Entry Systems and Technology Division
Ames Research Center

National Aeronautics and
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Simulations of Yarn Micro-Mechanics of Woven Heat Shield Materials

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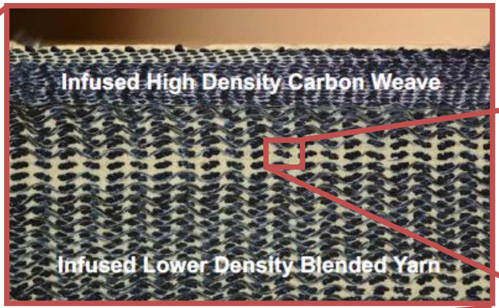
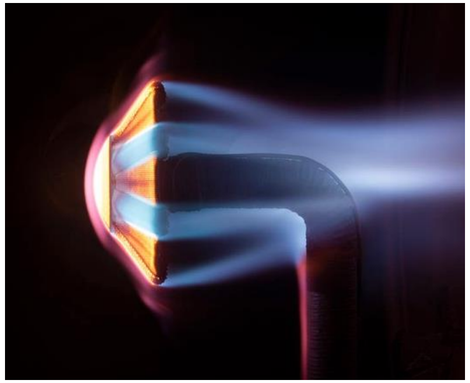
ENTRY SYSTEMS MODELING

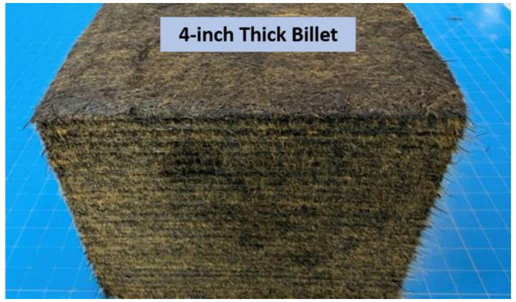
Relevant Ablative Materials that are Fibrous

3D Woven Mid-Density Carbon Phenolic (3MDCP)



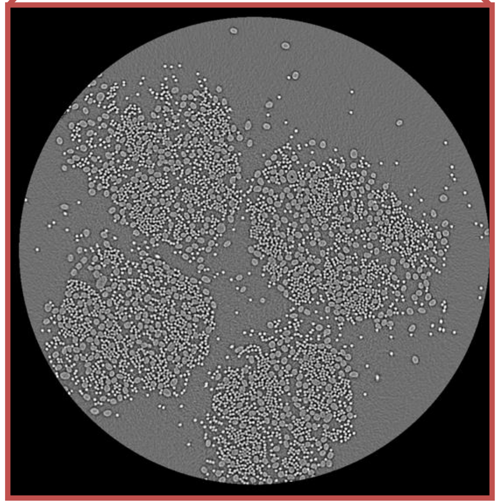


Adaptable Deployable Entry and Placement Technology (ADEPT)



