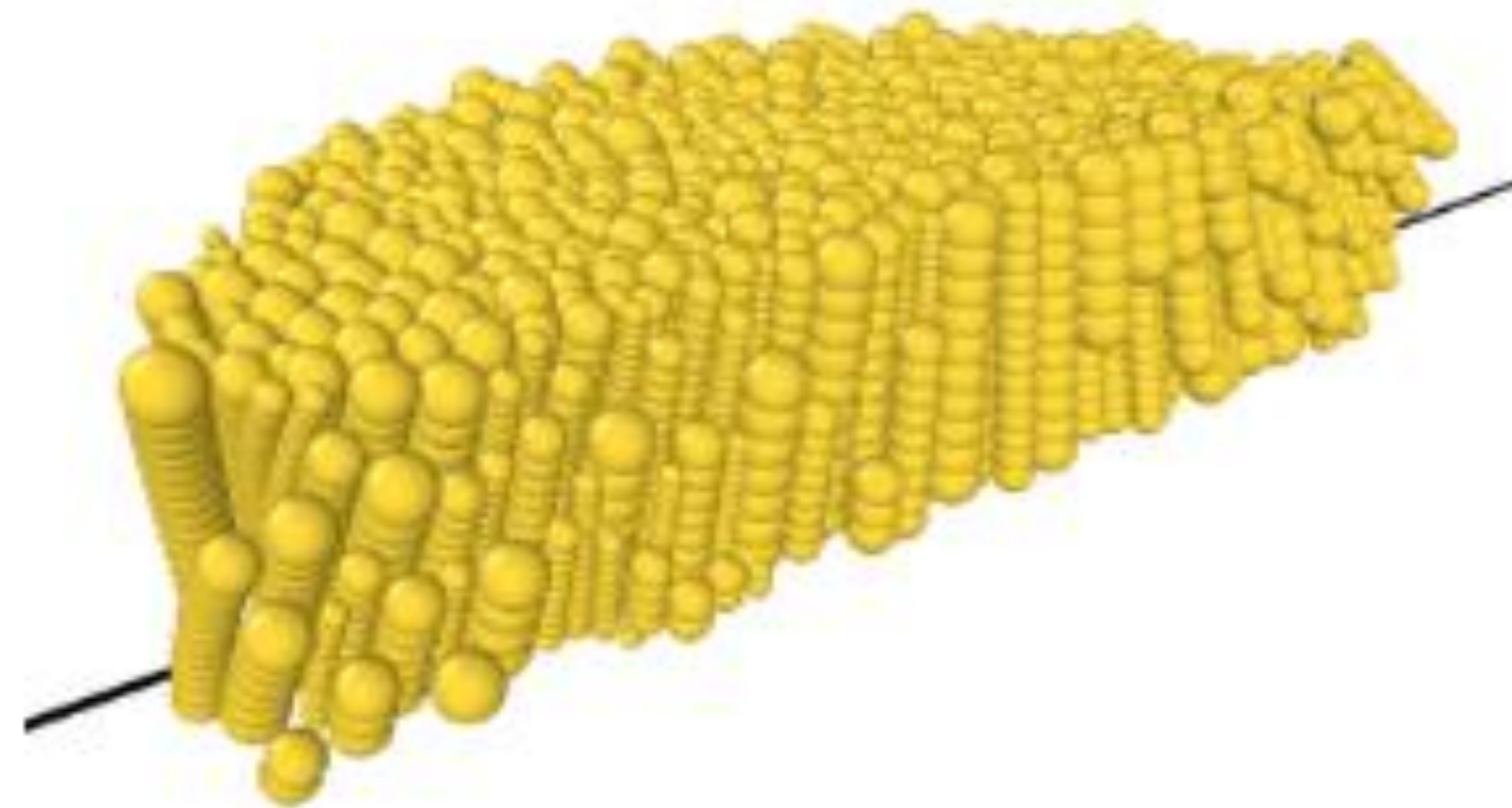
Part I

Fiber characterization
from image segmentation



Part II

Yarn-scale simulations

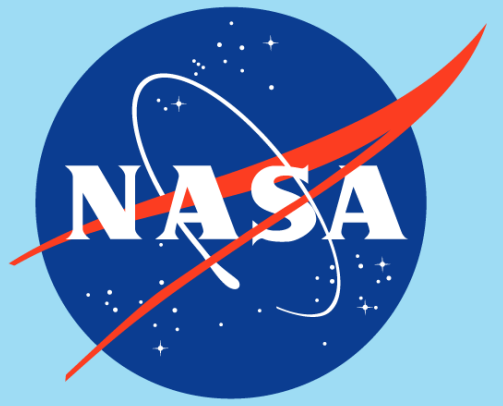


Part III

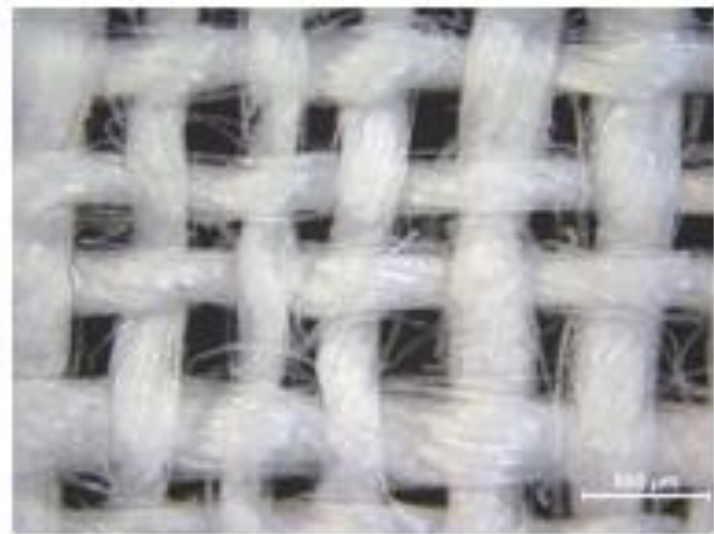
**Weave-scale
simulations**



Matching Experimental Dry Weaves



1-ply plain weave (B608)



