U.S. ARMY RDECOM

Micromechanical FE modeling of tensile failure of unidirectional composites: Experimental routes

ARL

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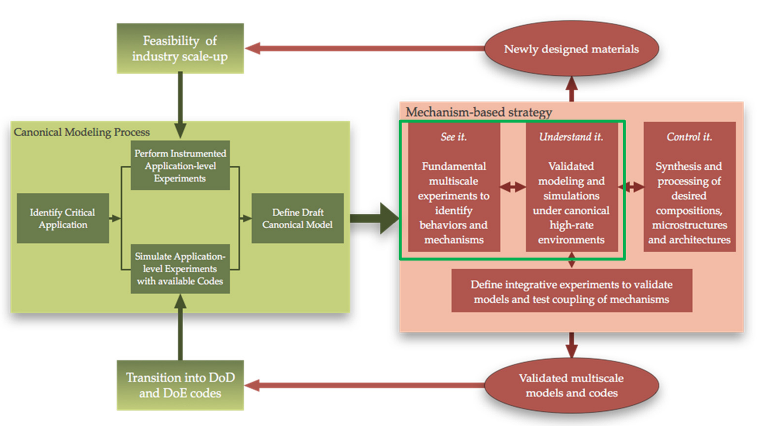
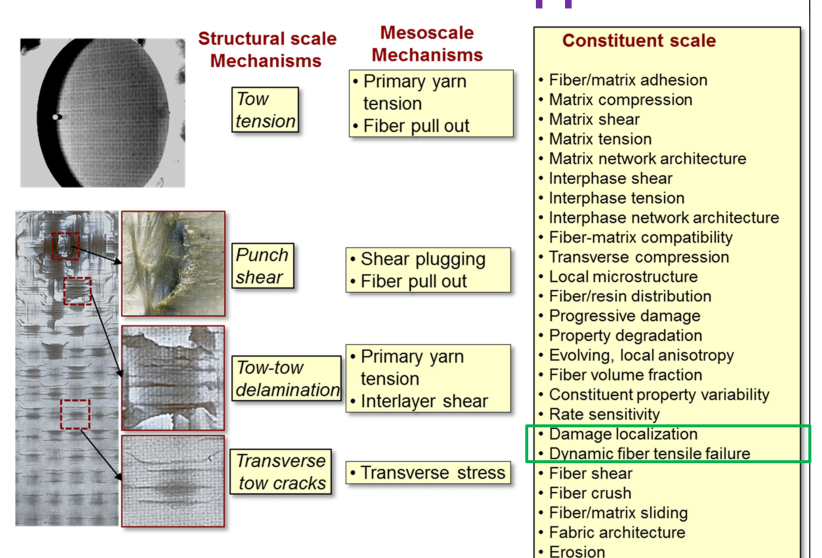
Enterprise for Multi-scale Research of Materials