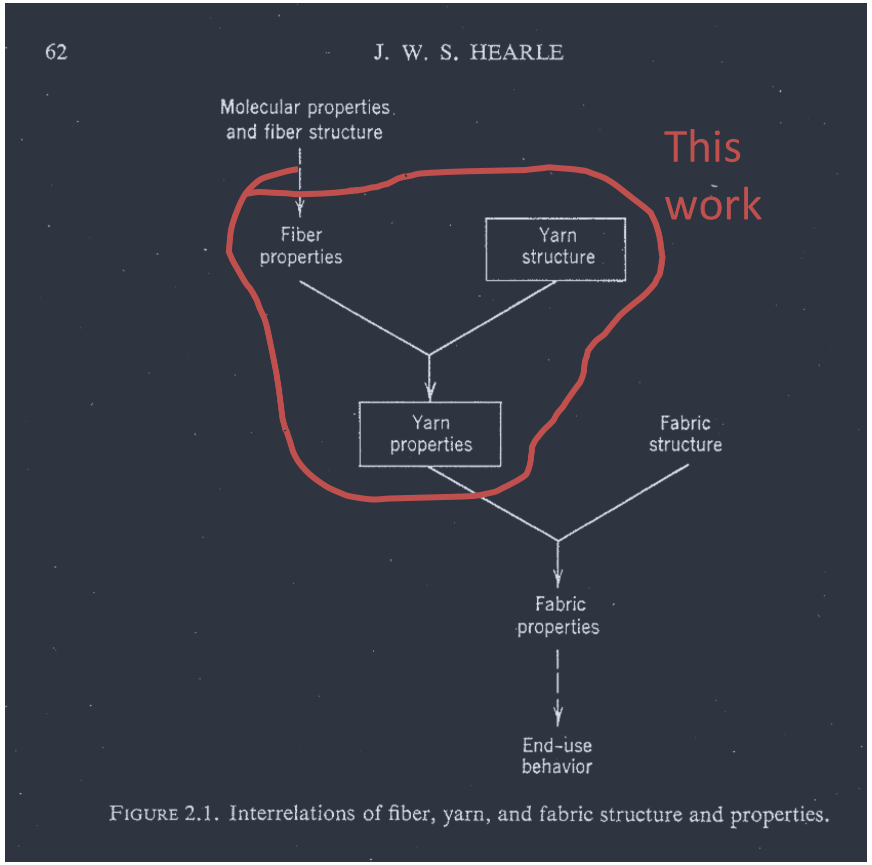
MERINO

Macro scale properties of ablative materials are dictated by their micro and meso-scale properties and geometry



D Ellerby et al, MS&T, 2019 • A Vanaerschot et al, Composite Structures, 2017, 173, 44-52
Jonathan Boustani, NASA Ames Summer Series 2022 • *Phillipe et al. SCITECH 2024*

Understanding Fibrous Materials

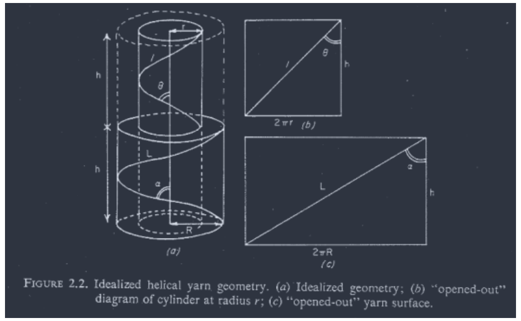


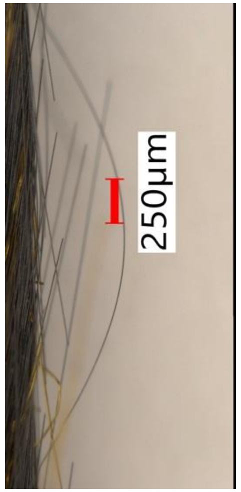
J. W. S. Hearle: Lots of foundational yarn work from the 60's!!

This presentation is focused on validation case of 3MDCP yarn simulations, but these simulation method could be used for many other things (MERINO, ADEPT, Parachutes, etc.)

Fiber Properties: Moduli, strength and strain at breakage, plastic deformation, contacts, friction, fracture

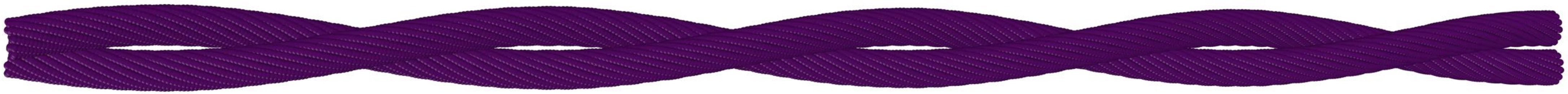
Yarn Structure: twist, entanglements, plies, stretch breaking





Discrete Element Method (DEM)

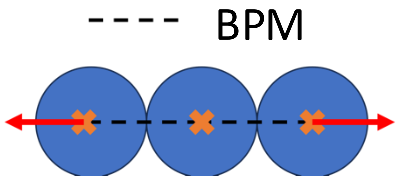
- Particle based method similar to Molecular Dynamics
  - Not atomistic: **particles/spheres** represent enough material to be a continuum
  - Typically used for granular/powered flows (think Sand!)
- Captures Fiber Micromechanics:
  - *Between two fibers*: **contacts**, **friction**
  - *Within a fiber*: **stretch/compress, bend, shear, twist, fracture**
  - Can also model **thermal conductivity** within and between fibers and expansion within fibers
- Captures **adaptive system geometry**: Twisting, stretch breaking, ply counter-twist, entanglements