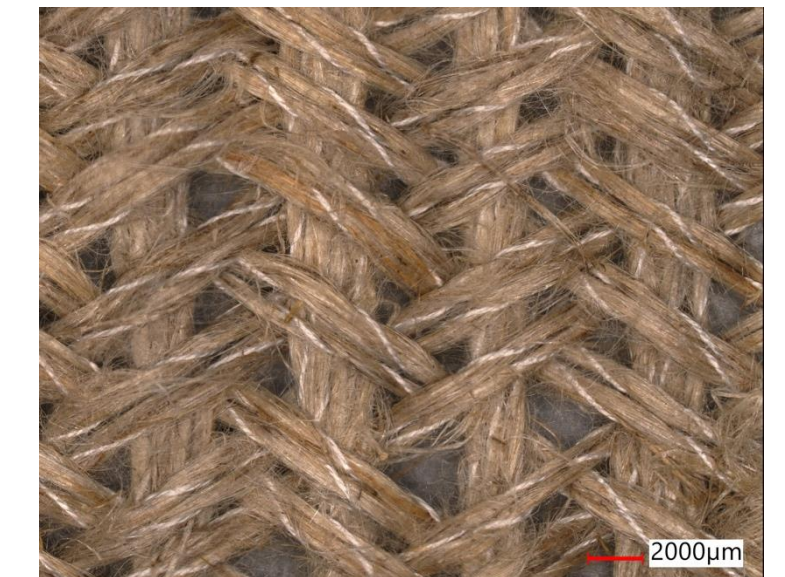
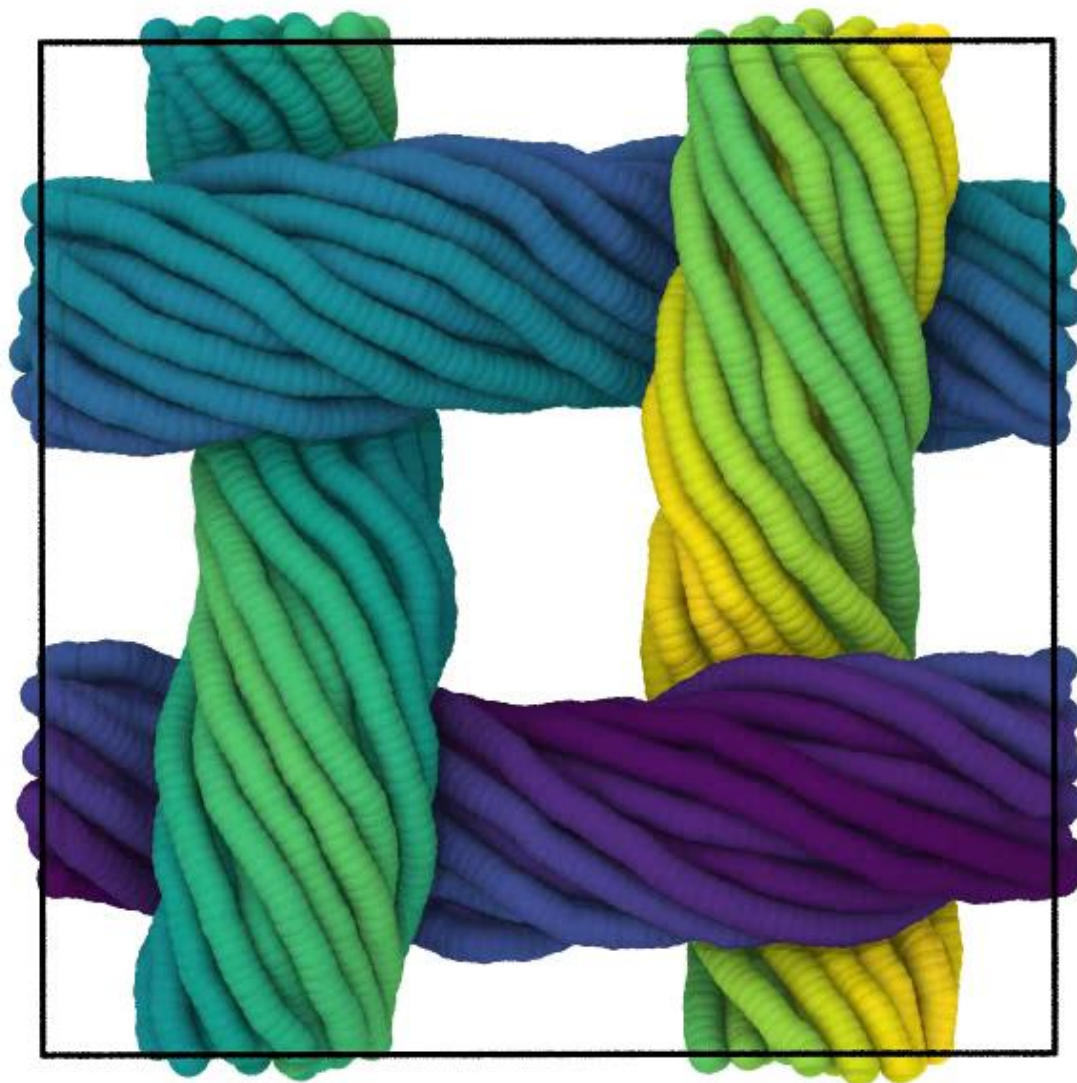
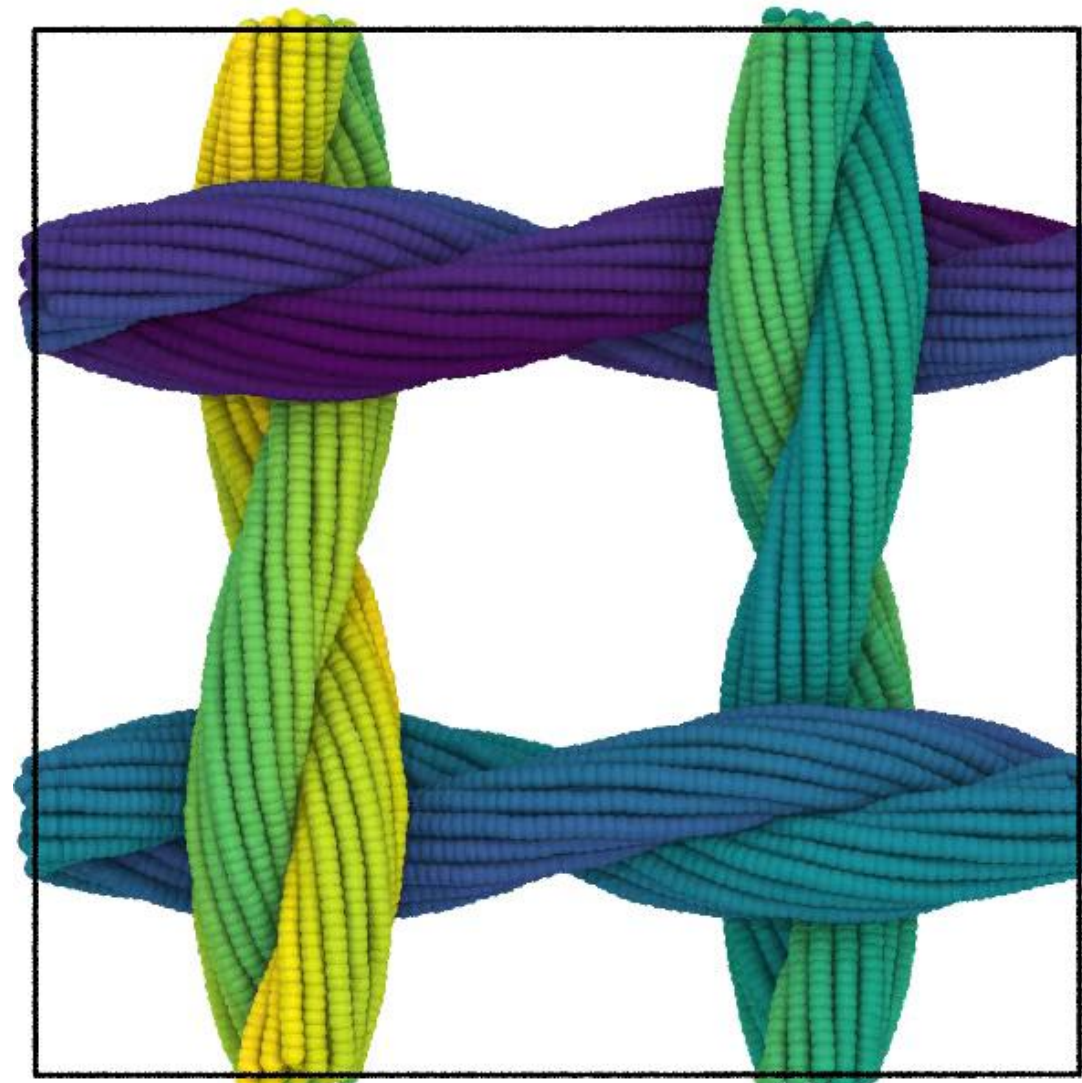
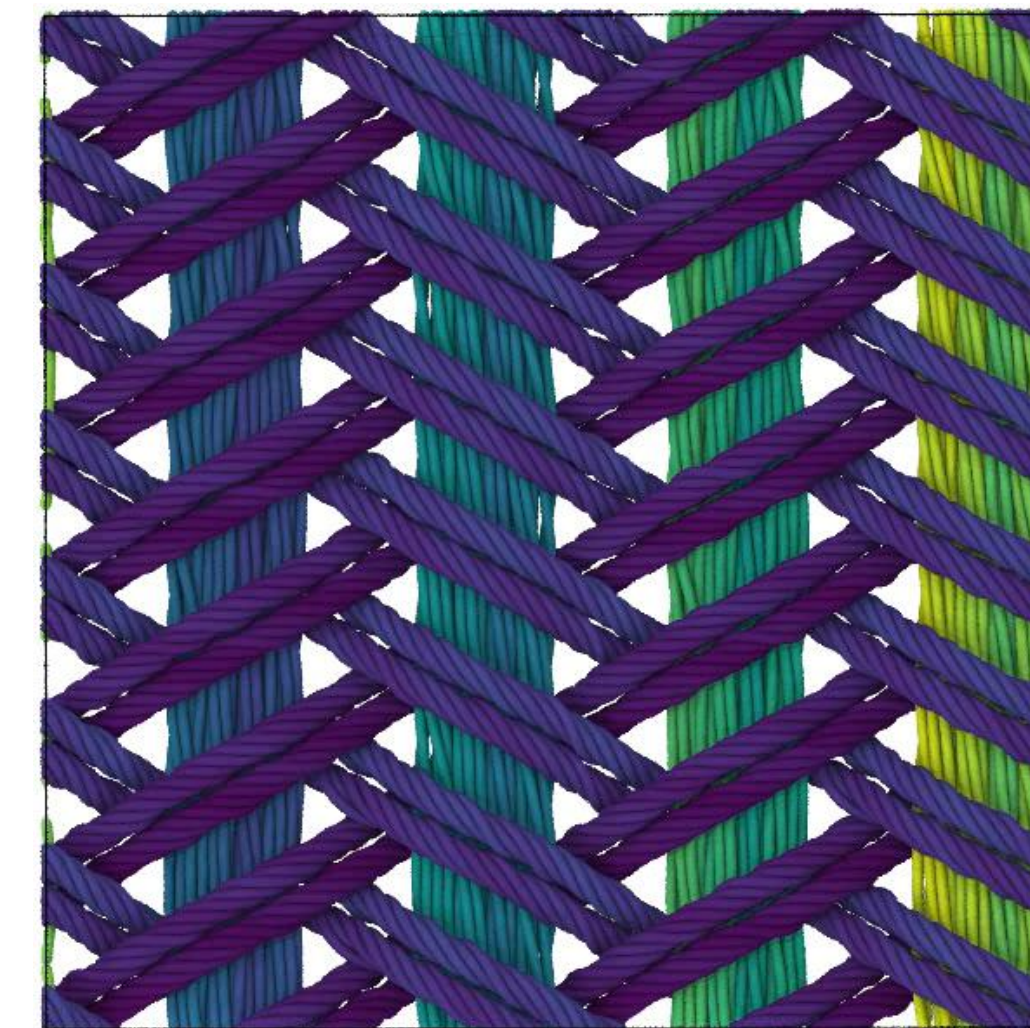
2-ply plain weave (B601)



Twill weave (Bcomp)



Triaxial braid (AnP)



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

Chen, X. et al. Comparative Assessment and Unification of Bond Models in DEM Simulations. *Granular Matter* **2021**, 24 (1), 29.

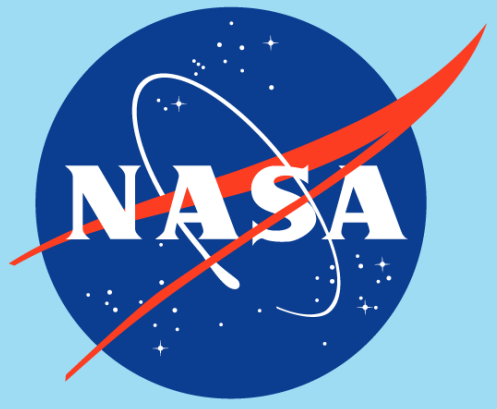
Wang, Y. et al. Digital-Element Simulation of Textile Processes. *Composites Sci. Tech.* **2001**, 61 (2), 311–319.

Santos et al. Particles23, 2023.