How We Fit

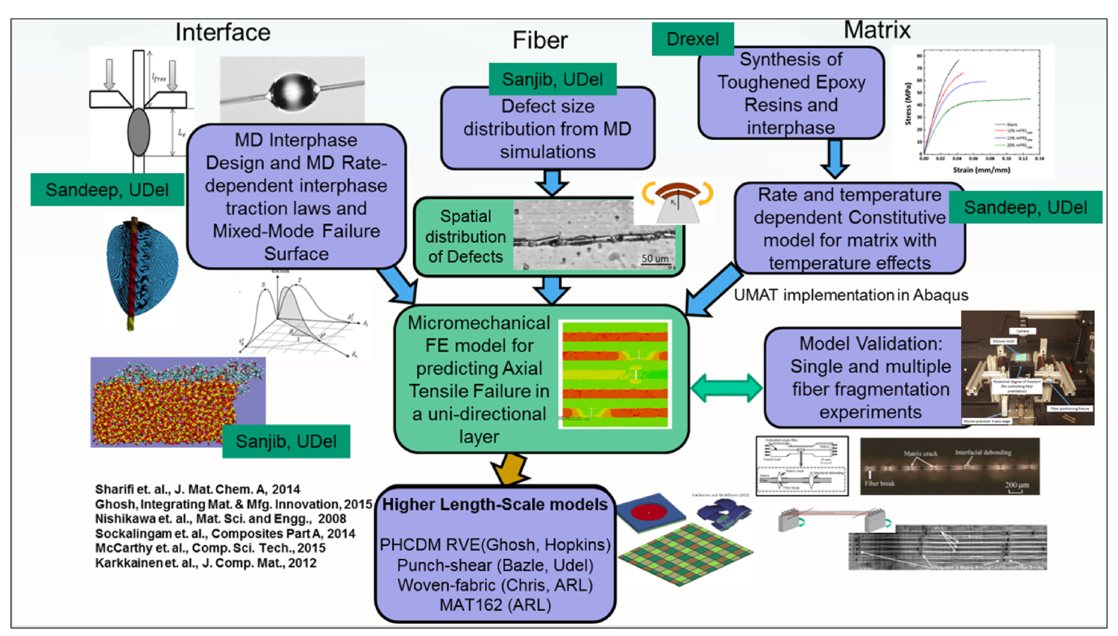
Materials-by-Design Process



Mechanism-based Approach



Interaction with composites CMRG tasks



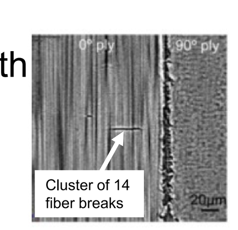
Key Goals

- Tensile strength along the fiber direction (XT) is one of the key properties identified in the objective function for composites

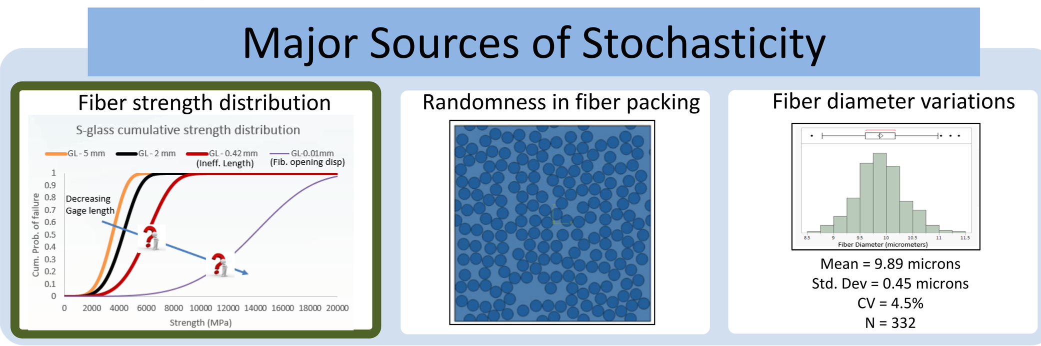
OBJECTIVE FUNCTION

$$[F(t,x).W_d]_{max} = \mathcal{F}(E, X_D(p), XT, XPCS, XPSS)$$

- Brittle S-glass fibers, have gage-length dependent stochastic distribution of strength (Depends on size and spatial distribution of critical defects)
- Dynamic Localization and clustering of fiber breaks leads to catastrophic failure
- Cannot be modeled using RVEs



Major Sources of Stochasticity



To experimentally determine the statistical distribution (size and spatial) of Critical surface defects in S-glass fibers

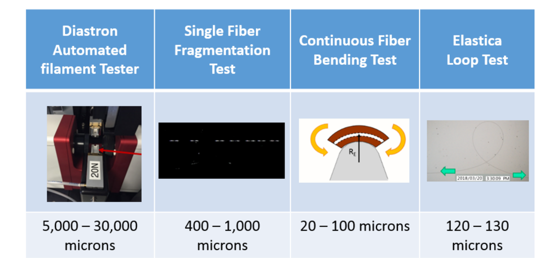
Use this input in micromechanical FE models to accurately predict the dynamic localization and clustering of multiple fiber breaks (which ultimately leads to composite failure)