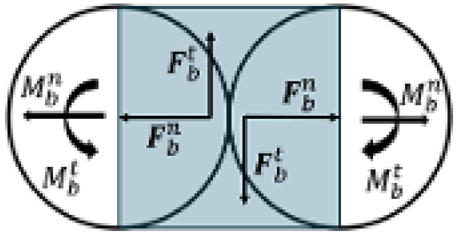


Yarn Simulations With Bonded Particle Model (BPM)

Within a Fiber

Fibers made of spheres connected with BPM





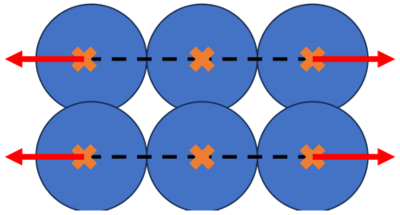
- Stretch/compression, bending, shear, twist forces handled via BPM

$$\mathrm{d}F_{\mathrm{n}}^{\mathrm{b}} = \frac{EA}{l_{\mathrm{b}}}\mathrm{d}\delta_{\mathrm{n}}^{\mathrm{r}} = \frac{EA}{l_b}v_{\mathrm{n}}^{\mathrm{r}}\mathrm{d}t,$$

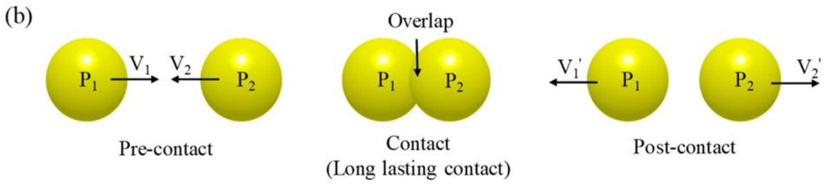
- **Fracture is modeled as deleting a bond when a stress or strain criterion is met**

$$\sigma_{\max}^{\mathrm{b}} = \frac{F_{\mathrm{n}}^{\mathrm{b}}}{A} + \frac{|M_{\mathrm{t}}^{\mathrm{b}}|r_{\mathrm{b}}}{I} > \sigma_{\mathrm{ten}}$$

Between Fibers



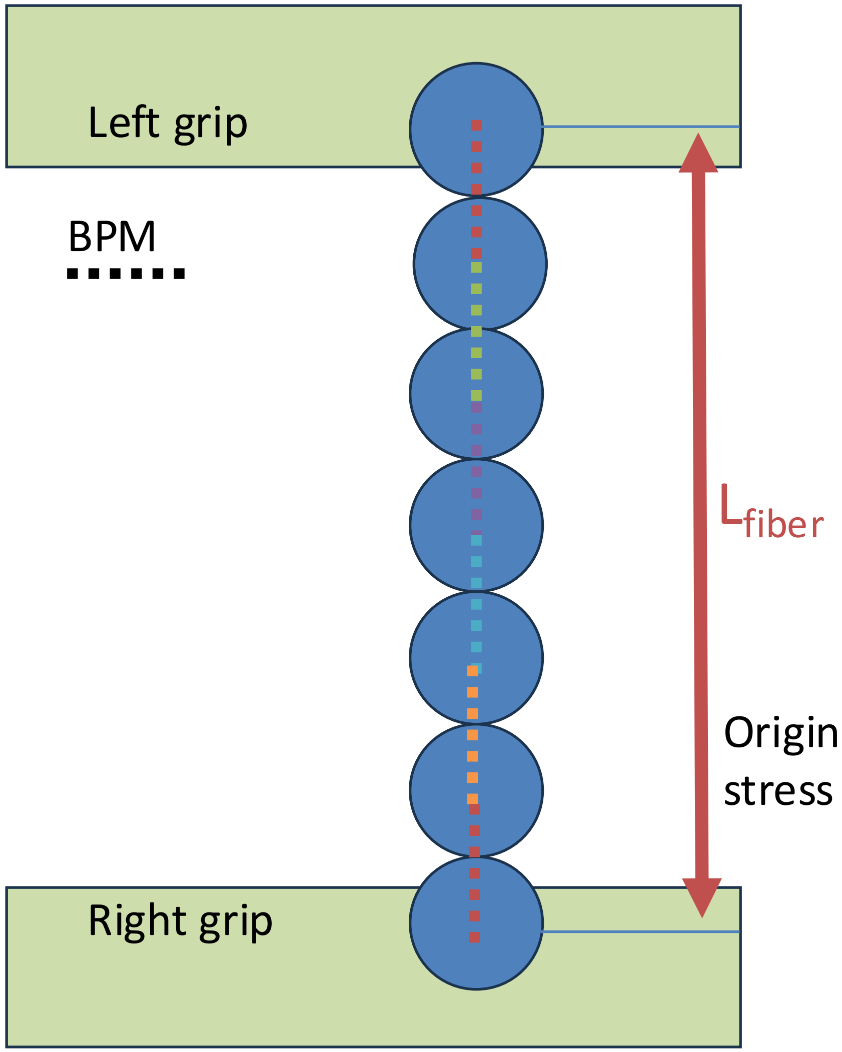
Soft body collisions:



- Collisions handled with hertz-Mindlin contact model
    - Models Normal and tangential forces including **friction** and **dampening**

Y. Guo, C. Wassgren, B. Hancock, W. Ketterhagen, and J. Curtis, "Validation and time step determination of discrete element modeling of flexible fibers," *Powder Technology*, vol. 249, pp. 386–395, Nov. 2013, doi: 10.1016/j.powtec.2013.09.007.

Weibull Breakage Model - Mechanics



Previous: Stress based Breakage Model:

- When tensile or shear forces exceed limits ($\sigma_{tensile}$ or τ_{shear}) bond is broken

$$\sigma_{max}^{b} = \frac{F_{n}^{b}}{A} + \frac{|\, M_{t}^{b} \,|\, r_{b}}{I} > \sigma_{tensile} \qquad \tau_{max}^{b} = \frac{|\, F_{t}^{b} \,|}{A} + \frac{|\, M_{n}^{b} \,|\, r_{b}}{I_{p}} > \tau_{shear}$$

New: Weibull Breakage applies a distribution to these limits

- Each individual bond has its own $\sigma_{tensile}$ and τ_{shear}, these are calculated by accounting for length of the bond vs the experimental length

$$\sigma_{0,bond} = \sigma_{0} \left(\frac{L_{calib}}{L_{bond}} \right)^{\frac{1}{m}}$$