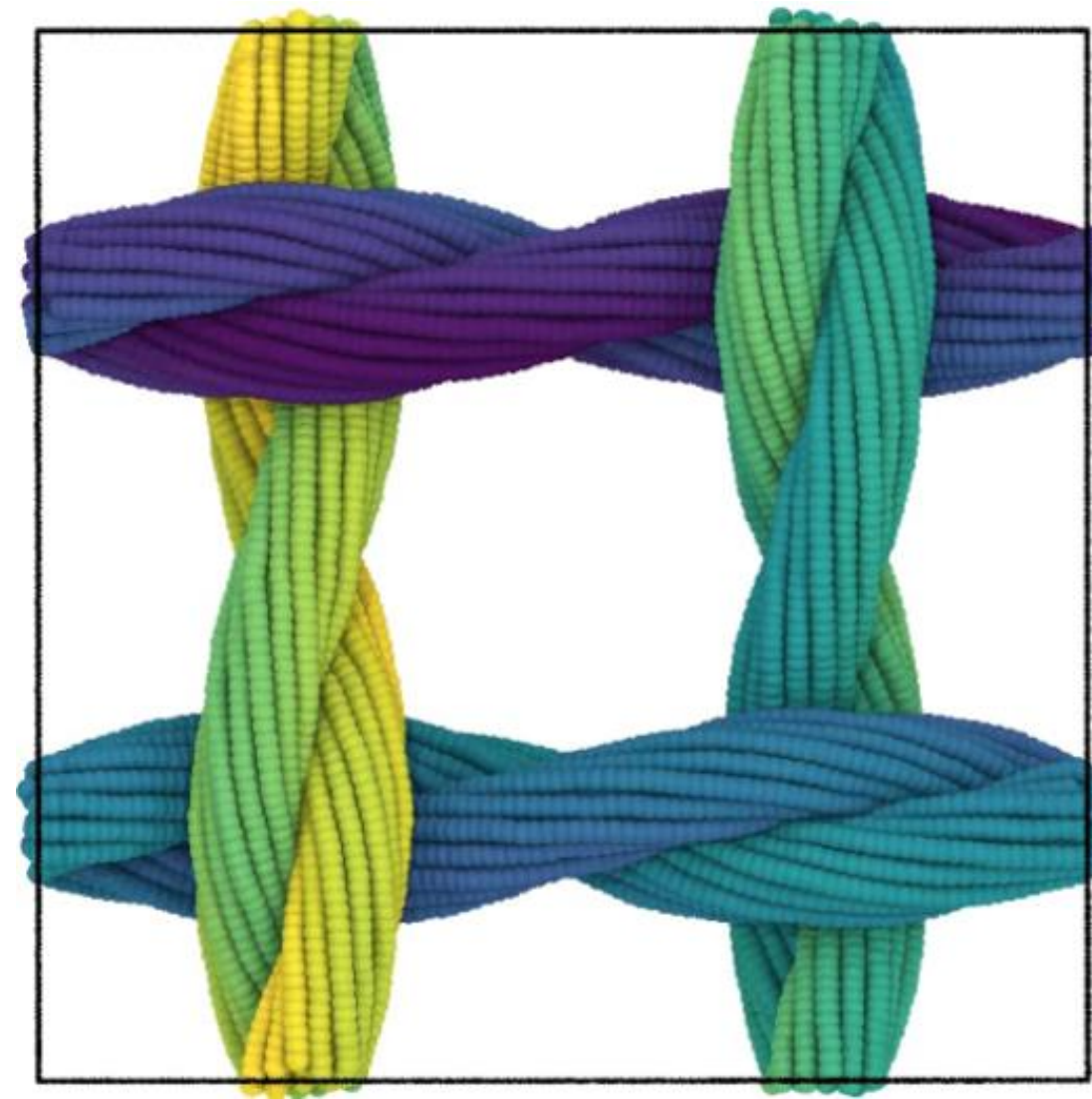
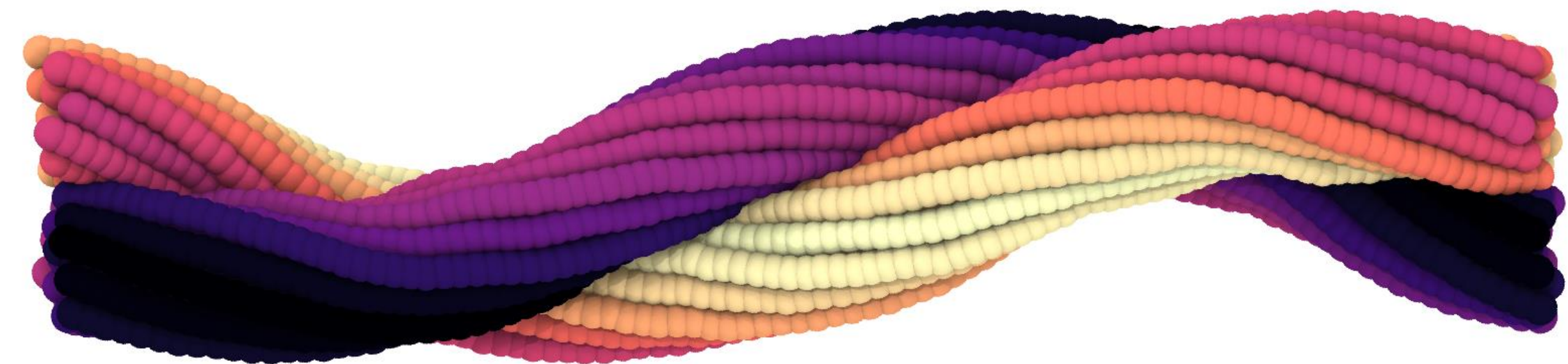
Lin, H. et al. 2011. Modelling and Simulating Textile Structures using TexGen. Adv. Louisepb/TexGen: TexGen v3.13.1 (v3.13.1).

Zenodo. <https://doi.org/10.5281/zenodo.8221491>

Ply Twist and Yarn Deformation



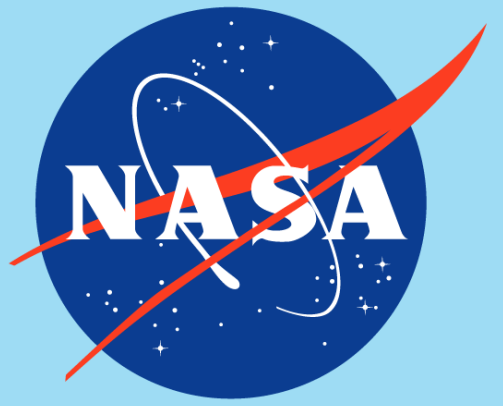
2-ply plain weave (B601)



Extracted relaxed 2-ply twisted warp yarn from B601. Yarns are deformed where they contact weft yarns. Coarse-grained fibers are uniquely colored.

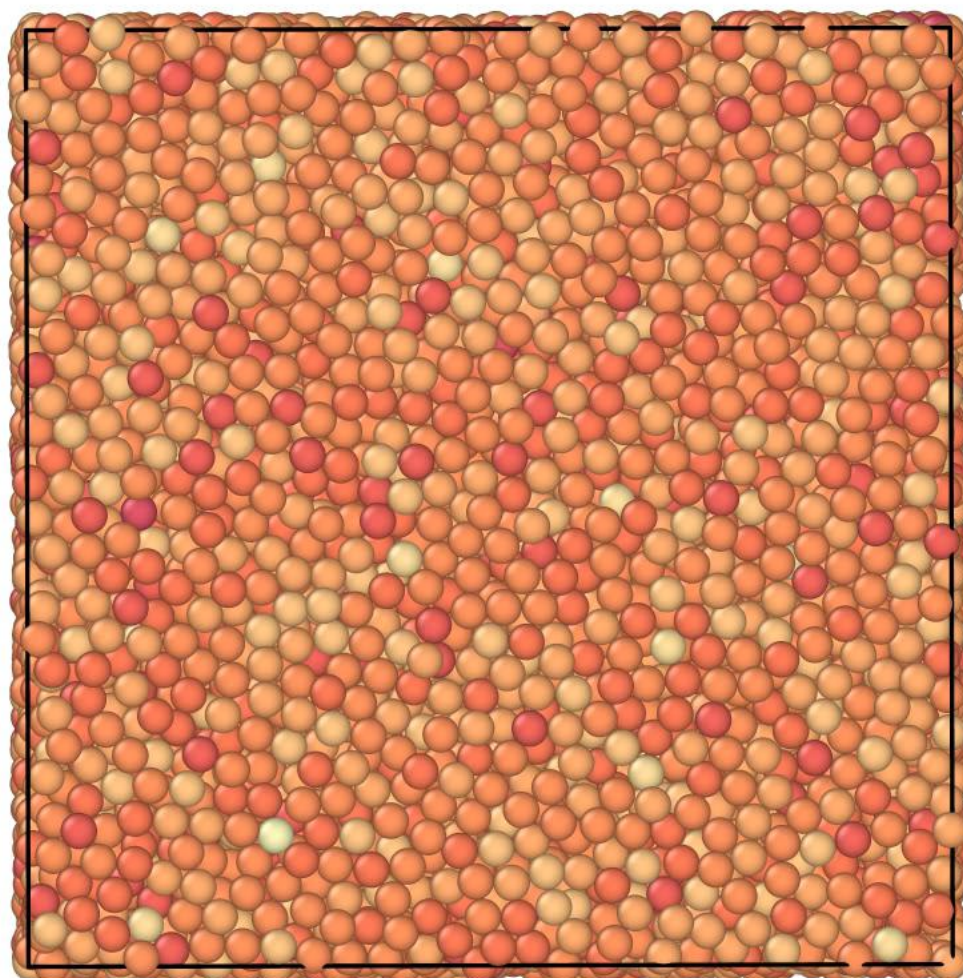
Deformation and microstructure are connected.

Modeling Resin at the Fiber Scale



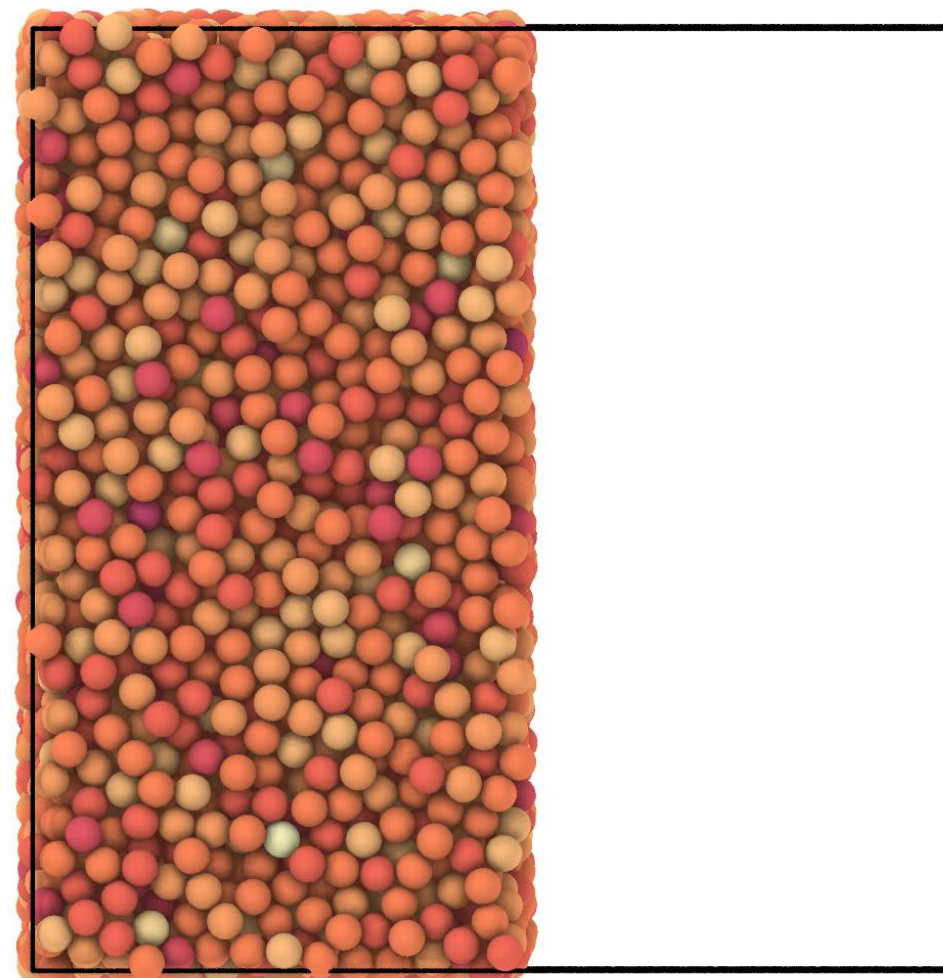
PLA, PA11 and PHA bonded network was parameterized with manufacture's information and validated with deformation simulations:

Tensile



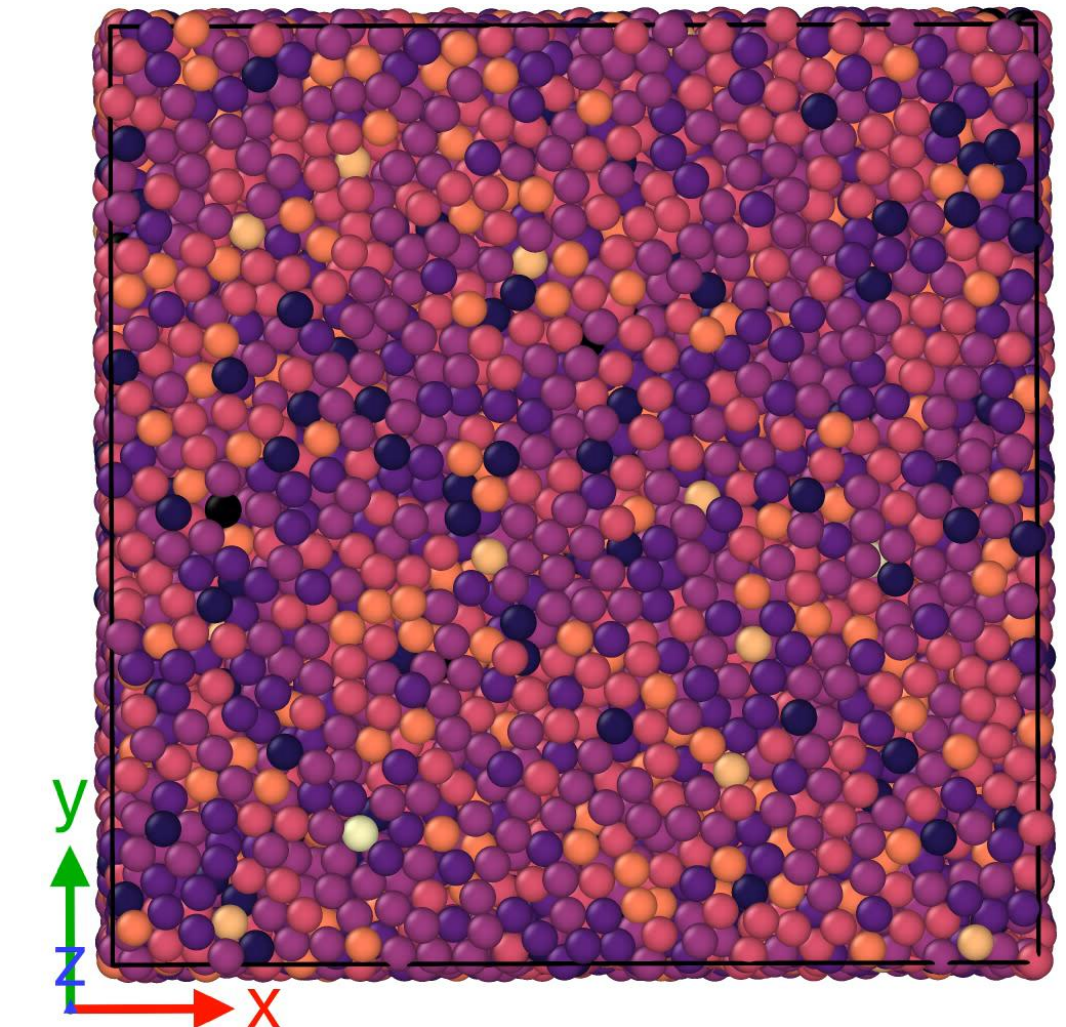
*Tensile strain-to-failure.
Particles are colored by the
number of bonds (black:2,
tan:17).*

Shear



*Shear strain-to-failure.
(left) all particles and (right)
fractured particles ($N_{bonds} < 10$).*

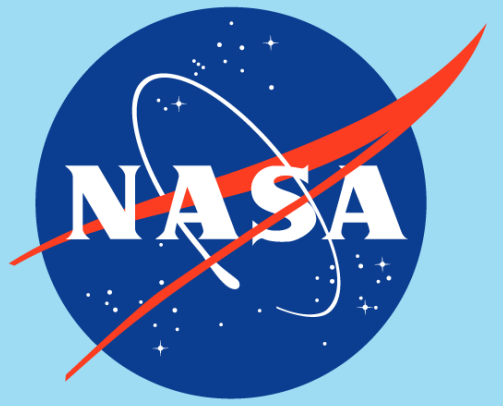
Oscillatory shear



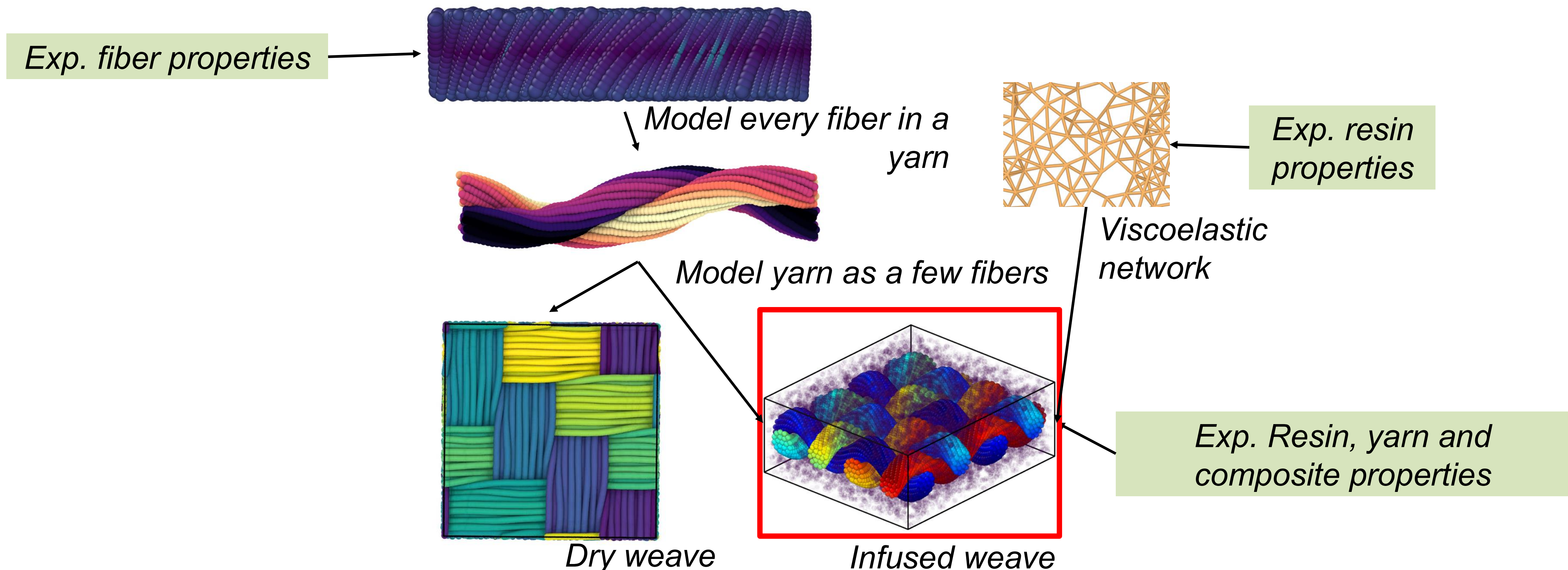
*Oscillatory shear sweep
(0.1 to 10 Hz).*

Bonded networks can capture complex fracture paths, elastic to visco-elasto-plastic behavior.
This will be useful for capturing resin, fiber and interfacial behavior woven composite.

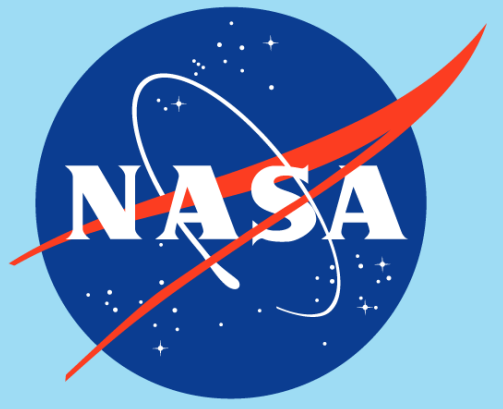
Next Steps - Composite



- More validation for resins, and coarse-grained yarns
 - Vibration dampening simulations
- Deformation of dry weaves, both experimentally tested and beyond (satins)
 - Simulation of composites, by combining resin and yarn models