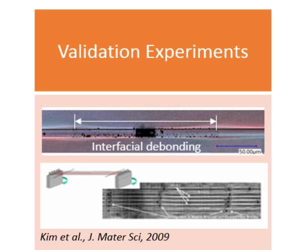
Integrative model of lower length-scale constitutive models for the fiber, matrix and interphase

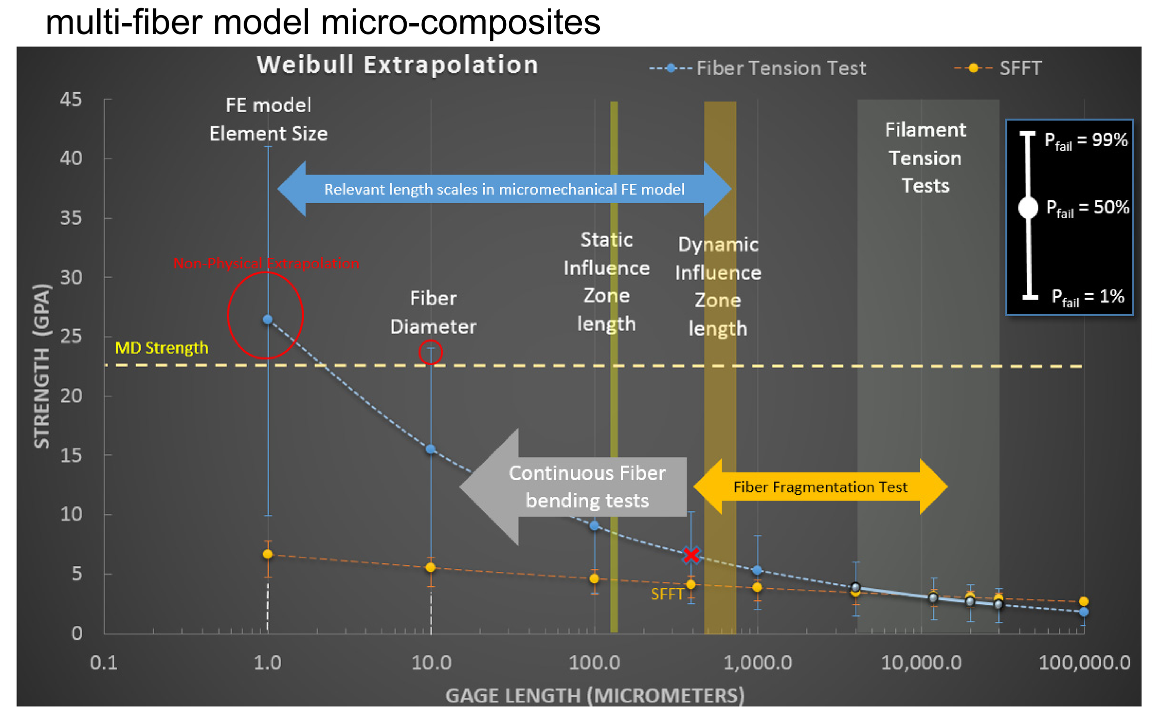
Materials by design: Provide feedback to MEDE collaborators in terms of tailoring the matrix and interphase as a system to maximize strength and overall energy absorption in composites during high strain rate tensile loading

Technical Approach & Major Results

- Establish distribution of fiber defect sizes and their spatial location as physical basis for mapping defects for dynamic modeling of micromechanical tensile failure
- New test methods required for extending to lower length scales and for model validation
- Experimental validation of the model using single and multi-fiber model micro-composites