Original tensile stress limit

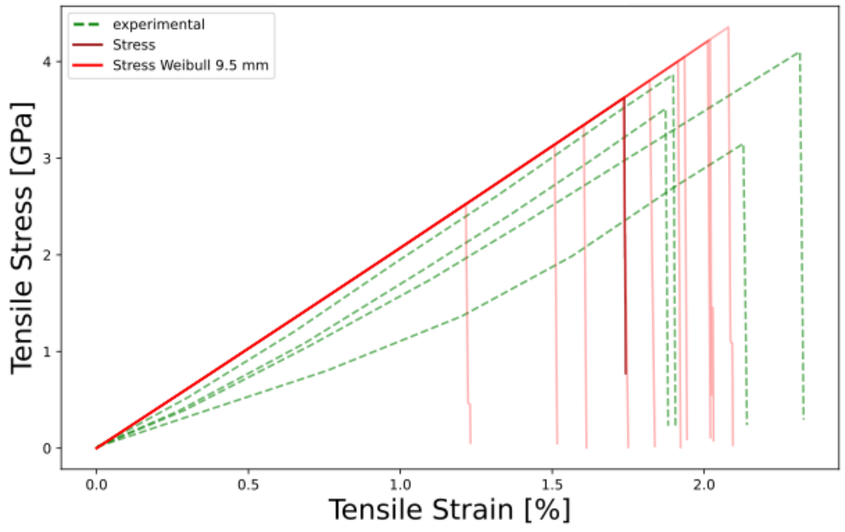
Random number unique to each bond

$$\sigma_{tensile} = \sigma_{0,bond} \left(-\ln(1-u) \right)^{\frac{1}{m}}$$

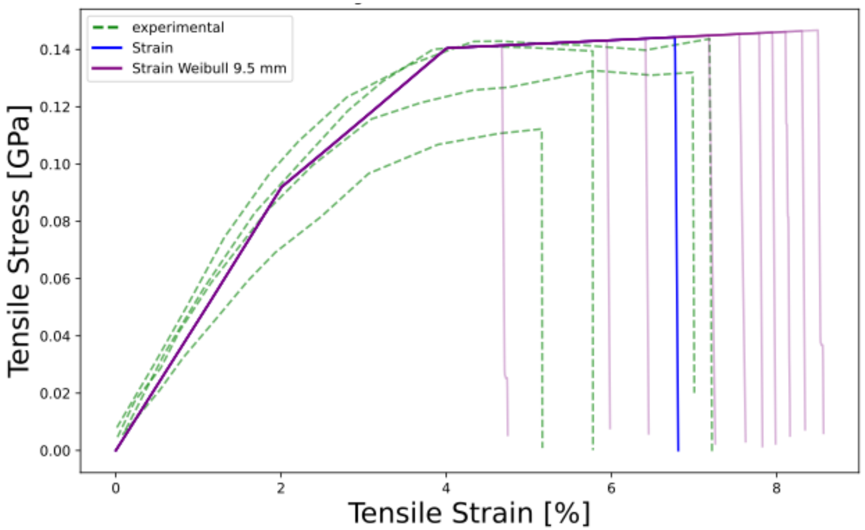
- Now fibers can break at the "weakest link" (bond where $\sigma_{tensile}$ happens to be lowest)
  - Fibers are also more likely to break the longer they are

3MDCP – Single Fiber – Carbon and Phenolic

Carbon Fiber



Phenolic Fiber



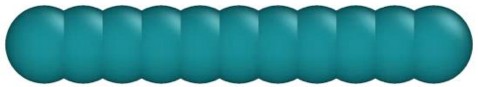
Carbon Fiber Input

- **Stress based Breakage (Dark Red):** Used reported Young's modulus and average strength

$$\sigma_{\max}^{b} = \frac{F_n^b}{A} + \frac{|\, M_t^b \,|\, r_b}{I} > \sigma_{\text{tensile}}$$

- **Weibull Stress based Breakage (Red):** Weibull Modulus (m), Characteristic Strength (σ_0), and Calibration Length (L_{calib}) from experiments