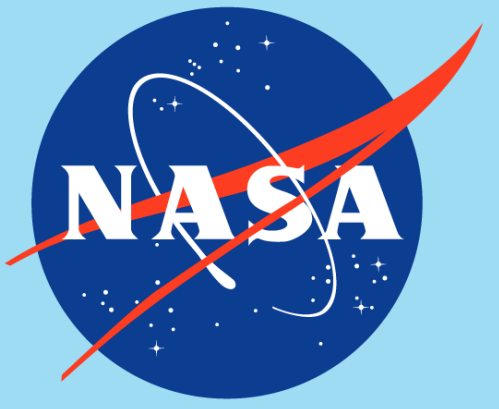


Key Takeaways

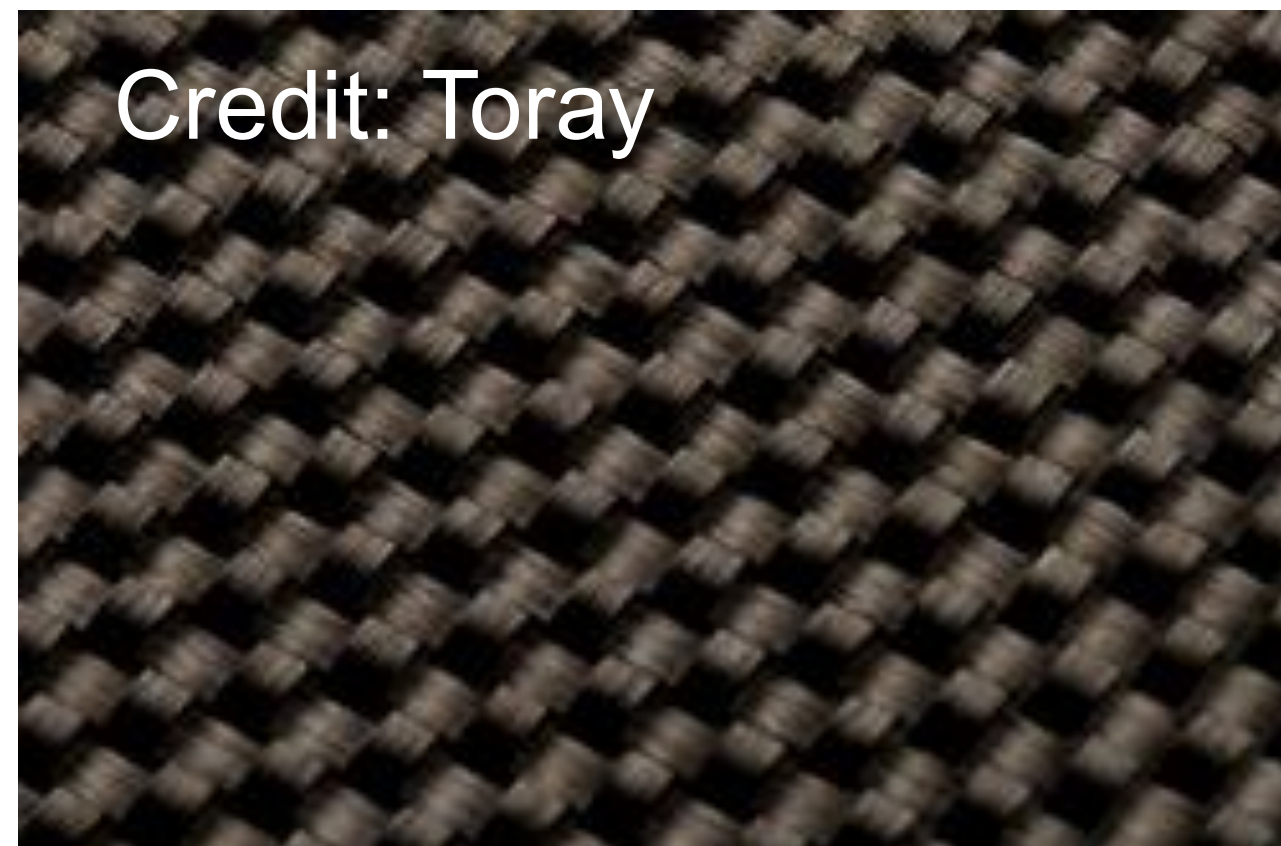


- Fiber cross sectional properties were calculated by image segmentation to quantify microstructure variation and influence of manufacturing.
 - Fibers are very deformable and non-circular (circularities of 0.2 were observed).
 - Fiber cross-sectional equivalent diameters D range from submicron to 20 μm
 - Fiber shapes range from flattened, aspect ratios $R_{\text{long}}/R_{\text{short}}$ up to 5, to round
 - Core perimeter likely drives deformation, and were calculated $P_{\text{core}} = 7 \mu\text{m}$.
- Explicit-fiber yarn simulations, parameterized from single-fiber measurements, resolved and identified slack as a cause for yarn strain-hardening tensile behavior.
- The bonded network model of PLA, PHA and PA11 resins captures tensile behavior, and can model an infused weave.
- Computational models of the weave unit cells matched pattern (including plain, twill and triaxial braid), yarn ply (1 to 2), and yarn twist from optical microscopy.

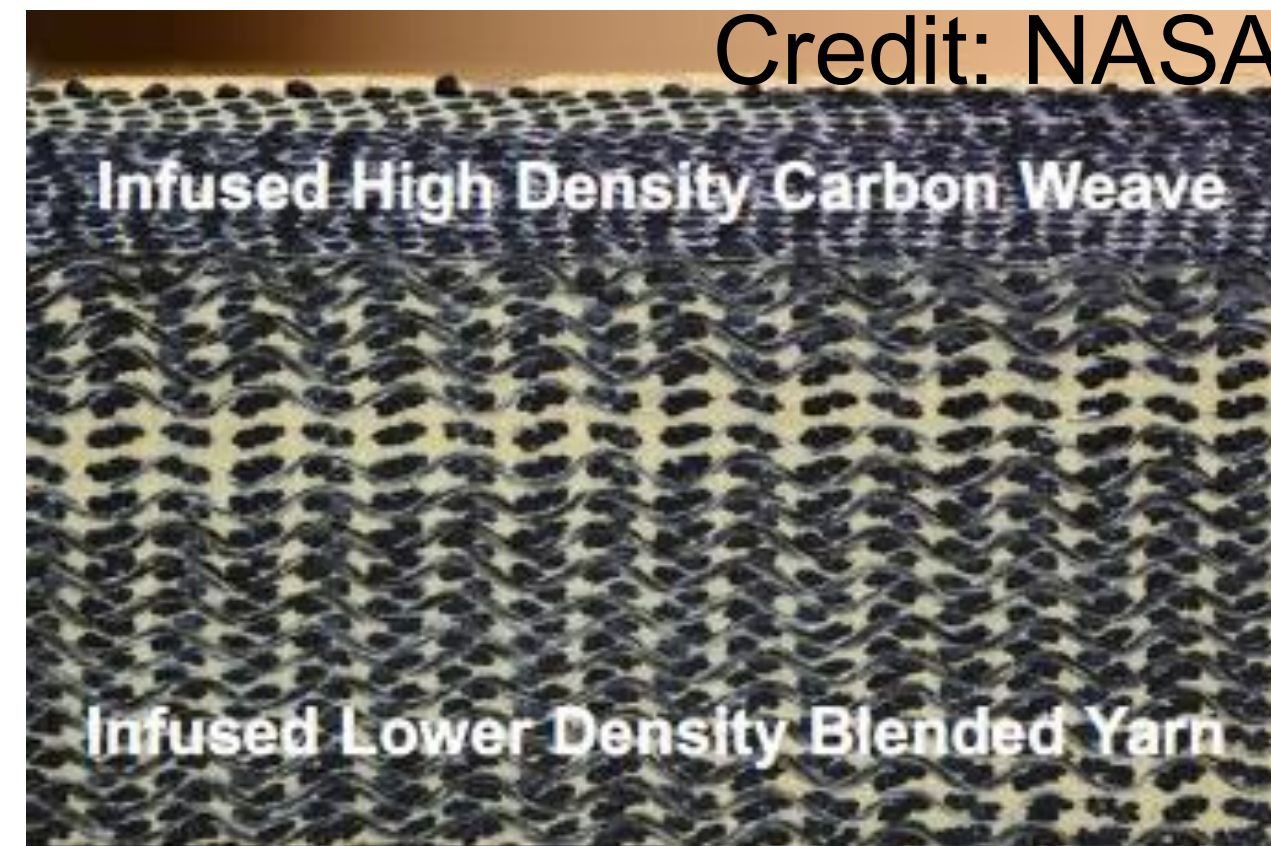
Future Directions and Other Materials



Explicit-fiber weave simulations

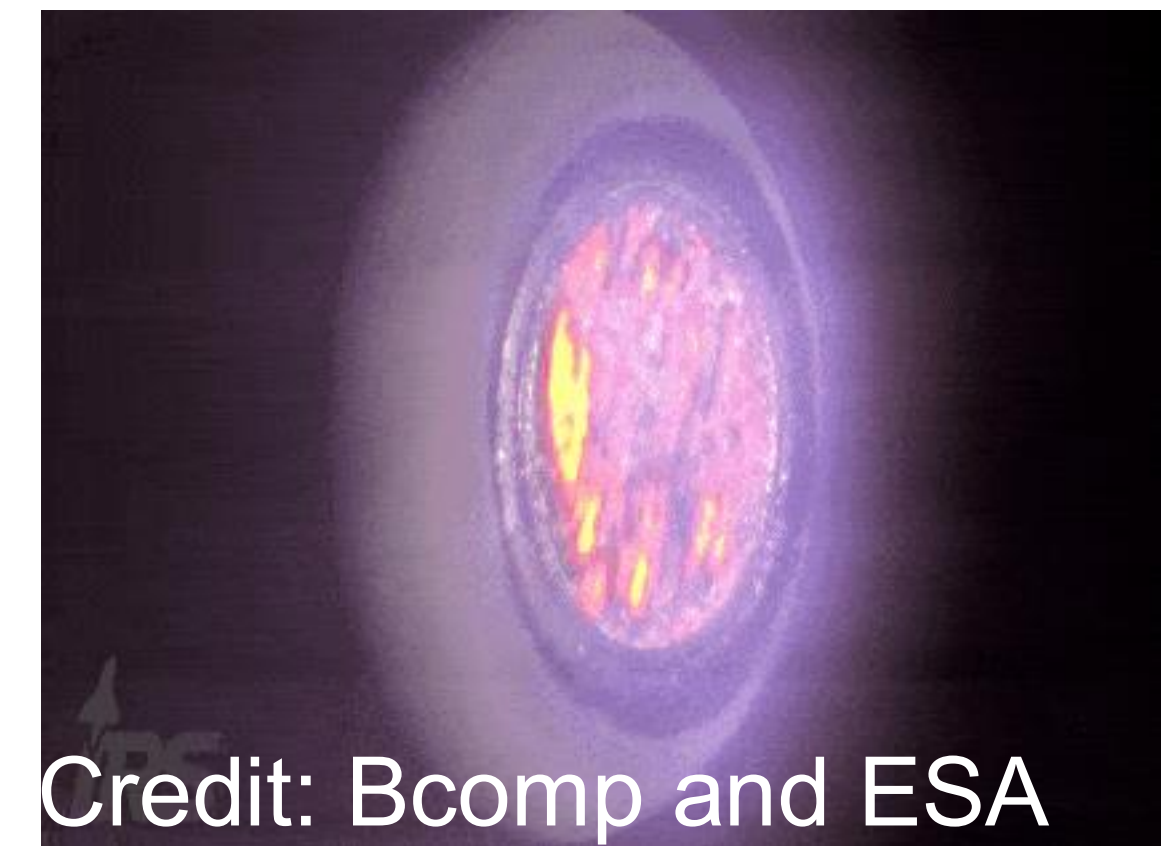


Carbon-fiber composites



Woven heat shields

SUMAC material



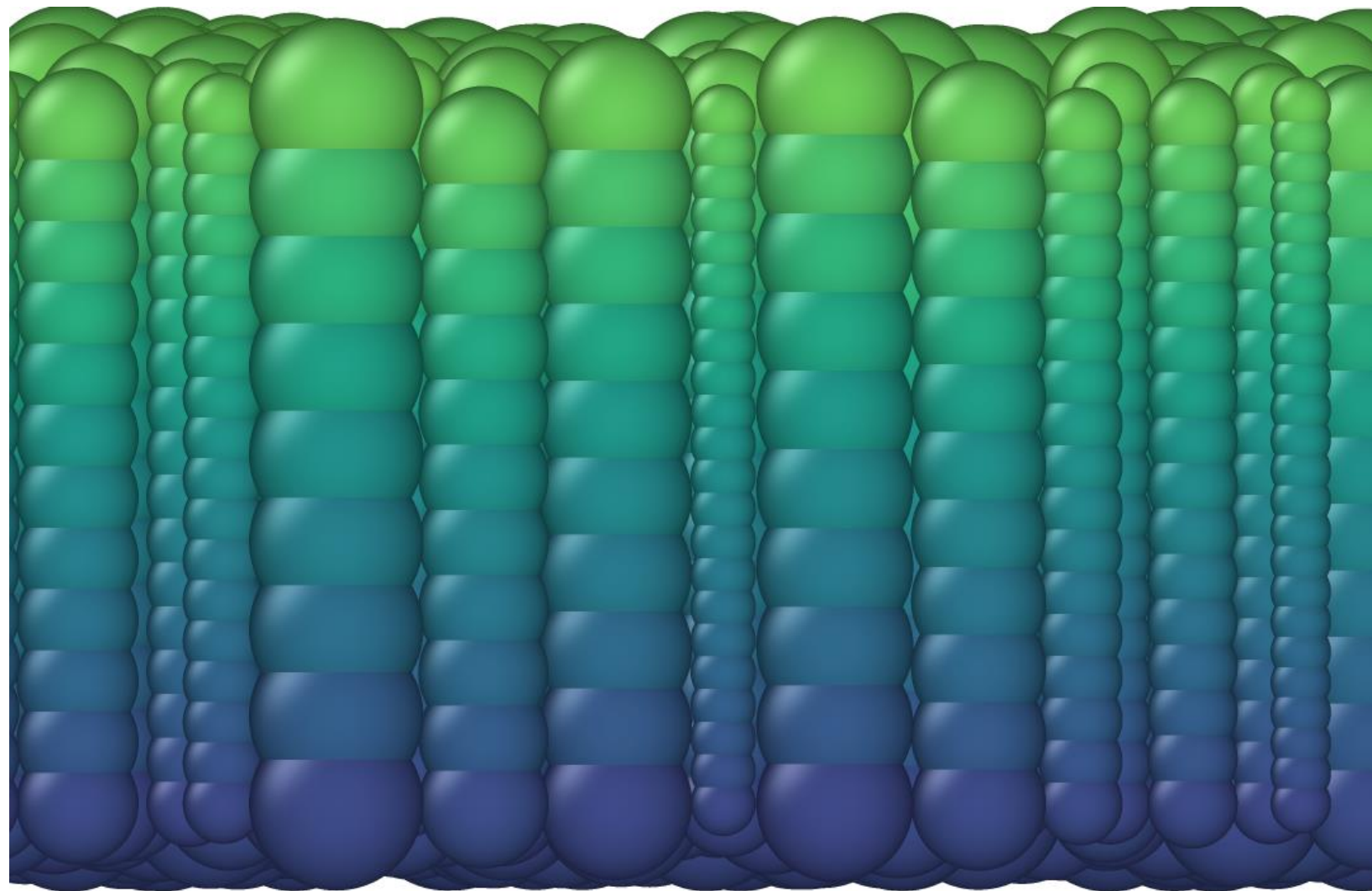
Credit: Bcomp and ESA

Capture the role of defects on material properties and performance

Demisable, RF-transparent, strong satellite components

We are always open to simulating other composite materials – **woven/nonwoven, carbon/polymer/ceramic/glass, coated/uncoated** – undergoing other process – **deformation, failure, thermal.**