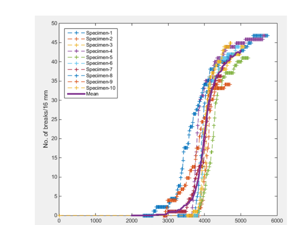




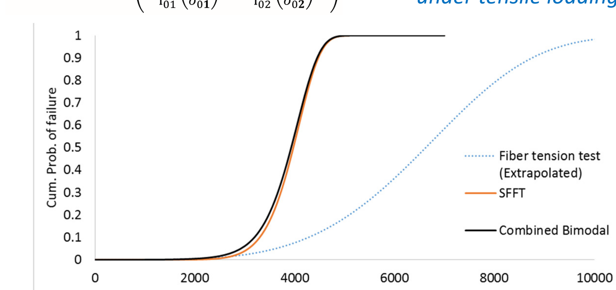
Bimodal Weibull distribution

Parameter	Value
l_{01}	16 mm
σ_{01}	3.05 GPa
$\beta 1$	4.31
l_{02}	0.365 mm
σ_{02}	4.29 Gpa
$\beta 2$	12.57

$$F(\sigma, l) = 1 - \exp\left(-\frac{l}{l_{01}}\left(\frac{\sigma}{\sigma_{01}}\right)^{\beta_1} - \frac{l}{l_{02}}\left(\frac{\sigma}{\sigma_{02}}\right)^{\beta_2}\right)$$



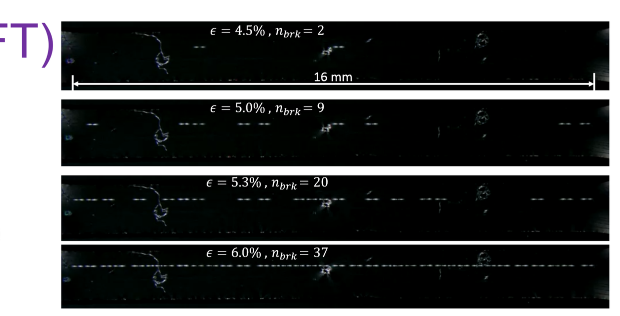
Progressive fiber fragmentation under tensile loading



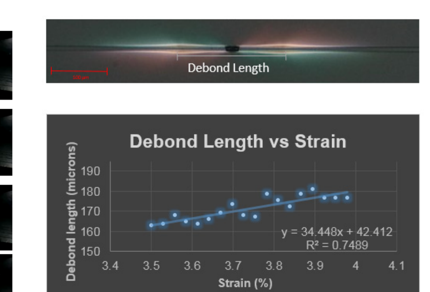
S-glass Cumulative Strength distribution at 365 microns

Single Fiber Fragmentation Test (SFFT)

- Single S-glass fiber embedded in DER353-Epoxy Dogbone
- Saturated fragment length of 365 microns (defects spaced within this length are shielded)
- Extrapolation of fiber tensile test data leads to over-estimation of mean strength by ~25%