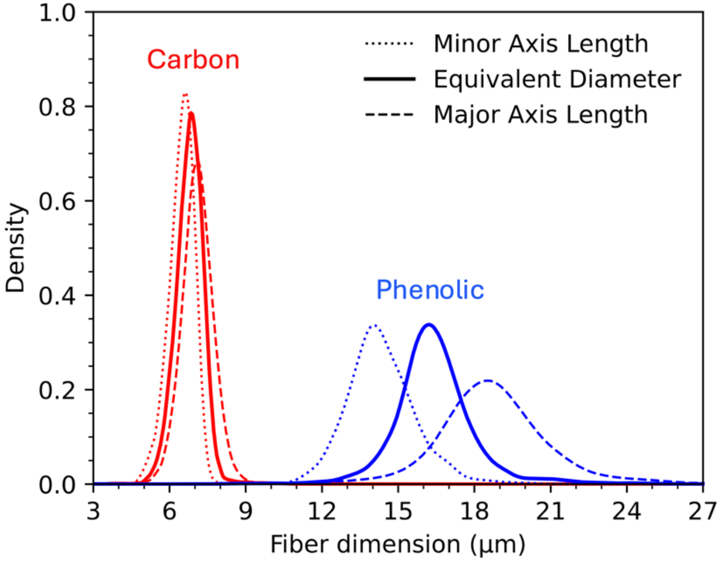
Phenolic Fiber Input



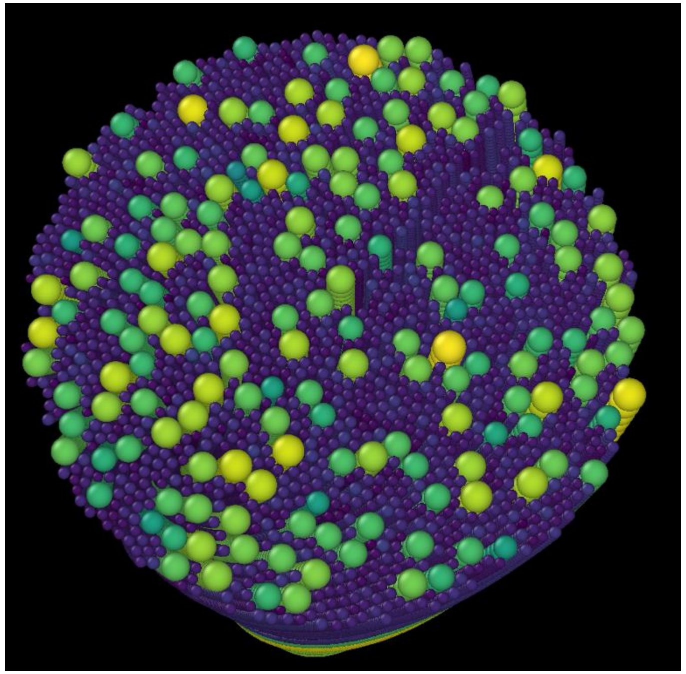
- Plastically deforms

- **Strain based Breakage (Blue):**
- **Weibull Strain based Breakage (Purple):**

3MDCP - Single ply yarn Geometry

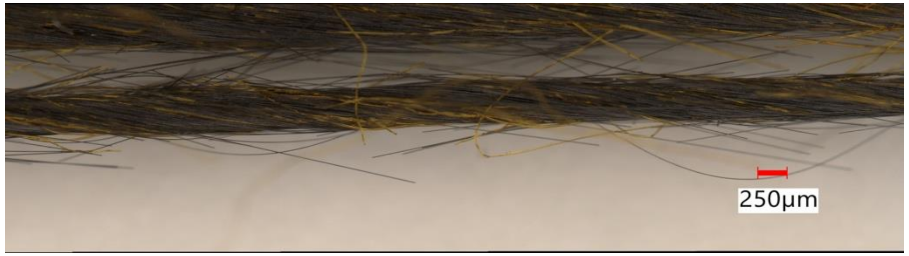


3MDCP Fiber diameter distribution from optical microscopy analysis in FY24-Cert-3 Milestone

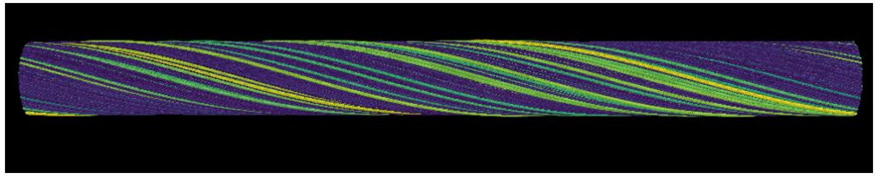


2D slice of 3MDCP single ply with matching experimental fiber radii distributions and area ratio for carbon and phenolic