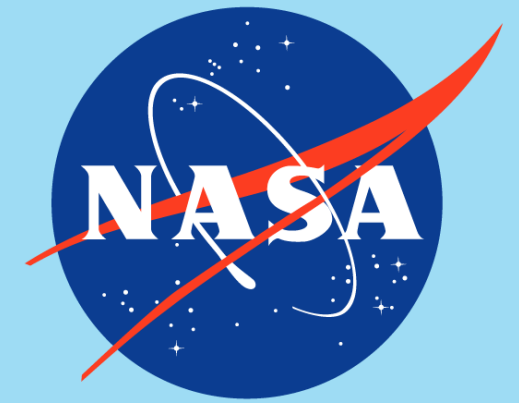
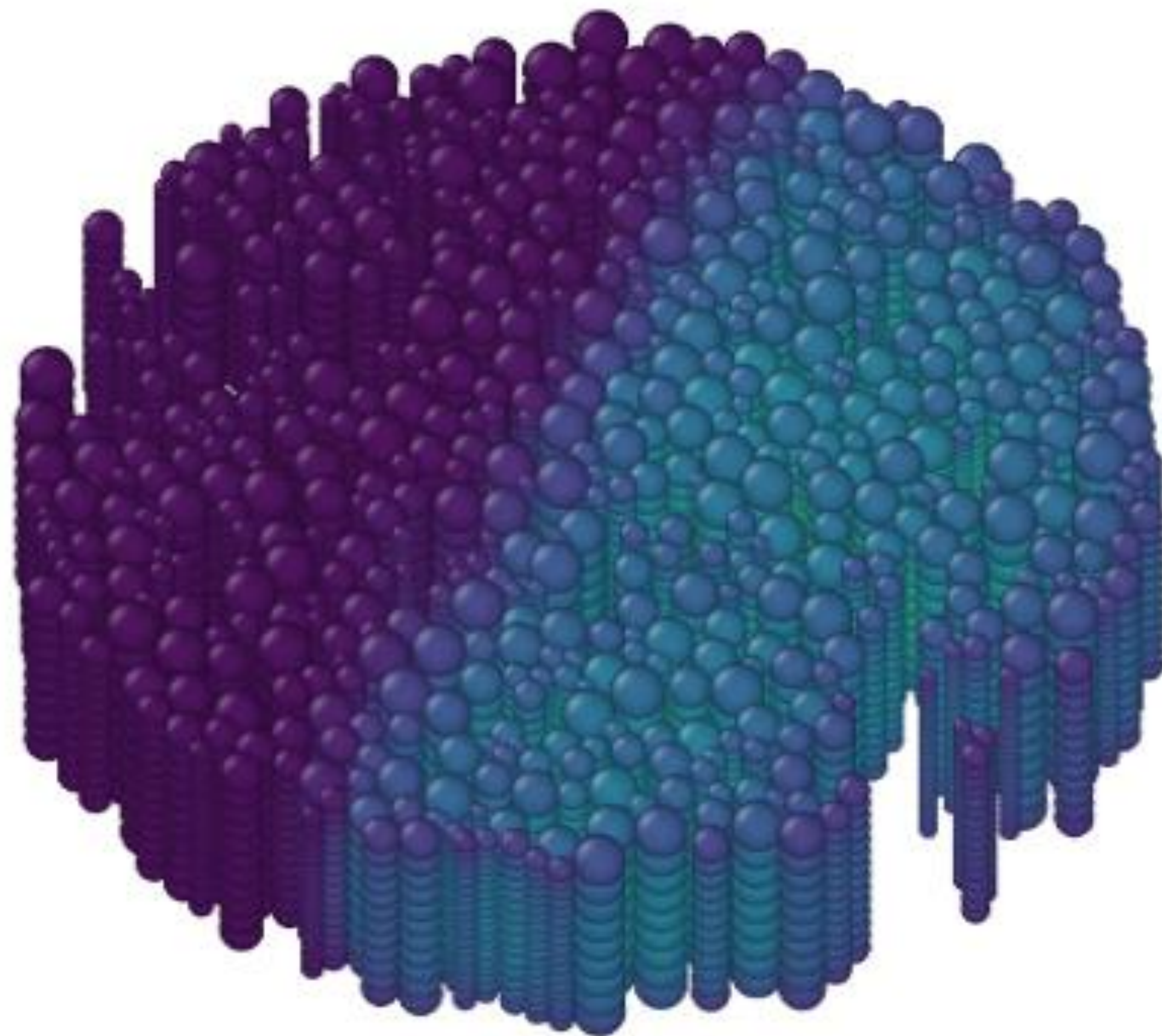
Thermal Expansion Coefficient



No validation yet, just heated the tops of the fibers and you can see here they expanded (Colored by displacement)

Could have used literature values for validation, but spent my time on mixed fibers

Radiation



Background Temp: 300K

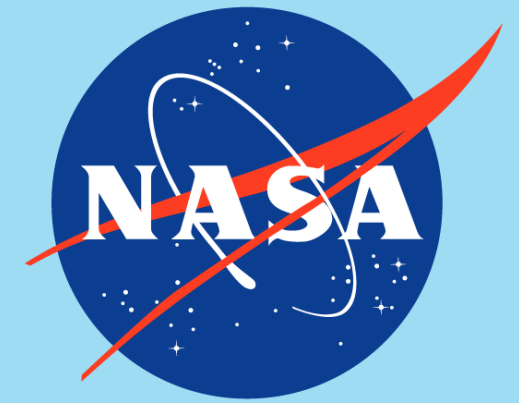
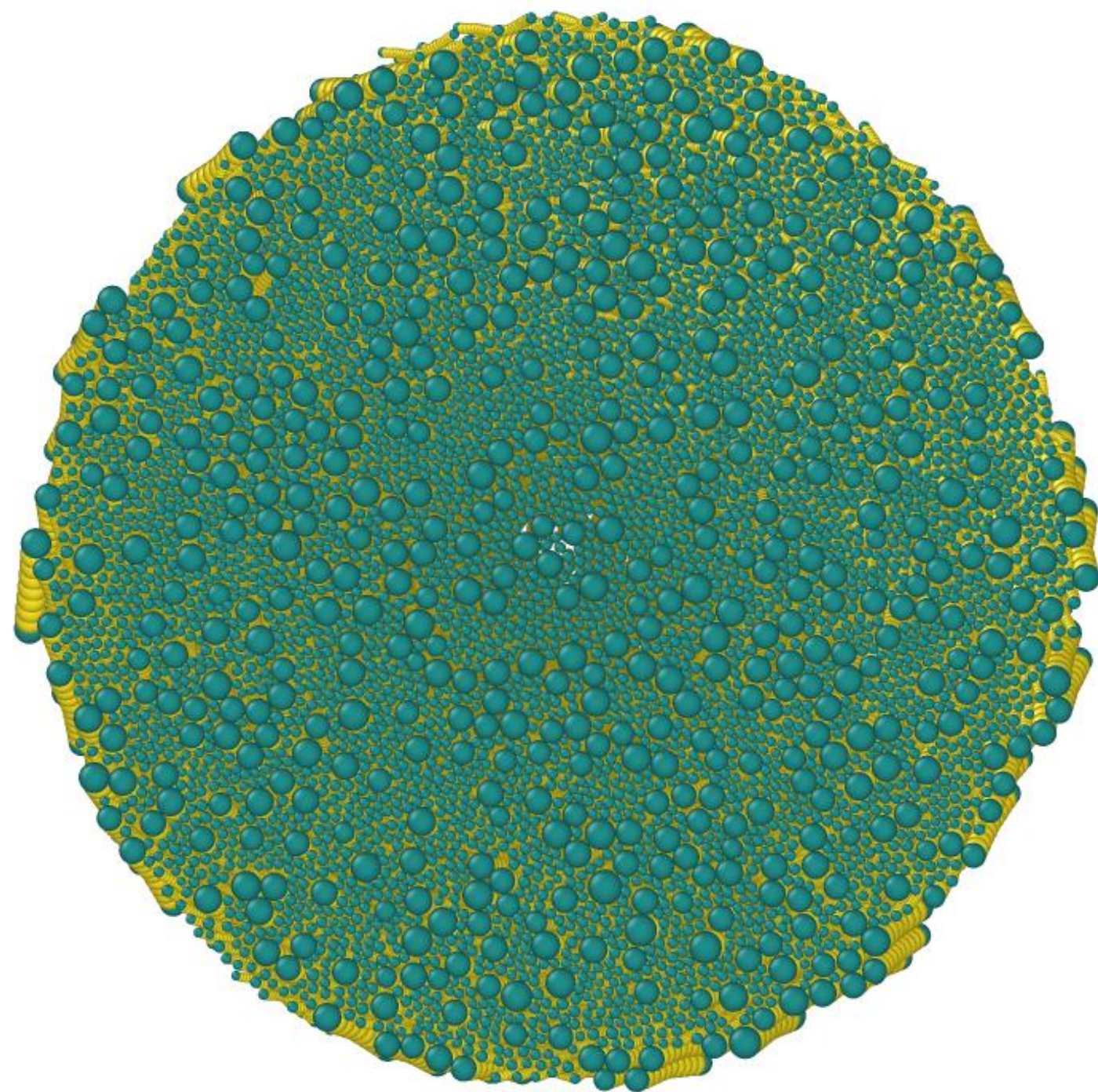
Yellow initialized Temp: 800k?