In-situ visualization using cross-polarized light

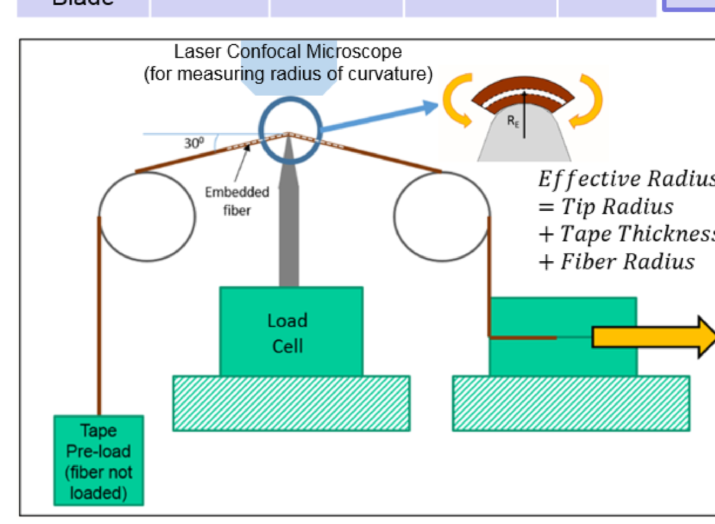


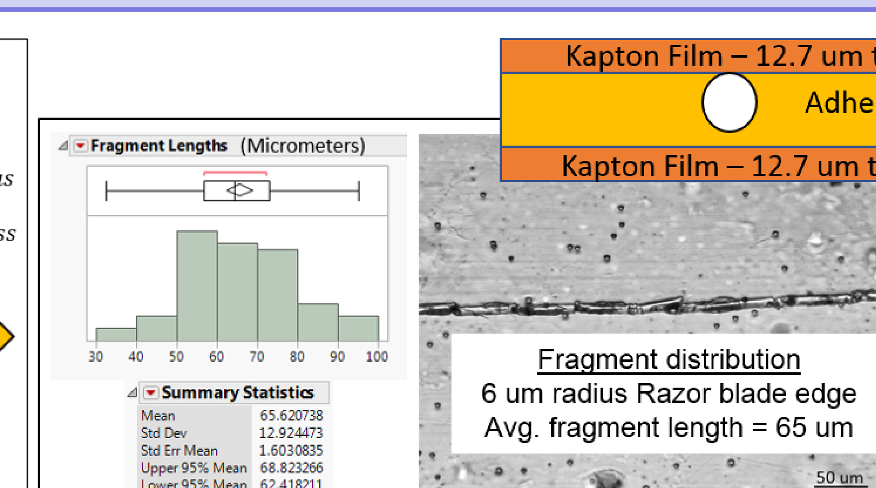
Interfacial debond growth accompanying a fiber break

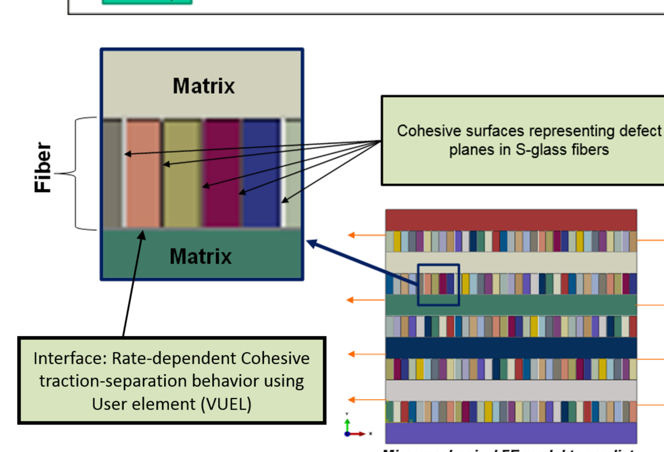
Measuring Critical Defect Distribution : Continuous Fiber Bending Experiment

Tip	Radius (µm)	Effective Radius, R_E (µm)	Max. Bending Stress (GPa)	Max. Strain %
Boron Fiber	55	79	5.7	6.3%
Blunted Razor Blade	31	55	8.2	9.1 %

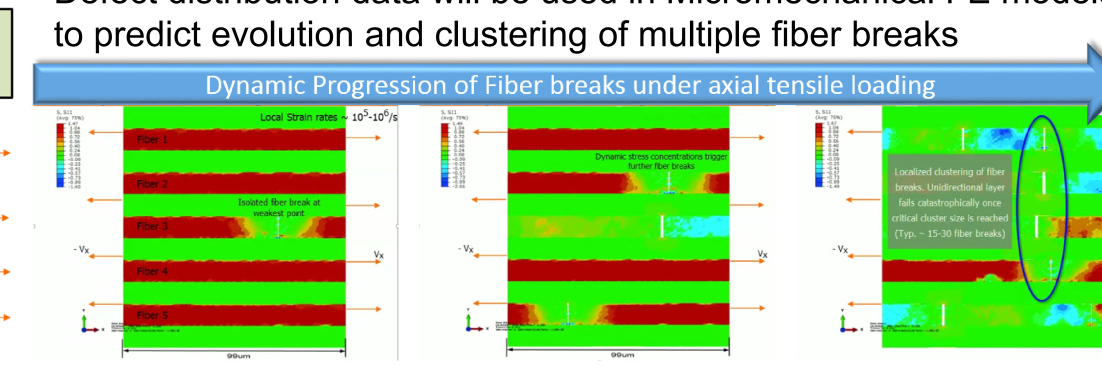
Sandwich specimen is moved over a distance of 25 mm to ensure that all cross-sections of the fiber are subjected to the same radius of curvature within this gage length