~1250 fibers: randomly packed, fibers are spaced due to rotation



3MDCP single ply image used to obtain ply radius and rotation

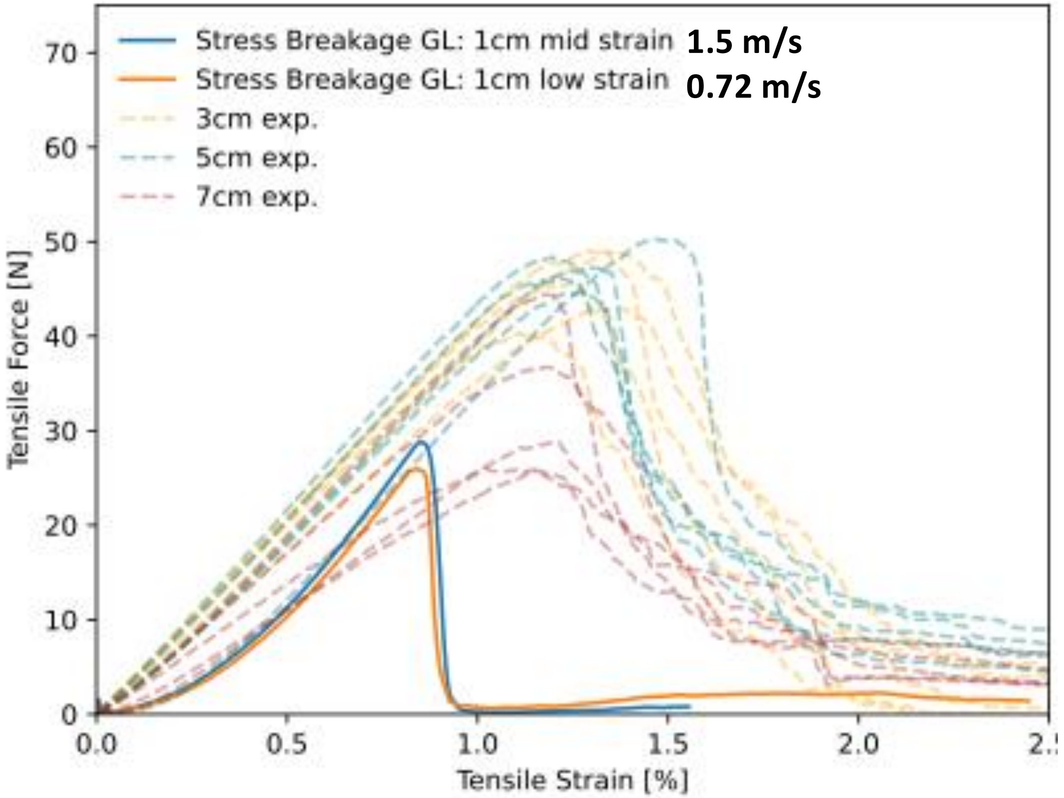


Simulated 3MDCP single ply yarn with length of 4000 µm and radius of 180 µm

Carbon

Phenolic

3MDCP - Single ply yarn – Stress based Breakage

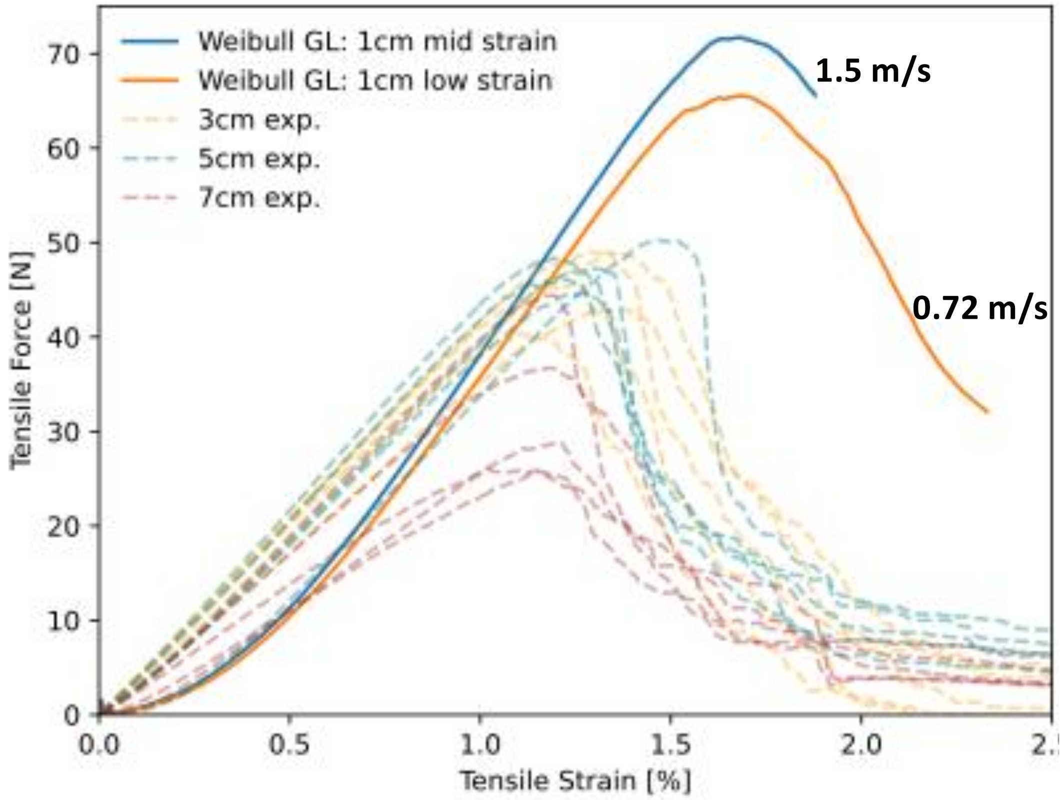


Tensile 3MDCP 1-ply yarn experimental (dashed-lines) and 3MDCP 1-ply yarn simulations (solid-lines) as varying strain rates

- Fine grain model captures 1-ply 3MDCP tensile modulus
- Simulations ran at 4-5 orders of magnitude faster strain-rate, Experimental Grip Velocity: ~**1.6e-5 m/s**
  - Breakage strength decreasing as strain-rate approaches experimental value
  - Most fibers break all at once, experiments shows breakage over ~1.5% strain

- Simulations ran at 1cm; experiments taken at 3, 5, and 7 cm gauge length

3MDCP - Single ply yarn – Weibull Breakage



Tensile 3MDCP 1-ply yarn experimental (dashed-lines) and 3MDCP 1-ply yarn simulations with Weibull breakage (solid-lines)