Purple initialized Temp: 300K

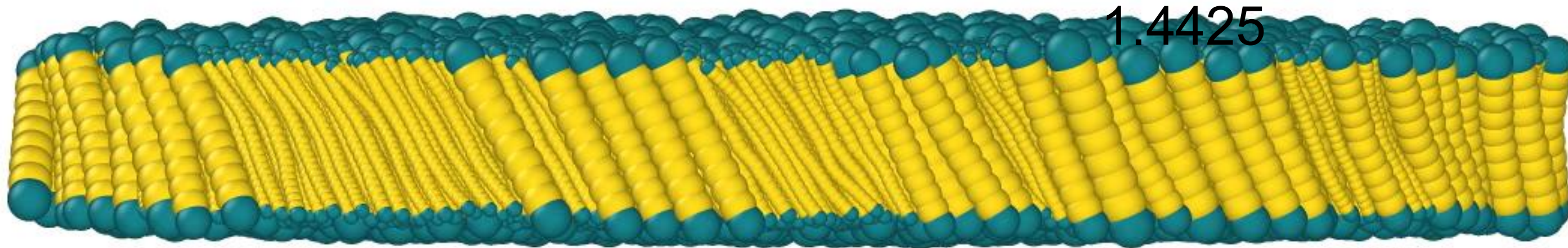
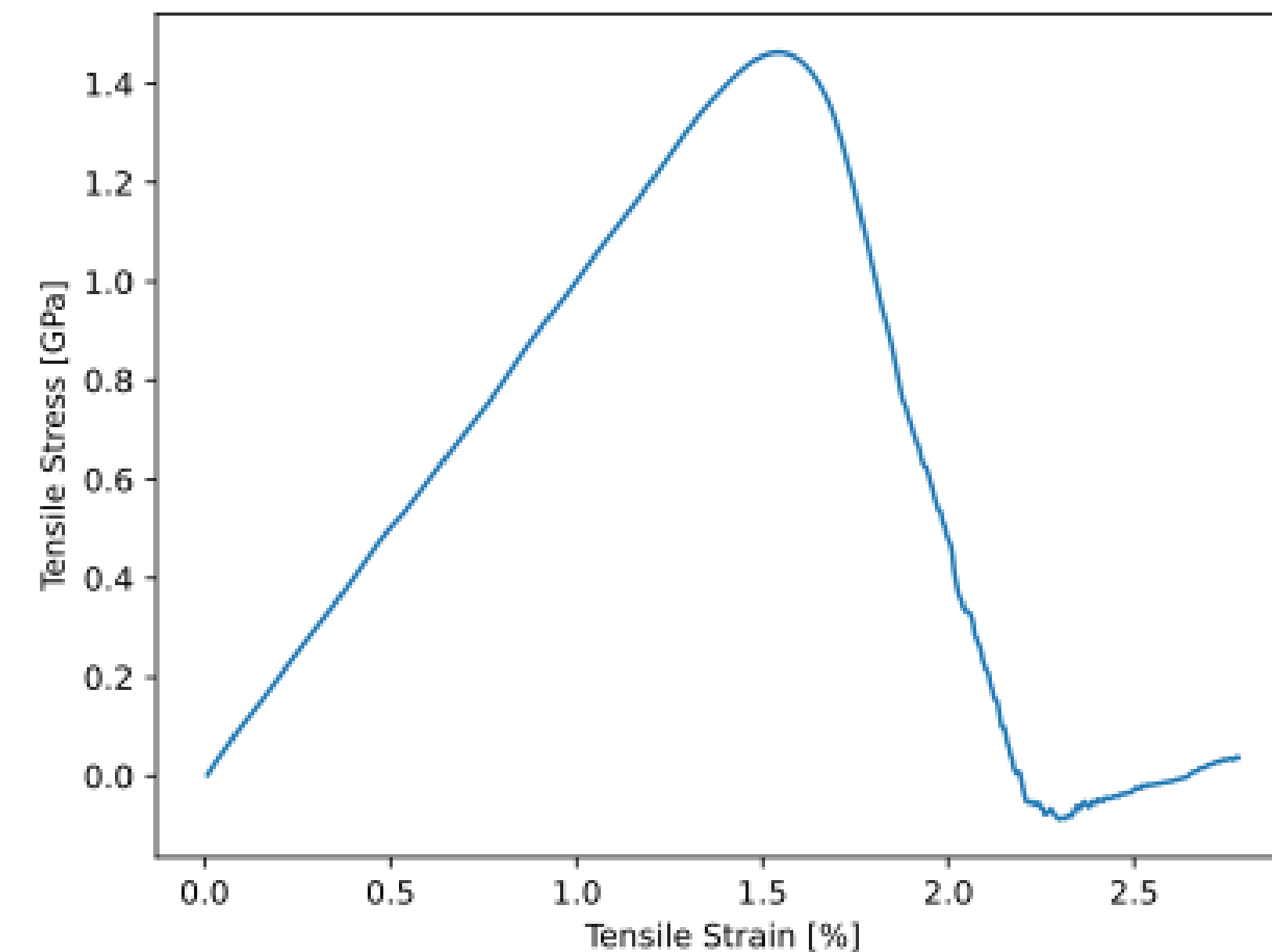
Bond conduction is turned on. I don't believe contact conduction is on here

Internal temp is higher than outside, radiation 'looks' to be working, but need a proper validation test to confirm

Mixed Fibers Twisted



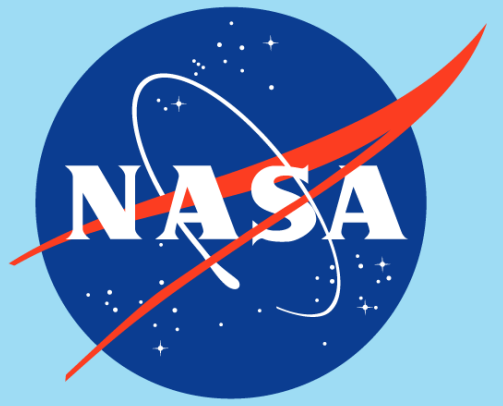
- Area Ratio
Carbon/Phenolic: 1.1745
- Experimental Ratio: 1.1742
- Volume averaged Young's Mod: 90 GPa
- Diameters:
 - Carbon: Gauss dist.
Ave: 6.507 with std: 0.4993
 - Phenolic: Gauss dist.
Ave: 16.25 with std 1.4425



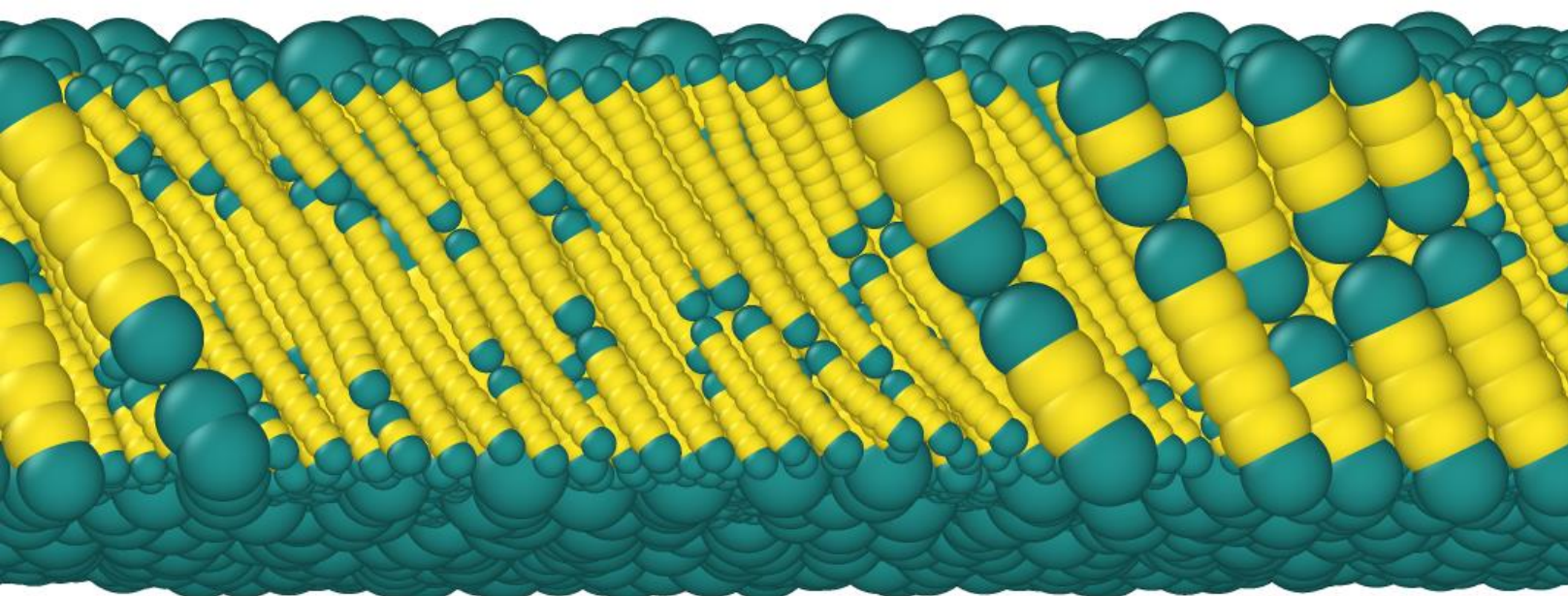
YM: 112 GPa, (1 order of magnitude higher than experimental, ~10 GPa)

Strength: 1.46 GPa (440 N, twice as high as experimental)