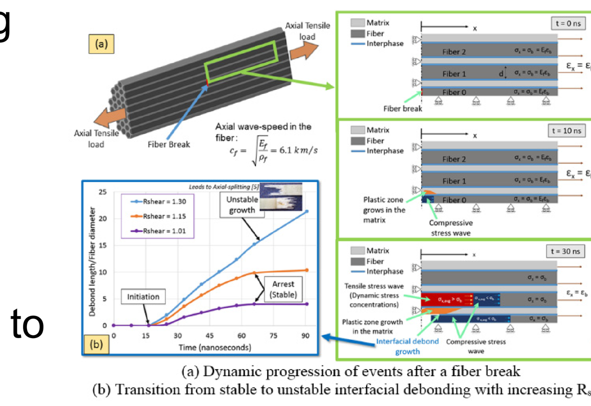


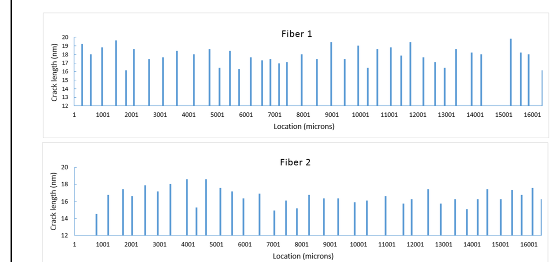
Defect distribution data will be used in Micromechanical FE models to predict evolution and clustering of multiple fiber breaks



Key Accomplishments

- Developed and validated a fiber-level FE modeling framework to capture the dynamic effects of a single fiber break while relaxing the inherent assumptions in theoretical shear lag models
- Identified influential non-dimensional parameter, R_{shear}, which gives insights into micromechanical damage mechanisms and demonstrated the need to tailor the matrix and interphase as a system

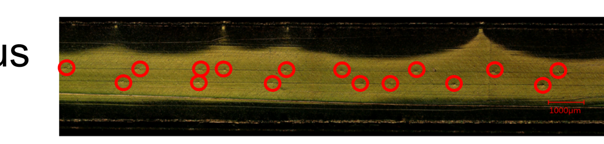




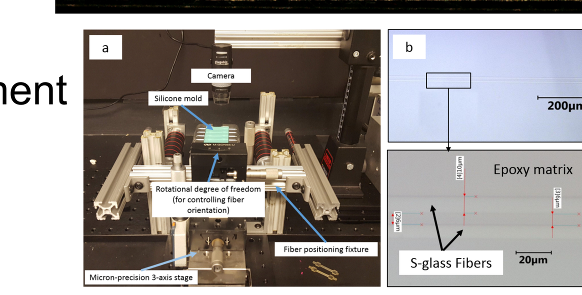
Critical defect distribution in S-glass fiber backed out from SFFT

- Extended the scope of SFFT using in-situ visualization of fiber break progression
- LabView script to track the locations of each fiber break in SFFT and index them
- In-situ observation of interfacial debond growth accompanying fiber breaks

- Developed novel experimental method (Continuous Fiber Bending Experiment) to characterize spatial distribution of critical defects in the fiber