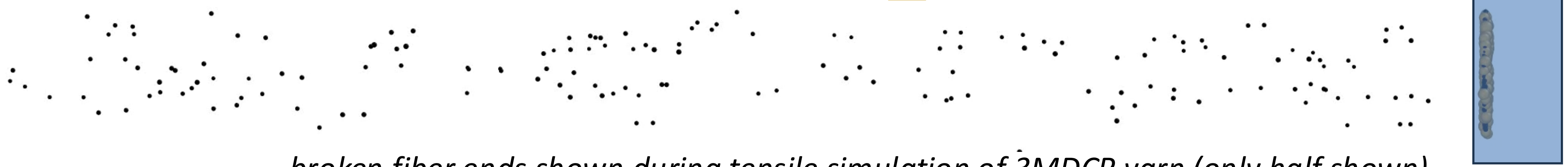
- Weibull breakage of 3MDCP yarn happens over longer strains
  - Breakage is less localized at grips, happening throughout yarn
  - % strain and strength at breakage much higher, although over predicting experimental results

- Simulations ran at 1cm; experiments taken at 3, 5, and 7 cm

Broken Carbon fiber end

Broken Phenolic fiber end

Grip Region

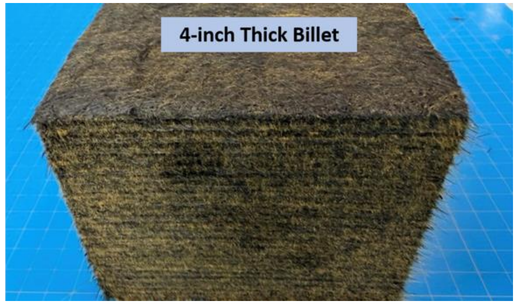


broken fiber ends shown during tensile simulation of 3MDCP yarn (only half shown)

Conclusions and Future Work

- DEM-BPM simulations can be predicted of yarn properties from fiber property inputs and yarn geometry
  - Breakage is complex and more work is needed for accurate strength predictions

- Moving into modeling felted fibrous materials such as MERINO
  - Interest in through thickness strength, planar shrinkage from charring of phenolic, needling process



Simulation paper picture
Cite patient