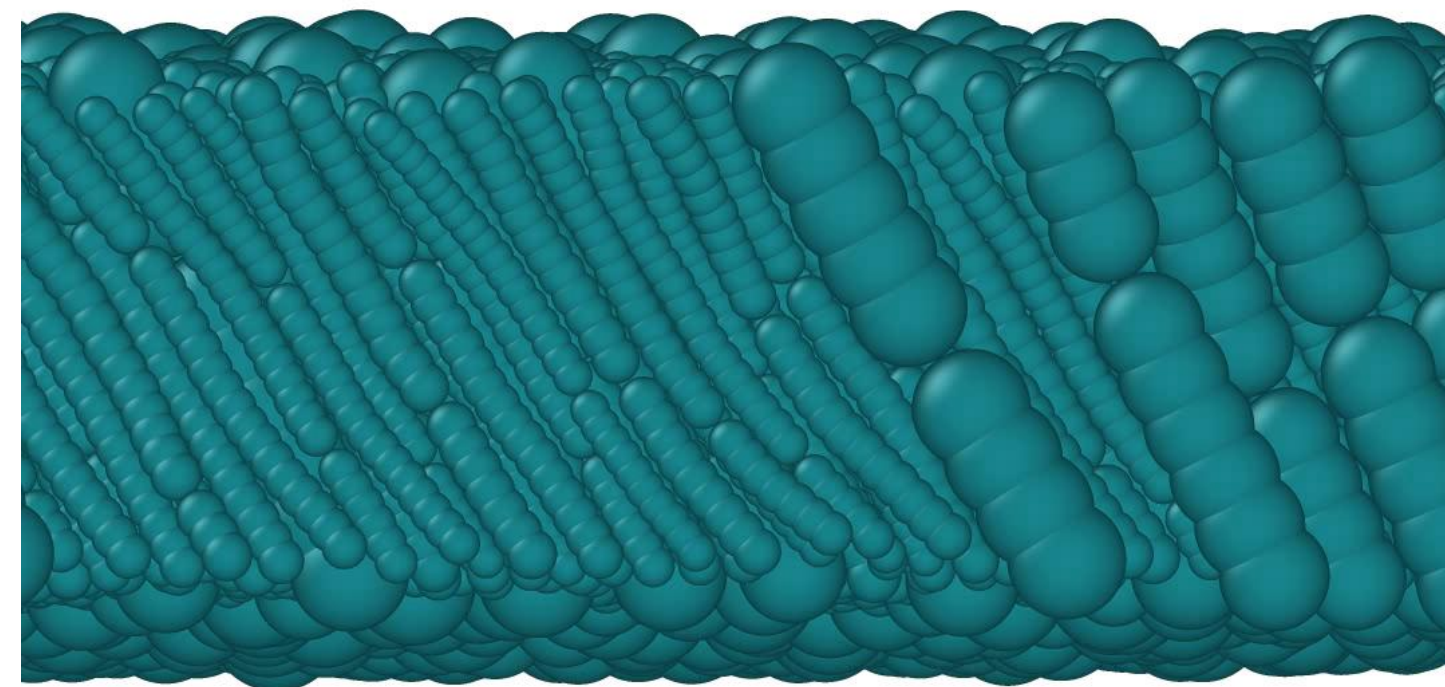
Stretch Broken Fibers



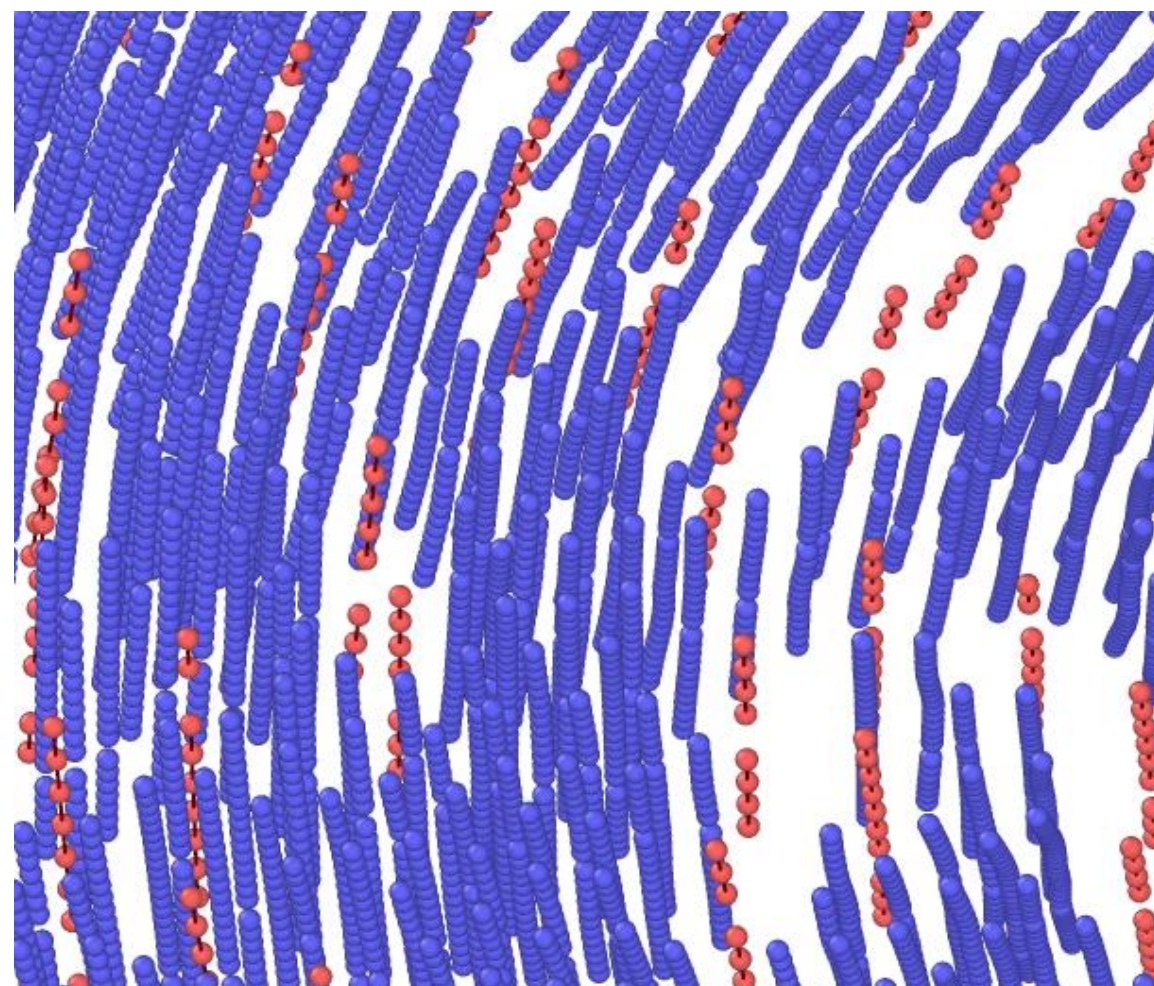
All fibers are broken in half randomly not in the grips region



Example without contacts



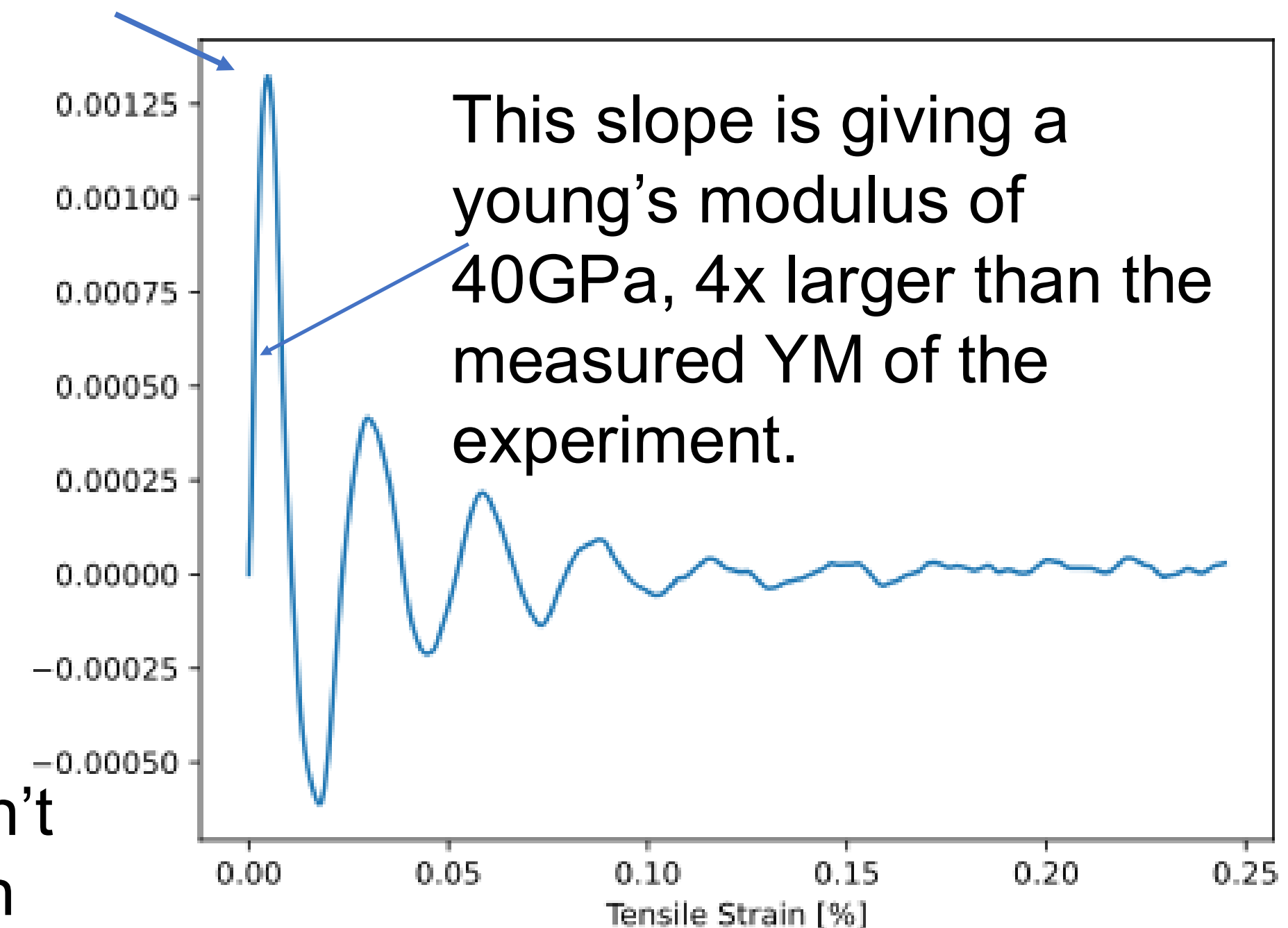
Bond visualization



Carbon fibers are very stiff, Here we're aren't measuring the young's modulus of a stretch broken yarn, it is a measurement of fibers being pulled faster than the fibers momentum responds

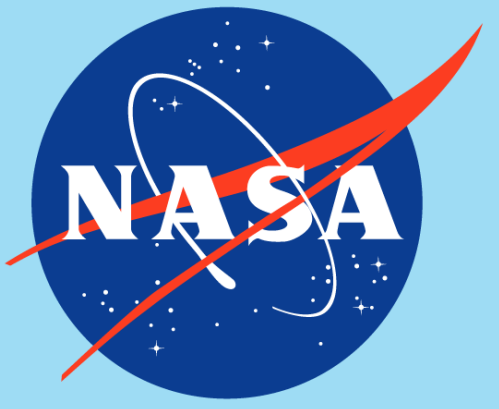
Options:

- Initialize with velocity on particles
- Ignore the initial part of the data until it reaches S.S. ?
- Decrease velocity we are pulling yarn at



Takes a lot more time steps

Explicit Porosity and Network Connectivity



1. Generate random packing:
 - a) 20,000 particles in Start from a low volume fraction
 - b) Vary triclinic box dimensions to satisfy a very low pressure tensor
 - c) Discrete element modeling (DEM) with frictionless Hertzian contacts
2. Add bonds:
 - a) contacting and next-nearest neighbors (within $\sim 1.5D$); 10-17 bonds/particle
 - b) Vary bonding radius $R_b = 7.5, 8.5 \mu\text{m}$ ($\langle N_{\text{bonds}} \rangle = 11, 13.4$ respectively)
3. Add Porosity explicitly
 - a) Delete spherical segments of material
 - b) Vary pore radius $R_p = 3 \mu\text{m}, 9 \mu\text{m}$ (0.5D and 1.5D)
 - c) Vary porosity $\phi = 0.01, 0.1$