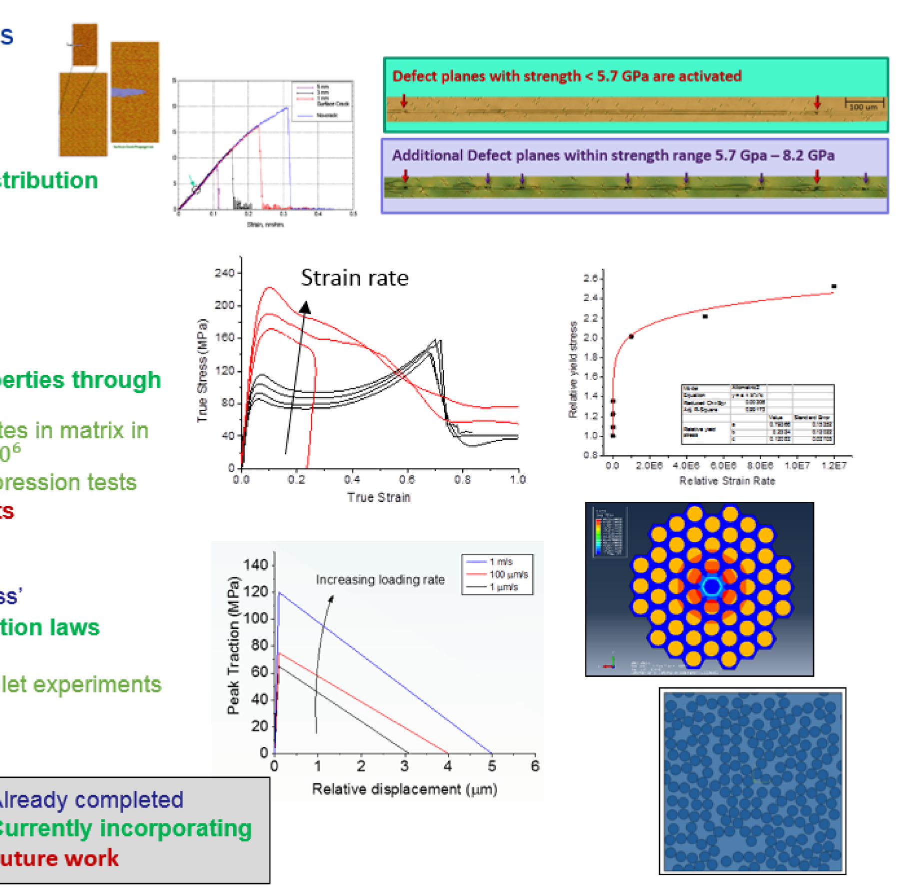
- Designed and manufactured precision fiber-placement fixture(a) to create precisely controlled multi-fiber microcomposites(b) for FE model validation



Project Roadmap

Unidirectional Continuous fiber composites
- Effect of Thermal Residual Stresses
- Fiber
  - Linear Elastic
  - Dynamic break
  - Incorporate Statistical defect distribution
    - Size distribution
    - Spatial distribution
- Matrix
  - Toughened Epoxy resins (Drexel)
  - Elastic – Plastic
  - Rate- and Temp-dependent properties through VUMAT
    - Model predicts local strain rates in matrix in the range of $1 \times 10^{5} - 6 \times 10^{6}$
    - Experimental data from compression tests
    - Hydrostatic pressure effects
    - Mode I fracture
- Interphase
  - Cohesive surfaces – 'Zero thickness'
  - Rate dependent Traction-separation laws through VUEL
  - Experimental data from micro-droplet experiments
- Unidirectional Fiber length scale models
  - Extend to 3D
  - Incorporate residual stress
  - Random fiber packing
- High rate axial loading
- Multi-axial loading and penetration

Already completed
Currently incorporating
Future work



Impact

- Generation of a defect-distribution based model capable of predicting progression of fiber breaks under a range of applied strain rates
- Framework for tailoring interface and matrix to enhance tensile properties and energy absorption in the composite
- Study the interaction of micromechanical damage mechanisms inside a realistic composite system
- Generate inputs for homogenized models at higher length scales : MAT-162 (ARL), PHCDM-RVE (Dr. Ghosh, Hopkins), Meso-scale woven fabric model (Chris, ARL)
- Will also provide direct input to dynamic Punch-shear models (Dr. Haque, UDel)

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